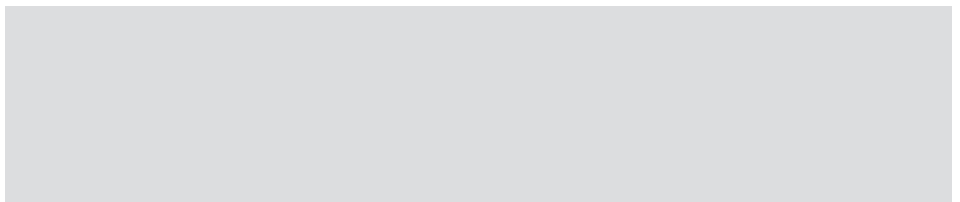


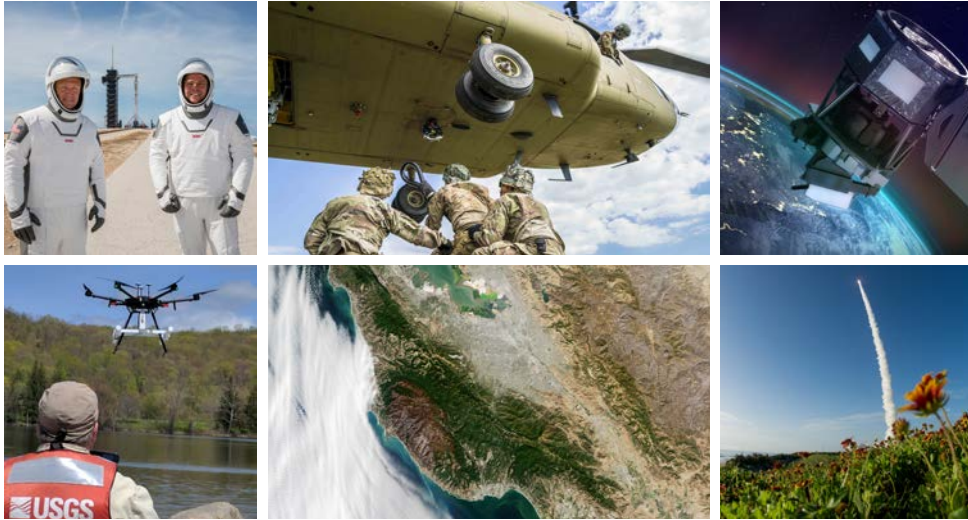


Aeronautics and Space Report of the President



**Fiscal Year
2020 Activities**





Aeronautics and Space Report OF THE PRESIDENT

Fiscal Year 2020
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, 2019, through September 30, 2020. 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. NASA astronauts Douglas Hurley (left) and Robert Behnken (right) participate in a dress rehearsal prior to the launch of NASA’s SpaceX Demo-2 mission to the International Space Station on May 30, 2020. Credit: NASA/Kim Shiflett. 2. A crew chief relays vital position information back to the CH-47 Chinook pilot from his side window as paratroopers from the 173rd Airborne Brigade prepare to hook equipment to the underside of the helicopter. Credit: U.S. Army/Maj. Robert Fellingham. 3. Artist’s concept of the Ionospheric Connection Explorer (ICON) spacecraft in Earth orbit. Credit: NASA Goddard’s Conceptual Image Lab/B. Monroe. 4. NASA’s Mars 2020 mission with the Perseverance rover onboard launches from Cape Canaveral Air Force Station in Florida on July 30, 2020. Credit: NASA/Joel Kowsky. 5. Burn scars from the SCU and CZU Lightning Complex fires in the San Francisco Bay area are shown in a September 26, 2020, natural-color image taken by the Operational Land Imager (OLI) on Landsat 8. Credit: Joshua Stevens, using Landsat data from the U.S. Geological Survey (USGS). 6. A USGS scientist flies a ground-penetrating radar system over the Connecticut River on a multirotor drone undergoing testing for the Department of the Interior. Credit: USGS/Carole Johnson.

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THE NATIONAL SPACE COUNCIL

Since its revival by executive order on June 30, 2017, the National Space Council advises and assists the President on national space policy and strategy, advises on international space activities, and fosters closer coordination and cooperation among the domestic civil, national security, and commercial space sectors. The Council's Chair, the Vice President, is supported by the National Space Council membership, which includes the heads of the agencies, offices, and departments responsible for the United States space enterprise. The Council meets regularly to publicly discuss the status of administration priorities and propose new recommendations to the President regarding national space policy and strategy. In addition to an audience composed of stakeholders from industry, government, academia, and nongovernmental organizations, Council meetings are livestreamed on the internet to encourage public engagement and transparency. The Council is supported by a Users' Advisory Group (UAG) composed of nonfederal senior leaders from industry, academia, and other non-governmental organizations. The UAG members are organized into six subcommittees: Exploration and Discovery, National Security Space, Economic Development and the Industrial Base, Technology and Innovation, Outreach and Education, and Space Policy and International Engagement. These subcommittees meet regularly to produce recommendations to the National Space Council for consideration.

Meetings of the National Space Council

The Council met on May 19, 2020, at NASA Headquarters in Washington, DC, marking the seventh meeting since the Council's revival in 2017. Prior to

the meeting, Vice President Mike Pence delivered remarks in which he previewed the forthcoming National Aeronautics and Space Administration (NASA) and Space Exploration Technologies (SpaceX) “Demonstration 2” mission to the International Space Station. This was the first crewed launch from American soil since the retirement of the Space Shuttle in 2011 and a result of the NASA Commercial Crew and Cargo program. The meeting included reports from the Department of Energy, Department of Commerce, Department of Defense, Department of State, and NASA. During the meeting, departments and agencies provided updates on the progress of key programs and milestones across the civil, commercial, and national security space sectors. In particular, the Department of Commerce released new regulations to improve the licensing process for U.S. commercial remote sensing operations and NASA provided updates on the innovative hardware and systems required to implement the administration’s direction for a crewed mission to the lunar surface by 2024 and sustained presence on the Moon in preparation for missions to Mars. Due to the unprecedented circumstances associated with the COVID-19 pandemic, this was the only Council meeting convened in fiscal year (FY) 2020.

Space Policy Directive Implementation

Recommendations from previous meetings and other administration priorities have been articulated in Space Policy Directives (SPDs), of which five were issued between 2017 and the end of FY 2020. The implementation of the existing SPDs is ongoing and summarized below.

Space Policy Directive-1 (SPD-1) amended the 2010 National Space Policy, also known as Presidential Policy Directive-4, to require NASA to expedite and return landing Americans on the Moon, to include the first American woman, by 2024, followed by a sustainable lunar presence by 2028 in preparation for crewed missions to Mars. To accomplish the goals of SPD-1, the National Space Council has actively encouraged NASA to conduct necessary internal reforms and secure the unique capabilities of commercial and international partners in the effort.

Space Policy Directive-2 (SPD-2) requires certain departments and agencies to streamline regulatory requirements to ensure there are no undue barriers to the

acceleration of commercial space activities. As announced at the seventh meeting of the National Space Council, the Department of Commerce succeeded in updating its regulations on commercial remote sensing to keep United States industry at the forefront in an increasingly competitive global market. The National Space Council continues to support the efforts of the Department of Transportation to streamline the Federal Aviation Administration's launch and reentry regulations to better reflect the increasing cadence and technological developments of the space transportation industry.

Space Policy Directive-3 (SPD-3) provided for the creation of the Nation's first space traffic management architecture to ensure protection of the national and economic security of the United States. Amongst other tasks from SPD-3, the Departments of Defense and Commerce were tasked to develop transition plans and cooperative agreements to implement SPD-3.

On February 19, 2019 Space Policy Directive-4 (SPD-4) tasked the Department of Defense to create a legislative proposal to establish the United States Space Force. With the President's signature on December 20, 2019, the Space Force was legally established as the sixth armed service within the FY 2020 National Defense Authorization Act. In January 2020, Vice President Mike Pence swore in General John W. "Jay" Raymond as the first Chief of Space Operations of the Space Force at the Eisenhower Executive Office Building in Washington, DC.

On September 4, 2020, the President issued Space Policy Directive-5 (SPD-5) (Appendix E), which outlined cybersecurity principles for space systems. In particular, SPD-5 recognized that cybersecurity threats to space systems are diverse and complex, and emphasized that robust public-private cooperation is essential to enhance the security and resilience of the infrastructure that supports space activities. The National Space Council has identified the risks associated with the space industrial base, and SPD-5 encourages government and industry to work together to combat cybersecurity threats.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA

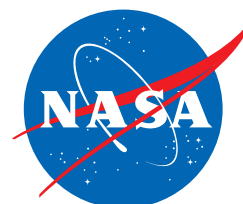
Human Exploration and Operations Mission Directorate

Exploration Systems Development

The Exploration Systems Development (ESD) programs—the Space Launch System (SLS), Orion, and Exploration Ground Systems—provide the foundation for humanity’s return to the Moon and exploration beyond. Progress steadily continues toward the uncrewed Artemis I mission, the first integrated test of the ESD programs that will pave the way for future crewed Artemis missions.

Orion

Orion will serve as the exploration vehicle that will carry the crew to space, provide emergency abort capability, sustain astronauts during their missions, and provide safe reentry from deep space return velocities. In fiscal year 2020 (FY 2020), NASA, along with the European Space Agency (ESA), assembled, tested, and integrated the Orion crew module for the Artemis I mission with the European service module. The integrated spacecraft successfully completed simulated in-space environments testing, verifying that Orion’s systems will perform as expected during Artemis missions. The campaign was completed ahead of schedule, and the spacecraft returned to the space coast for final preparations ahead of integration with the SLS rocket. In addition, the Agency completed the following tasks:



- Successfully tested the jettison motor built by Aerojet Rocketdyne for the Launch Abort System (LAS) on Orion. With the series of static tests completed, Orion's LAS jettison motor is qualified and ready for flight on the Artemis II mission with astronauts.
- Successfully tested the attitude control motor (ACM) that provides steering for Orion's LAS during an abort. The 30-second hot fire of the ACM, built by Northrop Grumman, was conducted at the company's facility in Elkton, Maryland. This was the third and final test needed to qualify the motor for human missions, beginning with Artemis II.
- Completed a rigorous test campaign with the Orion spacecraft at Plum Brook Station in Cleveland, Ohio. The test campaign subjected the spacecraft to the extreme temperatures and electromagnetic conditions it will endure during its uncrewed test flight around the Moon and back to ensure it will perform as designed.
- Shipped the launch abort motor for Orion's LAS from Promontory, Utah, to Kennedy Space Center (KSC) in Florida to undergo testing in preparation for use on the second Artemis mission. The launch abort motor is one of three motors on the LAS and is capable of producing about 400,000 pounds of thrust to steer and pull the crew module away from the rocket.
- Completed testing on a duplicate of Orion called the Structural Test Article (STA), needed to verify the spacecraft is ready for Artemis I. The STA testing required to qualify Orion's design began in early 2017 and involved 20 tests, using six different configurations—from a single element to the entire full stack, and various combinations in between. At completion, the testing verified Orion's structural durability for all flight phases of Artemis I.
- Moved panels for the Artemis II Orion stage adapter to a large, robotic welding machine. Three panels were built by AMRO (A Michael Riley Operation) Fabricating Corp. in South El Monte, California, and shipped to Marshall Space Flight Center (MSFC), in Huntsville, Alabama, where engineers and technicians from NASA are joining them using a sophisticated friction-stir welding process to form the Orion stage adapter.

- Completed the cone panel with openings for windows for the Artemis III Orion crew module and shipped the panel to the Michoud Assembly Facility (MAF), in New Orleans, Louisiana. This is the first element machined for the Artemis III mission.
- Installed the spacecraft adapter cone that will connect the Orion spacecraft to its rocket for the Artemis I mission around the Moon. This is one of the final major hardware operations for Orion inside the Neil Armstrong Operations and Checkout Building at KSC prior to integration with the SLS rocket.

Space Launch System

With the powerful Space Launch System (SLS) rocket and Orion spacecraft nearing the end of testing and development, the Agency has the foundation needed to send humans back to lunar orbit. Preparations for Artemis I are well under way. Production is complete for the SLS engines—composed of four RS-25 liquid rocket engines, two solid rocket boosters, the massive core stage, and the interim cryogenic propulsion stage that provides Orion’s final push toward the Moon. In FY 2020 the Agency accomplished the following goals:

- Transported the core stage for the SLS rocket in early January 2021 from NASA’s MAF in New Orleans to the Agency’s Stennis Space Center (SSC) near Bay St. Louis, Mississippi. This allowed engineers to conduct the Green Run test series.
- Completed five of the eight Green Run tests on the core stage of the SLS rocket, continuing progress toward a milestone hot fire test in FY 2021. The Green Run tests are designed to verify all systems will operate as needed ahead of the Agency’s first Artemis launch.
- Completed a structural testing series to evaluate the upper part of the SLS rocket and four of the core stage structures. During the test campaign, five structural test articles underwent 199 separate test cases and more than 421 gigabytes of data were collected to add to computer models used to design the rocket. The successful completion of SLS structural qualification testing at NASA’s MSFC wraps up the largest test campaign at the

Center since tests conducted for the Space Shuttle Program, more than 30 years ago.

- Awarded a contract to Aerojet Rocketdyne of Sacramento, California, to manufacture 18 additional SLS RS-25 rocket engines to support Artemis. This modified the initial contract awarded in November 2015 to recertify and produce a total of 24 engines to support as many as six additional flights.
- Planned a letter contract for Northrop Grumman that supports building solid rocket boosters for the next six SLS flights. This initial step ensures that NASA can build the boosters for future SLS rockets that will be needed for the Artemis missions.
- Completed a full-scale booster test for the SLS rocket in Promontory, Utah. NASA and Northrop Grumman provided data to evaluate the motor's performance using potential new materials and processes that can be incorporated into future boosters.

Exploration Ground Systems

Exploration Ground Systems (EGS), based at KSC in Florida, was established to develop and operate the systems and facilities necessary to process and launch rockets and spacecraft during assembly, transport, and launch. EGS is preparing the infrastructure to support several different kinds of spacecraft and rockets that are in development, including the SLS rocket and Orion spacecraft for Artemis I. EGS accomplished the following milestones in FY 2020:

- Finished modifications and upgrades to prepare Launch Pad 39B at KSC. Engineers replaced or upgraded pad subsystems used for Apollo and the Space Shuttle Program to support the powerful SLS rocket and multi-user spaceport.
- Simulated critical portions of the countdown to ensure the Artemis I launch team is ready to handle any situation on launch day. Launch Team Training includes the Simulation Training Team, which combines a mix of NASA's EGS program, civil servants, and contractors with Jacobs under the Test and Operations Support Contract.

- Rehearsed booster stacking operations inside the Vehicle Assembly Building (VAB) at the Agency's KSC in preparation for the Artemis I launch. The team used full-scale replicas of booster segments, referred to as pathfinders, for the practice exercise in one of the tallest sections, or high bays, of the VAB, built for stacking rockets.

Advanced Exploration Systems

The Advanced Exploration Systems (AES) Division develops human exploration technology and manages the Gateway program, exploration spacesuit development, the Human Landing System (HLS) program, and surface mobility systems development. AES infuses technologies and develops high-priority capabilities using a combination of unique in-house activities and public-private partnerships to develop and test prototype systems that form the basis for future human space-flight missions. AES is responsible for Artemis missions beginning with the first human lunar landing mission of the program, Artemis III.

In FY 2020, together with the 23 other space agencies in the International Space Exploration Coordination Group (ISECG), NASA authored a supplement to the Global Exploration Roadmap (GER). AES teams led the development of this supplement and worked with groups throughout the Agency to produce it. The GER is a nonbinding document that space agencies coauthor to foster coordination and partnership opportunities. The iterative development process of the GER and the nine new member agencies that joined ISECG for the 2020 update demonstrate the growing interest in space exploration across the globe and emphasize the importance of cooperation to realize individual and common goals and objectives for ISECG members.

Exploration Capabilities

AES develops and demonstrates critical human exploration systems in order to reduce mission risk, validate operational concepts, leverage partner capabilities, and lower life-cycle costs for lunar and other deep space missions. In FY 2020, AES continued to advance technologies related to deep space habitats following successful completion of ground-based prototype testing, addressed knowledge gaps

for lunar environments and resources using low-cost CubeSats, and leveraged the International Space Station (ISS) as a testbed to advance the technology readiness of deep space systems. The Exploration Capabilities team accomplished the following risk-reduction milestones in FY 2020:

- Completed assembly and testing of two critical life-support subsystems for flight to the ISS to demonstrate their reliability in an actual operational environment. The 4-Bed CO₂ Scrubber, which removes carbon dioxide (CO₂) from the cabin air, is one of the technologies being considered to recover more than 75 percent of the oxygen from CO₂. The Brine Processor Assembly will recycle 98 percent of the water from concentrated urine brine using a semipermeable membrane that allows water to pass through into the cabin air. Demonstrating these capabilities is critical for achieving closed-loop life support systems for long-duration missions to Mars.
- Installed the Spacecraft Atmosphere Monitor (SAM) on ISS and began operations. A compact, autonomous, real-time air-quality monitoring system, SAM immediately detects trace contaminants that pose potential threats to crewmembers' well-being. This advancement is critical for future human spaceflight missions, especially missions to the Moon and Mars, when returning samples to Earth for testing will not be an option.
- Delivered the Universal Waste Management System (UWMS) for launch to the ISS. The UWMS is the next-generation space toilet that has been redesigned for greater crew comfort, more efficient water recovery, and less complex systems that reduce mass, volume, and maintenance time requirements. A duplicate UWMS was delivered to be installed on the Artemis II Orion, and the system is also compatible with Gateway standards, reducing the need for system redesign across vehicles and missions.
- Installed the Thermal Amine Scrubber (TAS) CO₂ removal device on the ISS. TAS was developed as a potential successor to the Carbon Dioxide Removal Assembly (CDRA) to improve reliability for long-duration missions. NASA's goal is to develop a CO₂ removal system that is reliable for more than three years. In addition, the medical community gave engineers the goal of reducing the CO₂ partial pressure in a spacecraft

atmosphere to 2 mmHg for crew health reasons. NASA teams are assessing several systems to improve CO₂ removal system reliability and reduce CO₂ partial pressure, but TAS is among the most mature and is the first to be demonstrated on the ISS. A reliable system that controls CO₂ at 2 mmHg is essential for Mars missions.

- Ignited Saffire-IV, the fourth in a series of large-scale, in-space fire investigations, after the Northrop Grumman Cygnus cargo spacecraft departed from the ISS and before its destructive reentry through Earth's atmosphere. The Saffire experiments test the reliability of fire safety measures for spacecraft and provide new data on the behavior of fire in space environments. Saffire-IV tested a Smoke Eater filter designed to clean up the cabin air after a fire. This experiment was remotely activated by Northrop Grumman operators, and NASA Glenn Research Center Saffire staff helped monitor the experiment as it burned in four installments. Saffire-IV burned the same materials that were burned in Saffire-II, but at different pressures and oxygen saturation for comparison.
- Continued ground testing of prototype habitats from Boeing, Lockheed Martin, Northrop Grumman, and Sierra Nevada Corporation to assess their extensibility to lunar surface and Mars transit habitats. The testing included creep testing of fabric materials for inflatable habitats and hypervelocity impact testing to characterize structural damage to inflatable habitats from micrometeoroid and orbital debris impacts.
- Delivered the Hybrid Electronic Radiation Assessor (HERA) for integration with the Orion Spacecraft for the Artemis II mission. The HERA monitors radiation levels inside Orion to alert the crew of their exposure to harmful deep space radiation.
- Began integration and testing of four CubeSats that will be flown on the Artemis I mission. These CubeSats will help answer questions about the thermal environments and abundance of water ice on the Moon, investigate the effects of deep space radiation on yeast DNA, and demonstrate solar sails for low-cost scouting missions to near-Earth asteroids.

Gateway

In pursuit of a sustainable lunar exploration program, NASA and its international partners have identified the need for an orbiting platform at the Moon that will serve as a staging point for astronauts on their way to the lunar surface and as an outpost for unprecedented deep space science and technology investigations. All major U.S. elements for the integrated Gateway spacecraft are under contract, with flight and ground hardware in development. Gateway development leverages existing commercial and international partnerships while seeking to forge new ones through international agreements with Europe, Canada, Japan, and others. In FY 2020, the Agency completed these accomplishments:

- Awarded Northrop Grumman a contract to develop the habitation and logistics outpost (HALO), an initial crew cabin for Gateway.
- Determined that HALO and the power and propulsion element (PPE) will launch to space together as the foundation for the initial Gateway capability. This eliminates the procurement of one launch vehicle and reduces the risk of on-orbit assembly.
- Continued development of the PPE, updating the contract with Maxar Technologies to reflect the decision to comanifest the PPE with HALO.
- Delivered first pieces of flight hardware for HALO to Thales Alenia Space Italy, a subcontractor for Northrop Grumman that is manufacturing components of the HALO.
- Identified the first two Gateway science payloads. One instrument built by NASA and another built by the ESA are designed to observe space weather and monitor the Sun's radiation environment, improving the capability to forecast weather for future crew missions.
- Selected SpaceX of Hawthorne, California, as the first U.S. commercial provider under the Gateway Logistics Services contract to deliver cargo, experiments, and other supplies to the Agency's Gateway in lunar orbit.
- Held the first Integrated Program-wide Sync Review, demonstrating System Definition Review—level maturity across the Gateway Program and its projects. Based on this review, the Program, technical authorities, and independent assessment via a Standing Review Board (SRB)

evaluated the program's progress and determined Gateway was ready to proceed to the next phase of development.

Exploration Extravehicular Mobility Unit

Under the Gateway Program, NASA is developing a flexible spacesuit architecture with common core subsystems for the spacesuit and vehicle interfaces that can be modified to support the needs of specific destinations and vehicles from low-Earth orbit (LEO) to the lunar surface. NASA intends to demonstrate the core spacesuit technologies and subsystems applicable to both LEO-based operations and surface exploration through a series of subsystem demonstrations at the ISS. The Exploration Extravehicular Activity (xEVA) Project made significant progress in the development of Exploration Extravehicular Mobility Units (xEMUs) and vehicle interfaces to spacesuit equipment (VISE) in FY 2020. The NASA-designed spacesuit pressure garment will extend the overall sizing range to accommodate a more diverse crew population, at the lower and upper bounds of crew anthropometry, while minimizing logistics required. Other key improvements in the xEMU over its predecessors include a highly mobile lower torso for walking and kneeling, as well as a modular life-support system that allows components to be swapped out as technologies mature or mission parameters change without having to redesign the entire subsystem. Additionally, the life-support system incorporates many new technological innovations to improve overall reliability, safety, and performance. NASA reached the following development milestones:

- Issued a request for information (RFI) seeking U.S. industry feedback to help refine and mature the acquisition strategy for production and services for xEVA hardware to enable a steady cadence of Artemis missions over the next decade.
- Completed ground testing and delivered the Spacesuit Evaporation Rejection Flight Experiment (SERFE) for launch integration on NG-14. The SERFE is designed to demonstrate the complete exploration spacesuit thermal loop operations on the ISS in preparation for the lunar surface suits that are planned for Artemis III. The thermal control system in the current spacesuit is a driver of overall suit reliability. This spacesuit water membrane evaporator is the core new technology in the thermal loop

and was designed to significantly enhance reliability and the safety of the crew.

- Completed the Delta Preliminary Design Review (dPDR) for the xEMU to include additional functions to better enable human lunar surface exploration. Key products from the dPDR included a final report on successful completion of the Phase 1 Multi-program Safety Review Panel; published interface requirements documents between the xEVA system and the HLS; updated xEVA System functional requirements; updated xEMU functional requirements; revised primary subsystem specification documents; and updated the xEVA Operational Concept document. With the successful completion of dPDR, the xEVA Project was able to transition to the next phase of the project: the building of the xEMU design verification test (DVT) unit.
- Completed primary xEMU component DVT evaluations and began integrating those components into the portable life-support and pressure garment subassembly DVT units.
- Completed a System Requirements Review for VISE in coordination with the HLS Program and ISS Program.

Human Landing System

NASA selected three U.S. companies to develop preliminary Human Landing System (HLS) designs: Blue Origin of Kent, Washington; Dynetics (a Leidos company) of Huntsville, Alabama; and SpaceX of Hawthorne, California. These teams offered three distinct lander and mission designs, which are driving a broad range of technology development and will contribute to the sustainability of NASA's lunar surface access architecture. NASA experts worked with the companies to streamline the review of deliverables and to impart legacy knowledge as they work through a ten-month base period that concluded in February 2021. Throughout the base period, NASA teams embedded with the companies co-conducted intensive adjudication processes that established design, construction, safety, and health and medical standards for each proposed landing system design. The companies also provided development and testing schedules; identified top risks; and provided plans for safety and mission assurance, verification, validation, and certification. In

parallel, NASA also worked with the three companies to refine the requirements for the Option A solicitation, issued in October 2020. Following the conclusion of the base period, NASA will select up to two companies to continue development to flight through Option A awards.

NASA and 11 U.S. companies completed work under the Next Space Technology Exploration Partnerships (NextSTEP) Appendix E awards. NextSTEP E companies conducted technical studies and demonstrations and built and tested systems-level ground prototypes for human landers. Results from NextSTEP E provided valuable insight into cryogenic fluid management, in-space propellant transfer, automated rendezvous and proximity operations, and precision landing and hazard avoidance. This work helped the Agency reduce schedule risk and refine its Artemis program requirements for the three companies competing to build HLSs.

Surface Mobility Systems

NASA established a human mobility systems project, and its team began collecting and refining requirements for these systems. The Agency issued an RFI for the Lunar Terrain Vehicle (LTV), a human-class rover that will extend the exploration range of suited crewmembers on the surface of the Moon.

Commercial Spaceflight Development

Commercial Crew Program

NASA's Commercial Crew Program (CCP) and its commercial partner SpaceX accomplished the national goal of returning human spaceflight to U.S. soil.

Both industry partners, Boeing and SpaceX, continued making technical and programmatic progress in maturing and certifying their commercial Crew Transportation Systems (CTS). This year, commercial partners transitioned from flight hardware production and final acceptance testing to flight demonstration missions and system certification. During FY 2020, both partners conducted orbital demonstration flights of their CTS.

On December 20, 2019, Boeing conducted their Orbital Flight Test (OFT), an uncrewed orbital demonstration flight to the ISS. Due to technical issues during launch and early flight, the Starliner spacecraft did not complete its demonstration

mission to the ISS and successfully returned to Earth. Though many flight test objectives were successfully accomplished, Boeing announced plans to re-fly the OFT mission prior to their Crew Flight Test (CFT) mission. Boeing completed programmatic and technical milestones during FY 2020, as they continue maturing flight systems and resolving identified flight issues in preparation for their upcoming OFT re-flight and CFT demonstration mission.

SpaceX completed several major programmatic and technical milestones and conducted major demonstration flights during FY 2020. SpaceX successfully conducted their launch escape demonstration test flight of the Crew Dragon spacecraft and Falcon-9 launch vehicle. This was the final major test of SpaceX's CST prior to carrying NASA astronauts to the ISS.

On May 30, 2020, SpaceX launched their Demo-2 mission to the ISS. Demo-2 carried NASA astronauts Robert Behnken and Douglas Hurley aboard the company's Crew Dragon spacecraft, returning human space launches to U.S. soil. On the following flight day, the Dragon spacecraft autonomously docked to the ISS, another U.S. human spaceflight first. At the conclusion of the ISS mission, the Demo-2 Dragon autonomously departed the ISS, reentered Earth's atmosphere, and splashed down off the coast of Pensacola, Florida, bringing the historic Demo-2 mission to a successful conclusion. During FY 2020, NASA certified SpaceX's CST, clearing the way for post-p-certification missions, planned for early FY 2021.

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.

Commercial Low-Earth Orbit Development Program

The Commercial Low-Earth Orbit (LEO) Development Program (CLDP) continues to make steady progress toward realizing NASA's vision of a self-sustaining market in LEO. The CLDP consists of several areas of responsibility to encourage and facilitate the development of a robust LEO economy, including demand stimulation, private astronaut missions, commercial element, and free flyer. The program

awarded eight demand stimulation contracts in areas such as glass optics and alloys, semiconductor chip manufacturing, retinal implants, and regenerative medicines. Within the last year, the program completed almost a dozen agreements to fly commercial-use items to the ISS. The program has also completed the first two milestones of the Axiom Space contract for the Commercial Port module. Looking forward, the program will continue to work with multiple companies to facilitate the execution of private astronaut missions.

International Space Station

In FY 2020, the ISS celebrated 20 years of continuous human presence in space, enabled by NASA and its international partners. The Space Station's focus continues to be research and technology development in such disciplines as biology and biotechnology, Earth and space science, human research, and physical science. Exploration research conducted on the Station in FY 2020 included experiments to better understand "normal" human adaptations to spaceflight, study how fluid shifts affect blood flow in astronauts, and learn how best to grow and harvest vegetables in preparation for long-duration missions. The ISS remains a testbed for technology, with FY 2020 seeing the installation of life-support improvements for urine distillation and water processing, as well as a biomolecule sequencer, which allows astronauts to identify potentially harmful microbes in space without sending samples to Earth. Through the end of Expedition 63 (October 2020), the ISS had hosted over 3,035 investigations from more than 108 countries/areas. During that timeframe, the number of investigators with research on the ISS exceeded 4,000.

Such research is enabled by frequent Commercial Resupply Services (CRS) flights from Northrop Grumman and SpaceX. In FY 2020, Northrop Grumman and SpaceX completed two cargo flights each to the ISS, totaling more than 25,700 pounds of science investigations, spacewalking tools, and critical supplies delivered. These cargo missions were complemented by those of our partners. International partners Roscosmos provided three Progress cargo missions, and the Japan Aerospace Exploration Agency (JAXA) was responsible for the H-II Transfer Vehicle (HTV-9) mission during FY 2020. Additionally, more than 7,800 pounds of investigations and equipment were returned to researchers on Earth by the

SpaceX Dragon capsule, while the Northrop Grumman Cygnus and HTV provided significant assistance as trash removal mechanisms by performing a destructive reentry. These resupply missions enabled ISS crewmembers to support new U.S. science investigations to advance human space exploration to the Moon and Mars and conduct research sponsored by the U.S. National Laboratory to benefit life on Earth.

In addition to the CRS missions, there was one successful Soyuz crew mission, two test flight missions (one crewed, one uncrewed), and three Soyuz crew return missions occurring in FY 2020. The departure of Soyuz 58S in October 2019 denoted the end of Expedition 60. Onboard Soyuz 58S were NASA astronaut Nick Hague, Russian Space Agency (Roscosmos) cosmonaut Alexey Ovchinin, and visiting astronaut Hazzaa Ali Almansoori from the United Arab Emirates (UAE). Soyuz 59S departed the ISS in February 2020, carrying NASA astronaut Christina Koch, Soyuz Commander Alexander Skvortsov of Roscosmos, and Luca Parmitano of ESA, marking the transition from Expedition 61 to Expedition 62. Koch set the record for the longest single spaceflight in history by a woman, a 328-day mission. Soyuz 62S arrived at the ISS in April 2020, carrying NASA astronaut Chris Cassidy, along with Anatoly Ivanishin and Ivan Vagner of Roscosmos. They joined Expedition 62 Commander Oleg Skripochka of Roscosmos and NASA astronauts Andrew Morgan and Jessica Meir. Shortly after their arrival, the Soyuz 61S spacecraft departed in April 2020 carrying the Expedition 62 Crew (Skripochka, Morgan, and Meir) and marking the end of Expedition 62.

The first test flight occurred in December 2019, when Boeing launched their uncrewed CST-100 Starliner spacecraft aboard a United Launch Alliance Atlas V rocket. However, the Starliner did not reach its planned orbit and therefore did not dock with the ISS. The spacecraft remained in a stable configuration and completed several test objectives. The spacecraft completed the first land-based touchdown of a human-rated space capsule in U.S. history two days after launch, wrapping up its OFT mission as part of NASA's CCP. The other test flight occurred in May 2020, when SpaceX launched their Crew Dragon, named Endeavour, to the ISS carrying NASA astronauts Robert Behnken and Douglas Hurley, who joined Expedition 63 commander and NASA astronaut Chris Cassidy and cosmonauts Anatoly Ivanishin and Ivan Vagner of Roscosmos. This SpaceX Demo-2 mission

was an end-to-end test flight to validate the SpaceX CST, including launch, in-orbit, docking, and landing operations, and pave the way for its certification for regular crew flights to the Station. For operational missions, Crew Dragon will be able to launch as many as four crewmembers and carry more than 220 pounds of cargo, enabling the expansion of the number of inhabitants on the ISS, increasing the time dedicated to research in the unique microgravity environment, and returning more science back to Earth. While onboard, Behnken and Hurley contributed more than 100 hours to supporting the orbiting laboratory's investigations, participated in public engagement events, and supported four spacewalks. They returned to Earth in early August 2020. It is the first time a commercially built and operated American crew spacecraft has returned from the ISS to complete a test flight, beginning a new era in human spaceflight. Both test missions supported the goal of NASA's CCP to provide safe, reliable, and cost-effective transportation to and from the ISS.

In FY 2020, the onboard crew and ground teams supported an unprecedented 13 spacewalks, or extra-vehicular activities (EVAs). In January 2020, two spacewalks completed the final battery installation on the Port Truss (P6) without issue, as well as the fourth and final Alpha Magnetic Spectrometer (AMS) spacewalk. The AMS is a cosmic ray particle physics experiment mounted outside the ISS producing science data that are valuable for the understanding of the formation of the universe and inform the search for evidence of dark matter. The AMS series of spacewalks completed very difficult tasks that had never been undertaken during a spacewalk. NASA succeeded in its endeavor to provide AMS with many more years of data collection.

The last of the lithium ion (LiION) batteries were installed within a four-EVA series in July 2020, completing the complement of ISS batteries on the Starboard Truss (S4). The new batteries provide an improved and more efficient power capacity for operations. Along with battery installation, the EVA crew moved a number of large items outside, including a robotic compatible box called the Robotic Tool Stowage that houses two ammonia-sniffing devices, called the Robotic External Leak Locators (RELL). They routed cabling for the ISS Ethernet System and prepared the ISS for the Nanoracks Bishop Airlock arrival on the SpaceX-21 mission in FY 2021. The new airlock significantly increases the capacity for public and

private research on the outside of the orbiting lab. It also enables the deployment of larger satellites and the transfer of spacewalking tools and hardware inside and outside the Station.

In FY 2020, the ISS Program continued strategic and long-term planning for an eventual transition of NASA operations in LEO to a future platform. This includes preparing the international partnership to continue joint operations in LEO and beyond, ensuring a robust economic demand for services in LEO, and working to transition from a government-based economy to a privately based market.

As part of this, NASA announced a five-point plan to open the ISS for business so U.S. industry innovation and ingenuity can accelerate a thriving commercial economy in LEO. A wide array of companies expressed interest in pursuing commercial activities, private astronaut missions, and future commercial destinations. NASA awarded Axiom Space, Inc., the opportunity to connect their private module to the front of the Station in February 2020, and five companies requested the use of the Station for commercial activities, which required the companies to partially pay for the services. In late FY 2020, the ISS Program transferred all work to accelerate this thriving commercial economy in LEO to the HEOMD Commercial Spaceflight Development Division, with the ISS Program continuing to provide support for all initiatives.

The aforementioned summarizes the many ways the ISS is facilitating the growth of a robust commercial market in LEO for research, technology development, and crew and cargo transportation, and remains the sole space-based proving ground and stepping-stone for achieving the goals of NASA's Artemis program.

Human Spaceflight Capabilities

Rocket Propulsion Test

During FY 2020, the Rocket Propulsion Test (RPT) Program safely performed 793 tests of rocket engines and components at various levels of thrust. Hot fire test time totaled 12,600 seconds. In addition to the hot fire tests, RPT facilities performed 658 hours of thermal vacuum testing for vehicle certifications and facility checkouts in preparation for the vehicle certifications. These tests were completed with only three facility-caused test delays, resulting in a 99.6 percent stand

availability, exceeding the Agency performance goal of 90 percent as defined in the Space and Flight Support (SFS) section 15-1 of the NASA Management and Performance report.

Marshall Space Flight Center

At Marshall Space Flight Center (MSFC), a 24" Solid Motor test campaign for the Space Launch System (SLS) booster insulation material performance characterization was conducted at the Solid Propulsion Test Article (SPTA) facility. At Test Stand 115, Virgin Orbit testing, Boeing thruster testing, Blue Origin nozzle testing, and Methane Engine Thrust Assembly testing were completed, and Long-Life Additive Manufacturing Assembly engine hardware testing started. At Test Stand 116, ESA Vega testing was started and completed, and Blue Origin Thrust Chamber Assembly testing was started.

Armstrong Test Facility (formerly Plum Brook Station)

Armstrong Test Facility (ATF) completed thermal vacuum testing of the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) at the In-Space Propulsion (ISP) Facility with Phase II testing being conducted.

The ISP Facility signed an agreement with Sierra Nevada Corporation to perform thermal vacuum testing of the Dream Chaser Cargo System in FY 2021. Work on the ISP steam ejector rehabilitation project is complete. Construction to integrate a rental steam plant is in progress to demonstrate facility exhaust capability. A smaller effort to address system thermal expansion and contraction during operations remains to be designed and implemented.

ISP provided cost estimate input for three HLS Appendix H Government Task Agreements to perform proposed testing for two HLS partners.

Stennis Space Center

Testing for the SLS Core Stage at Stennis Space Center (SSC) was approved for COVID-related limited restart of mission-critical work. At the A-1 test facility, restart of the Run Tank Painting construction project was approved, and SLS RS-25 engine testing was ongoing. At the B test stands, RS-68 engine testing was ongoing, and the SLS Core Stage arrived for Green Run testing. Green Run testing

included modal testing, as well as stage avionics power-up and umbilical connections testing. Engine leak checks, hydraulic and thrust vectoring control checkouts, countdown simulation, and wet dress rehearsal were completed. In the E complex, SSC supported launcher testing and Exploration Upper Stage subscale diffuser testing and completed testing of the Subscale Engine Exhaust System.

White Sands Test Facility

The following activities were carried out at White Sands Test Facility (WSTF) in FY 2020:

- Ongoing testing of the Orion ESA Service Module at Test Stand (TS) 301, including cross feed testing.
- Acceptance testing of the Boeing CST-100 Launch Abort Engine for the CCP began testing at TS 301A in early November 2017 and completed testing of the last engine, Post Certification Mission (PCM) 3-4, in August 2020.
- Preliminary design reviews and critical design reviews (PDR and CDR) for the Small Altitude Steam System Boiler Replacement project.
- Acceptance testing of the Post Certification Mission 3 ship set of the Boeing CST-100 Orbital Maneuvering and Attitude Control and Reaction Control Systems thrusters for the CCP was completed at TS 401 and TS 406 in early 2020.

Human Research Program

In FY 2020, NASA sponsored research to mitigate human health and performance risks associated with long-duration spaceflight. Twelve Human Research Program (HRP)–sponsored investigations were conducted on the ISS over the fiscal year, with three studies completing data collection. Studies completed included the Fluid Shifts investigation, which finished its post-flight data collection of its 13th and final subject. Starting with the first yearlong mission crew, this study enrolled five Russian cosmonauts and eight U.S. astronauts over five years to investigate the effects of spaceflight-induced headward fluid shift on vascular, ocular, and central nervous system structure and function. The team included researchers from NASA, ESA, and the Institute of Biomedical Problems of the

Russian Academy of Sciences, as well as multiple U.S. and European universities, investigating one of HRP's highest exploration risks, the Spaceflight Associated Neuro-ocular Syndrome (SANS).

In the Autonomous Medical Officer Support (AMOS) study, HRP and the ISS Program developed a “quick-start” concept to use the Space Station as an exploration analog to test progressively Earth-independent medical operations. The AMOS technology evaluation in April 2020 demonstrated that astronauts can utilize a software tool designed to assist minimally trained or untrained users to conduct complicated medical procedures autonomously. For the demonstration, the crew used AMOS with no preflight training to autonomously perform ultrasound imaging of the bladder and kidneys, a plausible Mars mission medical scenario. This is the first time that fully autonomous, untrained imaging has been performed during spaceflight, and therefore is a major milestone in enabling medical capability for future exploration missions.

Additional ongoing Space Station studies to mitigate the risks of long-duration spaceflight included 1) the Food Acceptability Study, investigating how a repetitive menu affects food acceptability; 2) the Spaceflight Standard Measures project, which collects a set of core measurements from astronauts to better define human spaceflight risks before, during, and after long-duration missions; 3) the Team Task Switching Study, assessing the impact on human factors and performance of switching crewmembers' operational tasks to improve individual and team effectiveness; and 4) the Vertebral Strength Study, undertaking pre- and post-flight physiological measurements using quantitative computerized tomography (CT) and Magnetic Resonance Imaging–based modeling to assess dynamic vertebral strength and injury risk following long-duration spaceflight.

HRP-solicited research included the 2020 Human Exploration Research Opportunities, or HERO, appendices. Appendix A sought knowledge and characterization of the potential role of sensory stimulation countermeasures within crew habitats that may have an impact on brain changes in sensory, cognitive, and motor areas in long-duration missions. HERO Appendix C requested proposals for an integrated suite of immune and stress countermeasures for future long-duration deep space missions for testing in an Earth-based analog (Palmer Station, Antarctica) and will then be tested on the Space Station. Effective strategies were

sought in the HERO appendices to adapt stem cell technology to assess the effects of radiation quality, chronic low dose–rate exposure, differences in individual susceptibility across multiple tissue types, and individual risk assessment on space radiation carcinogenesis.

HRP research publications included “Telomere Length Dynamics and DNA Damage Responses Associated with Long-Duration Spaceflight,” which was published in *Cell Reports*. These studies examined telomere length dynamics in astronauts pre-flight, during flight, and post-flight, as well as telomerase activity oxidative stress. The authors observed that telomeres lengthened during flight and were shorter than pre-flight controls after flight. Oxidative stress was also upregulated, indicating that the observed telomere length dynamics may be an adaptive response to chronic oxidative stress. These datasets provide a valuable roadmap of some of the health risks for long-duration spaceflight.

The purpose of the *Science Advances* publication, “Genomic Mapping in Outbred Mice Reveals Overlap in Genetic Susceptibility for HZE Ion- and Gamma-Ray-Induced Tumors,” was to study the effects of high-charge and -energy (HZE) particle irradiation in a genetically heterogeneous population and identify regions of the genome associated with increased tumor incidence. The study revealed that genetic susceptibility plays a significant role in tumorigenesis following radiation, rather than radiation type. This study supports the use of human epidemiological data exposures to predict cancer risks from galactic cosmic rays astronauts may be subjected to on long-duration missions.

A majority of long-duration spaceflight astronauts have developed ocular structural and functional changes, collectively termed SANS. The Ocular Health Study was the first prospective research study to investigate these changes in long-duration astronauts. Recently, HRP, in collaboration with multiple external scientists, developed a quantitative approach analyzing high-resolution ocular magnetic resonance images and published these findings in the journal *npj Microgravity*. Over the past year, ocular and brain structural changes observed in astronauts during and after spaceflight that further characterize SANS were also published in the journals *JAMA-Ophthalmology* and *Radiology*. The methods and outcomes described here represent another step forward for the ability to objectively study SANS and test the effectiveness of potential countermeasures. Future studies will

determine if persistence of these structural changes alters ocular function and if countermeasures being tested will be effective in preventing SANS. This research helps to define key measures and novel tools required to monitor astronaut health on long-duration missions and determine the efficacy of countermeasures to protect astronaut health and performance.

HRP funds the Translational Research Institute for Space Health (TRISH) with its mission to lead a national effort to translate cutting-edge emerging research into mitigation strategies for exploration missions, as well as educate the next generation of space biomedical scientists. TRISH focuses on rapidly translating fundamental research concepts into practice, thereby generating tangible health outcomes to protect astronaut health. The Institute supported a total of 65 science and technology projects in FY 2020, with 20 ending in the fiscal year. TRISH also administered four solicitations in FY 2020, which included TSRAD-2020, which called for program projects utilizing complex human-based models for radiation countermeasures; TRISH-IND-2020, which solicited for proposals from U.S.-based companies developing behavioral health solutions; TRISH-RFA-2001-PD, inviting space health postdoctoral fellowship applicants; and the TRISH Faculty/Scientist Exchange, which promoted bidirectional collaborations between NASA intramural scientists and the external community.

In FY 2020, the HRP completed the following key milestones:

- Delivered the Level of Care IV Medical System Foundation, establishing a medical design process to enable the integration of medical capabilities into exploration vehicles and mission design. The medical system model provides traceable evidence-based requirements development of products that are now being transitioned to the NASA Health and Medical Technical Authority for use with the Gateway Crew Health and Performance System.
- Completed the Anthropomorphic Test Device Injury Assessment Reference Values model to mitigate crew injury during dynamic phases of flight. The model allows the identification and update of NASA requirements and standards to address injury risk during dynamic events like spacecraft landings and is provided to the Orion and CCP.

- Used the Space Linear Acceleration Mass Measurement Device to measure the mass of cargo bags planned for return on SpaceX-21. This device is typically used to measure astronaut masses, but HRP helped to repurpose the device for use by the CCP. By measuring the mass of cargo bags planned for return on SpaceX-21, the Space Station Program and SpaceX seek to reduce uncertainties in the vehicle center of gravity that could cause instability during reentry for the Dragon2 vehicle.
- Presented the most current evidence for using strict 6° head-down tilt bedrest. The bedrest analog will be used to test countermeasures against SANS.
- The Multi-model Ensemble Risk Assessment (MERA) team delivered the latest update to the cancer risk model to the NASA space radiation operations group. The cancer risk model calculates an astronaut's risk of cancer incidence and cancer mortality from exposure to the space radiation environment. As part of the transition to operations, the MERA team worked closely with the operations team to support the implementation of the new model into the operational framework.

Space Communications and Navigation

NASA's Space Communications and Navigation (SCaN) Program is responsible for leading the Agency's space communications and tracking through the management of its space communications networks, as well as developing advanced space communications and navigations technology. It also serves as the Agency's representative in domestic and international fora in the areas of spectrum management; space communication architectures and data standards; and positioning, navigation, and timing policy. SCaN continued to lead the development of advanced space communication and navigation technology for the benefit of scientific and human exploration missions in near-Earth and deep space and commercial space enterprises.

NASA operates and maintains three space communication networks—the Near Earth Network (NEN), Deep Space Network (DSN), and Space Network (SN)—composed of a ground network and its on-orbit Tracking and Data Relay Satellites. Consistent with prior years' successes, the three space communications networks

provided approximately 252,644 tracking passes while maintaining an extremely high proficiency level of 99 percent or better, well above the 95 percent requirement, even during the COVID-19 pandemic. In this capacity, NASA served as a reliable partner to a wide range of external customers (other U.S. and international government agencies and commercial entities) for human exploration, robotic spaceflight launches, low-Earth and deep space science, and SmallSats (including CubeSats and NanoSats).

Astronauts and spacecraft depend on this reliable uplink and downlink of communications for the delivery of commands and essential crew instructions, as well as the retrieval of health and safety information and science data, to individual mission control centers. During FY 2020, SCA networks provided 24/7 global near-Earth and deep space communication and navigation (C&N) services to more than 100 NASA programs and other U.S. Government, international civil space agencies, and commercial missions, including human spaceflight C&N requirements of the ISS. Several of these missions have more than one spacecraft, although these are counted as a single mission. Also, several missions are supported by more than one of the three networks; these are also counted as single missions. The networks provided launch and early-orbit telemetry, tracking, and communication services to more than 15 Expendable Launch Vehicles (ELVs) in FY 2020.

The SN began working transition activities with customers in preparation for the completion of the Space Network Ground Segment Sustainment (SGSS) project. Activities included support to SGSS for project integration, testing, deployment, training, and transition to operations. After a five-month stand-down of on-site work at WSTF due to COVID-19, SGSS finished FY 2020 targeting SN Initial Operations Capability in the first half of FY 2021. SCA's DSN Aperture Enhancement Project continued the addition of two 34-meter antennas at the Madrid Deep Space Communications Complex in Spain, which will increase the DSN's capacity to support future human spaceflight and robotics missions. One 34-meter antenna was transferred to site personnel for maintenance activities and initiated Project Interface Testing (PIT) in September 2020 with successful delivery to operations on January 22, 2021.

To advance private-sector entrepreneurial space activities, the networks continue to make technical and programmatic progress to mature commercial space

capabilities with the reorganization of the networks. At the end of FY 2020, the Goddard Space Flight Center (GSFC) NEN and SN initiated plans to reorganize to better align with SCaN's commercialization plans. Plans call for government assets to be operated and maintained by the Advanced Communications Capabilities for Exploration and Science Systems (ACCESS) project and the Near Space Network (NSN) to serve as the network that will provide Earth proximity communication services. The NSN is to provide these services via commercial and government ACCESS providers.

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

September 2019, in connection with its annual meeting held in Cornwall, England, hosted by the United Kingdom Space Agency. SCA_N serves as the Executive Secretariat for the IOAG and continues to coordinate quarterly teleconferences.

SCA_N's advancements in optical communications in FY 2020 have positioned the program to complete critical components of the architecture in the near term. The Deep Space Atomic Clock (DSAC) was launched on the Orbital Test Bed spacecraft on June 25, 2019, and will revolutionize navigation in deep space. With the DSAC onboard, a spacecraft traveling beyond Earth orbit will need only a one-way signal from Earth to navigate autonomously, which will free up valuable time on SCA_N's DSN. DSAC also has a high degree of clock stability, meaning it can maintain its accuracy over years.

The Laser Communication Relay Demonstration (LCRD) passed Mission Operations Review in May 2020 and was launched on December 7, 2021. LCRD will be NASA's first long-period optical communications project that will demonstrate benefits for both deep space and near-Earth missions from geosynchronous orbit. LCRD will also validate that advanced relay operations are possible and could be used for future relays, like at the Moon and Mars. As part of the optical communications architecture, SCA_N also completed a system critical design review for the Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal, which will be onboard the ISS and communicate directly with LCRD.

Optical communications enabling NASA's Artemis mission to the Moon by 2024 and on to Mars is closer to realization, thanks to leadership and guidance provided by SCA_N within the Consultative Committee for Space Data Standards (CCSDS). This international consortium of the world's major space agencies and commercial partners, whose management council is chaired by SCA_N, recently released its first two industry standards for interoperable, free-space optical communications. Commonly known in the spacefaring community as Blue Books, the CCSDS Recommended Standards publications establish comprehensive technology standards for the international space community. These include highly detailed specifications for the manufacture and use of interfaces, technical capabilities and protocols, and other controlling standards such as encoding regimes. These publications are the culmination of a multiyear standardization effort in CCSDS, with active participation from NASA, ESA, Centre national d'études spatiales (CNES),

German Aerospace Center (DLR), JAXA, and others. The standard is designed for photon-starved free space optical communications, as occurs for missions to deep space, the Moon, and low-power Earth-orbiting missions. Initial missions using the standards will include Deep Space Optical Communications and Optical Comm on Orion, with a planned ESA mission as well.

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

SCaN continued leading NASA's efforts in U.S. interagency and international Positioning, Navigation, and Timing (PNT) policy management. Since 2007, it has sponsored the National Space-Based PNT Advisory Board, an independent Federal Advisory Committee Act (FACA) board, and, as Executive Director, coordinated its biannual sessions. Its success led to the NASA Administrator's 2019 appointment of SCaN as Executive Secretary of the National Space Council UAG, another FACA board. The UAG held its fifth meeting in July 2020, where it approved four key recommendations and identified critical areas for cooperation with the PNT Advisory Board in protecting Global Positioning System (GPS) space users from harmful interference. NASA continued assisting the USAF with the implementation of GPS Block IIIIF, the next batch of 22 GPS satellites, to protect and improve GPS capabilities to support space users. Efforts include 1) preserving current navigation capabilities within the Space Service Volume (SSV), the region of space between LEO and Geosynchronous Orbit (GEO);

2) implementing Laser Retro-reflector Arrays to enable high-precision measurements; and 3) implementing Canadian-furnished GPS Search and Rescue (GPS SAR) payloads. NASA continued working with foreign Global Navigation Satellite System (GNSS) service providers to develop an Interoperable Multi-GNSS SSV that will expand the PNT capabilities beyond what any one GNSS can provide on its own. NASA began work on a second edition of “The Interoperable GNSS SSV” booklet for release in 2020–2021, which further improves the analyses and expands the scope beyond GEO altitude and into lunar space. Other efforts include the development of the international GNSS-based Medium Earth Orbit Search and Rescue, of which GPS SAR is the U.S. contribution, to locate emergency beacons.

Space Life and Physical Sciences Research and Applications

Space Life and Physical Sciences Research and Applications was reorganized in July 2020. The HRP was transitioned into the Human Spaceflight Capabilities (HSC) office within the HEOMD, while Biological and Physical Sciences was moved into the Science Mission Directorate and established as a new division, the Biological and Physical Sciences Division.

Biological and Physical Sciences

Biological and Physical Sciences (BPS) at NASA continues its strategy to explicitly align research on two primary thrusts, enabling exploration and pioneering scientific discovery. This structure is in keeping with the framework for research prioritization recommended by the National Academies of Sciences, Engineering, and Medicine in their 2011 Decadal Survey for Life and Physical Sciences Research at NASA and reaffirmed in their midterm assessment report, released in 2018.

Cold Atom Lab

The Cold Atom Lab (CAL), operating aboard the ISS, had an exceptional year in 2020, despite challenging external circumstances, including the necessity, due to COVID-19, to command the facility from CAL team members’ homes. Highlights included the completion of the first science phase with the initial science module, which is the part of the hardware that generates and contains the Bose-Einstein

condensates. Also, the project upgraded to a new science module, which added the capability of utilizing atom interferometry. CAL investigators published preliminary results in an issue of the science journal *Nature*, which featured CAL on the cover.

Following the successful astronaut integration of the new science module, the project team conducted the first demonstration and use of an atom interferometer in orbit, whereby an atomic wave packet is split into two spatially separated packets and then recombined, producing an interference pattern. Such atom interferometers form the basis of a new generation of exquisitely precise quantum sensors. These sensors are particularly well suited for space applications due to the long interrogation times available in free fall because sensitivity typically increases as the square of this interrogation time. Subsequent measurements conducted by the team demonstrated the utility of atom interferometry for measurements of magnetic fields and of the recoil an atom experiences when it emits a photon.

These results herald a future in which space-based quantum sensors become a widely used tool for scientists wishing to explore the universe. Applications range from tests of general relativity and searches for dark matter and gravitational waves to spacecraft navigation and prospecting for subsurface minerals on the Moon and other planetary bodies. Indeed, the team pursued measurements in many of these areas over the course of 2021.

Beyond long interrogation times, CAL is significant for atomic physics because the lack of gravity allows investigators to use vastly weaker traps, as atoms do not need to be supported against gravity. This perturbs the system less and allows investigations of physics that cannot be studied any other way. One of the most significant examples came from the first science phase, where one of the Principal Investigators was able to create a Bose-Einstein condensate in a novel trap shaped like a bubble. Due to gravity, atoms would fall to the bottom of a trap on Earth and researchers could not form a condensate with that shape. Studying the behavior of quantum gases in this novel topology may give new insights into the structure of neutron stars, which have been theorized to support condensate shells.

Other experimenters this year have worked on perfecting methods to cool and manipulate atoms in microgravity, either by expanding the atoms into very weak traps or by using a technique called delta-kick cooling, which can be thought of as

something of a “magnetic freeze ray” for atoms. Delta-kick cooling chilled atoms in one direction to temperatures well below 100 pico-Kelvin above absolute zero.

Due to the significant contributions of CAL to atomic and molecular physics, as well as its promise as a pathfinder in establishing a future of quantum science in space, the American Institute of Aeronautics and Astronautics awarded CAL the prestigious Space Science Award in 2020.

Burn Rate Emulator

ISS experiments obtained unique data focused on fire prevention, especially in spacecraft. Data obtained from a flat burner fed by gaseous fuel provided information on both gaseous and solid material flammability, flame ignition, and extinction. Test results are applicable to both partial- and microgravity environments, and data on gaseous combustion limits can be applied to both gases and solid materials such as paper and plastic.

Structure and Response of Spherical Diffusion Flames

Another ISS combustion experiment obtained data on chemical kinetics associated with combustion. To study chemical kinetics, researchers use simplified flame configurations—gas jet, flat-flame, static and flow reactors—where the flows are slower, and the flames are near the extinction limit. In terrestrial laboratories, these flames are dominated by buoyancy, so we can only study the chemical kinetics with high accuracy in microgravity.

This information is useful terrestrially in computational simulations to increase burning efficiency and reduce pollution. Because the majority of energy use in the U.S. economy is still produced by combustion, such as to drive electrical power plant boilers or for transportation in internal combustion engines, this information has the potential to reduce greenhouse gas emissions via more efficient fuel use, as well as reduce harmful particulate pollution.

Packed Bed Reactor Experiment

Both terrestrial and space-based chemical flow equipment utilize cylinders filled with small spheres coated with either reactants or catalysts. Known as packed bed reactors, on Earth they form the working heart of chemical reactors and scrubbers.

In the microgravity environment, they have been used in hardware such as the Volatile Removal Assembly, which converts wastewater to potable water on the Space Station, and the intravenous fluid generation hardware that used ISS water to produce normal saline that meets all requirements for medical use.

In spite of those successes, engineers do not have a detailed understanding of how fluid flows through these systems in microgravity, so space-based systems generally rely on engineering judgment. As a result, NASA conducted the Packed Bed Reactor Experiment-2 (PBRE-2) to validate equations that can be used to design these reactors for reliable and optimal performance in partial- and microgravity conditions. Specific quantities measured in over 1,300 runs included flow pattern transitions between bubbly and pulsed flow, pressure drops, and mass transfer rates. These tests used 2-mm-diameter beads as opposed to the 3-mm-diameter beads that were previously used in the first PBRE. The smaller spheres may have trapped gas pockets within the bed, thus not providing fluid access to the entire bed and degrading filter performance.

Electrostatic Levitation Furnace/Electromagnetic Levitation Furnace

U.S.-funded investigations on the ISS to characterize material properties continued in FY 2020 in ESA's Electromagnetic Levitation facility and started in JAXA Electrostatic Levitation Furnace facility. Performing electromagnetic and electrostatic levitation in the microgravity environment of the ISS provides an opportunity for better understanding the physical properties of metals and bulk metallic glasses.

Levitation provides the opportunity to perform “containerless” experiments that eliminate the interactions between a sample and the container wall. While levitation experiments can be conducted on Earth, the microgravity environment provides more accurate data because it removes sedimentation effects as the samples are melted and solidified.

Levitation experiments in FY 2020 provided data for 1) better manufacturing of cast superalloy components to improve efficiency, safety, and reliability of rocket and jet engines; 2) understanding the ability of metallic liquids to form bulk metallic glasses, which are an emerging class of materials with several applications, including cryogenic gears for planetary exploration; 3) investigating

thermophysical properties of high-temperature materials to allow more efficient and reliable production of metallic parts using these alloys; and 4) understanding and controlling the sources of thermophysical properties measurement error and providing a baseline dataset for quantifying uncertainty in measurements.

Gravitational Effects on Distortion in Sintering

Liquid phase sintering, a process to shape or form solid materials, is a manufacturing mainstay for fabricating a wide array of products such as metal-cutting tools, automotive engine connecting rods, and self-lubricating bearings. Future applications of liquid phase sintering may include in-space fabrication and repair, as well as using lunar regolith as a feedstock to fabricate structures on the Moon or using sintered metal powder to fabricate replacement components during extraterrestrial exploration.

There is considerable experience with liquid phase sintering on Earth in 1 g, but the behavior under reduced gravity conditions is not well understood. To that end, the BPS-sponsored Gravitational Effects on Distortion in Sintering (GEDS) investigation focuses on determining the underlying scientific principles to forecast density, size, shape, and properties for liquid phase sintered bodies over a broad range of compositions in microgravity conditions. Processing of the GEDS experiment was completed on the ISS in FY 2020, with the investigation team analyzing the samples in FY 2021.

Fundamental Physics

Research community-based Science Definition Teams evaluating a variety of potential fundamental physics missions reported on their first-year assessment of science objectives, science requirements, and mission concepts in 2020. Detailed reports were delivered to NASA in the following research areas:

- Fundamental physics with Optical Clock Orbiting in Space, with a target precision of one part in 1,018;
- Deep Space Quantum Link, for fundamental research into quantum entanglement over light-second Earth–Moon distances; and
- Dust Research Experiments at the Moon, for studying fundamental interactions between dust, charge, and plasma effects on the lunar surface.

In addition, a new International Fundamental Physics Science Definition Team was established in FY 2020 to determine the research objective, requirements, and implementation concept for a COMplex PLASma FaCiliTy (COMPACT) for the ISS.

Space Biofilms

Biofilm growth has been observed on both American and Russian spacecraft as well as on the ISS. These biofilms can sometimes jeopardize key equipment like spacesuits, water recycling units, radiators, and navigation windows. Biofilm formation also increases the risk of human illness and therefore needs to be understood to enable safe, long-duration human space missions.

The Space Biofilms investigation, a collaboration between the Physical Sciences and Space Biology programs, characterizes the mass, thickness, and morphology of biofilms that form in space by analyzing different microbial species grown on different materials. The investigation also aims at elucidating the biomechanical and transcriptomics mechanisms involved in biofilm formation in space.

New knowledge from this investigation may lead to improved methods and materials for controlling biofilm formation in space. The Space Biofilms investigation was conducted on the ISS in FY 2020 and the results returned to the ground for analysis.

Rodent Research

The Rodent Research (RR)-10 mission launched aboard SpaceX-21 to the ISS, and the flight study was completed in 2020. RR-10 investigates how spaceflight affects the cellular and molecular mechanisms of normal bone tissue regeneration. Bone tissue health depends on regenerative adult stem cells in bone marrow (osteoprogenitors) differentiating into mineralizing osteoblasts and balancing bone tissue loss due to normal wear and tear.

During spaceflight, microgravity disuse and space radiation can increase bone degeneration and hinder stem cell-based bone tissue regeneration, resulting in dramatic bone tissue loss. RR-10 aims to increase our mechanistic understanding of the biological processes that underlie stem cell-based bone tissue regenerative deficits in space. This understanding is critical to further applied research aimed at

maintaining tissue regenerative health when sending astronauts on long-duration space missions. The mission could uncover new ways to improve therapies for humans both in space and on Earth by finding candidate next-generation countermeasures and new biomarkers that may be used for diagnostic purposes.

Cell Biology

The BioScience-04 mission is the first study to investigate the multiplication of nervous system stem cells in microgravity. This experiment will test whether these important cells from the brain and spinal cord divide faster into daughter cells in the microgravity environment of space. In addition, the experiment will allow scientists to study the cell-signaling pathways that determine cell function, proliferation, and differentiation.

Cell replacement therapies would greatly benefit people with neurological disorders or neurological diseases like multiple sclerosis but are not yet practical because no existing method generates stem cells in sufficient numbers quickly enough. This mission was launched aboard SpaceX-16 in November 2018 and launched again for further study on SpaceX-21 in December 2020, to better understand these cells, which are vitally important to nervous system health.

Microbial Research

Candida albicans is a common member of the human gut flora, and more than 25 percent of the general population has the fungus in their system. For most people, it is a slight annoyance or not a problem at all, but for those with suppressed immune systems, a *C. albicans* infection can be dangerous and potentially even life-threatening.

Because the conditions of space weaken the immune systems of spaceflight crewmembers, they face higher risks to their health should they develop infections. Given that this common and potentially dangerous microbe could pose a risk to astronauts, it is important to gain a clearer picture for planning future spaceflights. The Micro-14 life science research mission will characterize changes in the growth of *C. albicans* in microgravity and allow insight into what conditions in the environment influence these changes.

This Space Biology mission, launched on Space X-21, will identify mechanistic pathways associated with adaptation processes that might provide diagnostic and/or therapeutic insights for controlling and treating yeast infections both in space and on Earth.

Deep Space Exploration Research

In 2020, Space Biology completed development of hardware that will send science experiments to the Moon and back to Earth as part of the Artemis I mission to the Moon. Plant seeds, yeast, algae, and fungi will travel in the Artemis crew capsule to investigate how the deep space environment, especially radiation, affects these specimens.

These studies are key pathfinder investigations that will provide the first data on how the cislunar environment impacts biology since the Apollo 17 mission, 47 years ago. The investigations will use cutting-edge, state-of-the art science techniques, which were not available in 1972, to provide unprecedented data to characterize the physiology, genetics, and mechanisms of life in deep space. The findings will be used to define future experiments with the objectives of fostering human exploration to the Moon and Mars. Launch is currently targeted for June 2021.

Lunar Exploration Instrument

A new initiative developing a Lunar Exploration Instrument for space biology Applications (LEIA) began in earnest in 2020 and will provide a testbed for our model organisms beyond low-Earth orbit (BLEO). The project will utilize autonomous radiation-tolerant research hardware compatible with a wide range of flight opportunities as part of an essential pivot to keep pace with the upcoming Gateway, lunar, and Mars missions actively pursued by NASA and commercial partners.

The first iterations will be based on the successful BioSentinel hardware, with increased functionality to be added as the project progresses. A science working group has been assembled and is defining science requirements for hardware that will support future BLEO research. This group will be an active partner with the project and will provide guidance for hardware development for future missions as our knowledge evolves.

Spectrum Multi-Spectral Fluorescence Imager

The Spectrum Multi-Spectral Fluorescence Imager was installed during 2020 and is now ready for use aboard the ISS. Spectrum provides a new, valuable capability for Space Biology researchers to study the effects of microgravity on plants and other organisms.

Using Spectrum, scientists can identify which genes are expressed in biological cells through fluorescence imaging. Biological organisms will be grown in Spectrum's environmental chamber under controlled lighting, temperature, humidity, and carbon dioxide levels. As these organisms grow, specific genes will be activated or "turned on" under microgravity conditions. These activated genes will produce proteins labeled with fluorescent markers. These fluorescent proteins can be identified using the Spectrum imaging system.

Understanding which genes are expressed in biological cells is key to understanding how biological organisms respond and adapt to the stresses of spaceflight. This knowledge will help future space researchers select or genetically engineer plants for survival in space—a critical component for food production during long-duration space missions or settlements on the Moon or Mars.

Plant Research

Radishes were grown in space for the first time ever in 2020. Radishes are good candidate plants to grow on the ISS because they mature quickly (harvest ≤ 28 days after planting), their genetic and metabolic information are readily available, they are nutritionally desirable, and they provide a wealth of information that can be analyzed by biochemical, physiological, and genetic approaches.

Knowledge from the Plant Habitat-02 study will be essential for the transition from Earth-bound cultivation of plants to growth conditions in space to one day support the establishment of human habitats on the Moon, Mars, and farther outposts.

GeneLab

The NASA GeneLab open science database (<https://genelab.nasa.gov>) has been increasingly successful in enabling scientific discovery and space exploration through multi-omics data mining of its 296 spaceflight datasets. By the end of

2020, GeneLab had been the sole source for 50 scientific peer-reviewed articles directly linked to datasets. Thirty additional peer-reviewed articles were generated from gathering new knowledge on how life adapts to space through the aggregate analysis of multiple spaceflight omics datasets (e.g., changes in DNA content, gene expression, protein levels) archived in GeneLab.

At the heart of such increase are nine manuscripts, which were part of a special issue on space biology in the publication *Cell* and other Cell Press journals in November 2020, with 29 scientific papers and more than 200 authors worldwide. Many of these publications were the result of collaborative analysis done by more than 120 users from around the world who joined the GeneLab Analysis Working Groups and volunteer their expertise in bioinformatics to extract more information from these previously published data.

These findings advance our understanding of key crew-health threats for long-duration exploration and demonstrate the power of open science.

Science Mission Directorate

NASA's Science Mission Directorate (SMD) increases our understanding of Earth, the Sun, our solar system, and the universe. Through its partnerships with government and research organizations, academia, and industry, both in the United States and globally, SMD develops and utilizes space-, air-, ground-, and sea-based observatories to gather and analyze data that further our knowledge in the areas of Earth and planetary science, heliophysics, and astrophysics.

In FY 2020, SMD operated 76 missions. These missions are hallmarks of the research being done across SMD's five science divisions: Earth Science, Planetary Science, Heliophysics, Astrophysics, and Biological and Physical Sciences. Our Earth Science missions study Earth to advance scientific understanding of our home planet and identify and address societal challenges caused by evolving climate conditions. Planetary Science missions advance our knowledge of the origins and history of our solar system, identify the potential for life beyond our own planet, increase the body of knowledge necessary for humans to explore beyond low-Earth orbit, and assess threats to our planet from the impact of near-Earth objects. Heliophysics missions study the Sun and how its eruptions affect Earth and interplanetary space, while Astrophysics missions further our understanding of the universe and our place in it, including searching for other Earth-like planets capable of supporting life. Space biology research helps scientists understand the effects of microgravity on living systems, while physical science research enables scientists to understand the effects of microgravity on physical phenomena, such as fluid physics and combustion science.

SMD's Science Activation program leverages unique science infrastructure, content, and scientific experts to engage with learners of all ages. In FY 2020, working with community-based institutions, such as libraries, museums, science centers, and planetariums, the Science Activation program continued its work through 31 cooperative agreements, leveraging more than 220 partners in all 50 states. In 2019, the program was assessed by the National Academies of Sciences, Engineering, and Medicine and was lauded for its outreach to underserved learners. In addition, the Citizen Science Initiative was launched in 2019 and is composed of 22 funded projects that harness the energies of the public and use the rigors of science, resulting

in new discoveries. As of March 2020, there have been 43 refereed publications with named coauthors who are NASA citizen scientists.

In addition to these divisions, SMD is home to the Exploration Science Strategy and Integration Office (ESSIO), the James Webb Space Telescope Program Office, the Mars Sample Return Program Office, and the Joint Agency Satellite Division, which conducts reimbursable satellite programs with the National Oceanic and Atmospheric Administration (NOAA).

Earth Science

Earth is a dynamic, interconnected, living planet that continues to change, due to its own system processes and the impact of humans. The Earth Science Division uses data captured by research satellites, airborne and in situ campaigns, and integrative research activities to understand Earth systems. A key goal of the Earth Science Division is to help inform policy and decision makers for agriculture, water and food security, urban planning, disaster preparedness and response, transportation, climate and weather, and many other issue areas that benefit life on Earth. Through partnerships with other Federal agencies, academia, industry, research organizations, and foreign governments, the Earth Science Division seeks to continue to identify and make the observations necessary to understand our rapidly evolving planet through the coming decades. Below are several research and application highlights from FY 2020.

NASA, NOAA Analyses Show 2019 Is the Second Warmest Year on Record

In January 2020, independent analyses carried out by both NASA and NOAA found that Earth's global surface temperatures in 2019 were the second warmest since modern recordkeeping began in 1880. These temperature measurements indicate that the planet's long-term warming trend is continuing—the past five years have been the warmest of the last 140 years. Scientists have used climate models and statistical analyses of global temperature data to conclude these increases are mostly being driven by human activities, which have increased carbon dioxide and other greenhouse gas emissions into the atmosphere.¹

1 <https://www.nasa.gov/press-release/nasa-noaa-analyses-reveal-2019-second-warmest-year-on-record>

Cloud Processes in Western North Atlantic Ocean

From March through May 2020, NASA conducted the Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE), an airborne science campaign to help improve weather and climate predictions using data collected on cloud processes over the western North Atlantic Ocean. ACTIVATE was the first NASA field campaign to collect such extensive data of cloud processes in a single region.²

Global Survey Using NASA Data Shows Growth of Glacial Lakes

In August 2020, using 30 years of NASA satellite data, researchers working under a grant from NASA's High Mountain Asia Program found that the volume of glacial lakes worldwide has increased by approximately 50 percent since 1990 as glaciers melt and retreat due to climate change. Published in the journal *Nature Climate Change*, these findings will help researchers better understand how glacial meltwater is transported to the oceans, leading to improved accuracy of sea-level rise estimates and better assessments of the potential hazards to communities downstream of these often unstable lakes.³

JASON-2/Ocean Surface Topography End of Life

The Jason-2/Ocean Surface Topography Mission (OSTM), a U.S.-European partnership designed to measure sea surface height, successfully ended its mission on October 1, 2019. The mission, which launched in 2008, extended the long-term record of sea surface height measurements started by the TOPEX/Poseidon and Jason-1 missions. Since its launch, Jason-2/OSTM recorded a nearly 2-inch global sea-level rise, a critical impact of climate change.⁴

COVID-19 Response

As the world continues to respond to the COVID-19 pandemic, NASA resources have provided unique vantage points in observing the environmental, economic, and societal impacts of the coronavirus. For example, NASA's Ozone

2 <https://www.nasa.gov/press-release/media-invited-to-inside-look-at-nasa-marine-cloud-study>

3 <https://www.nasa.gov/press-release/global-survey-using-nasa-data-shows-dramatic-growth-of-glacial-lakes>

4 <https://www.nasa.gov/press-release/ocean-monitoring-satellite-mission-ends-after-11-successful-years>

Monitoring Instrument (OMI) onboard the Aura satellite and the European Space Agency's (ESA) TROPOspheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5P satellite collected data that indicated rapidly falling nitrogen dioxide levels around the world as people sheltered in place. NASA also funded several projects evaluating the impacts of the environment on virus spread, as well as the impacts of the pandemic itself, specifically assessing the effect of lockdown measures on food security, fire ecology, urban surface heat, clouds and warming, air pollution and precipitation, water quality, and aquatic ecosystems.^{5,6}

In addition, NASA datasets have been used to better understand how COVID-19 spread across the globe. The NASA Socioeconomic Data and Applications Center launched an interactive mapping tool that researchers have used to visualize global age and sex data overlain with updated COVID-19 spread data from The Johns Hopkins University of Medicine Coronavirus Resource Center. This tool is especially useful for localities that have limited access to spatial population data.

NASA, along with ESA and the Japanese Aerospace Exploration Agency, also collaborated on the COVID-19 Earth Observation Dashboard,⁷ bringing together current and historical satellite observations with analytical tools to create a user-friendly resource for both researchers and the general public to better understand the impact on the environment and socioeconomic activity caused by the global response to the COVID-19 pandemic. Key metrics being tracked include changes in air and water quality, climate, economic activity, and agriculture.⁸

Planetary Science

NASA's Planetary Science Division advances scientific knowledge of our solar system through exploration and research. Pushing the limits of spacecraft and robotic engineering, the division's portfolio of missions explores every major body

5 <https://www.nasa.gov/feature/nasa-monitors-environmental-signals-from-global-response-to-covid-19>

6 <https://www.nasa.gov/feature/esd/2020/new-projects-explore-connections-between-environment-and-covid-19>

7 <https://eodashboard.org/>

8 <https://www.nasa.gov/press-release/nasa-partner-space-agencies-to-release-global-view-of-covid-19-impacts>

in the solar system and many smaller ones. The data from these missions support research into questions that include the history and continued evolution of planets, moons, and small bodies (e.g., asteroids, comets); the origin of life and the potential for life elsewhere; and the hazards and resources present as humans explore space. In addition, the division's Planetary Defense Coordination Office identifies threats to Earth posed by impacts of near-Earth objects. Following are seven highlights from FY 2020:

OSIRIS-REx Prepares to Sample Asteroid Bennu and Make History

In preparation for its October 2020 touch-and-go sample collection from the asteroid Bennu, the Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) conducted close flyovers of its primary and secondary sampling sites in FY 2020. These flyovers were critical to understanding the hazardous terrain that the spacecraft will need to navigate to collect samples. The mission also conducted two critical rehearsals of the difficult maneuvers that were needed to descend to the surface with an extraordinary level of accuracy.

Water on Europa

In November 2019, an international team led by scientists at Goddard Space Flight Center announced the discovery of water vapor in plumes above the surface of Europa. One of Jupiter's 79 moons, Europa is an important target for exploration because it is theorized to have a water-rich ocean in its interior that gives it the potential to host life. Plumes have been observed erupting from its surface, but until this study, scientists did not have the ability to determine their composition. Confirmation of the presence of water vapor is further evidence in favor of an interior ocean and indicates a connection to Europa's surface, which makes NASA's Europa Clipper mission, launching in 2024 to investigate Europa and its habitability in detail, even more exciting.⁹

9 <https://www.nasa.gov/feature/goddard/2019/nasa-scientists-confirm-water-vapor-on-europa>

Comet NEOWISE Dazzles During the Summer of 2020

Comet C/2020 F3 (Comet NEOWISE) was discovered on March 27, 2020, by the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) mission during its survey operations to find and characterize small bodies, including asteroids and comets, that could pose an impact threat to Earth. Having survived its close passage by the Sun, Comet NEOWISE became the most visible northern-hemisphere comet to the naked eye since Comet Hale-Bopp in 1997. During the summer of 2020, it dazzled comet researchers, backyard astronomers, the public, and even astronauts on the International Space Station. NASA assets, including the Hubble Space Telescope, the Infrared Telescope Facility, Solar and Heliospheric Observatory (SOHO), and even the Parker Solar Probe, were used to study the structure and composition of Comet NEOWISE.¹⁰

Four Possible Missions to Study Secrets of the Solar System Selected for Concept Development

In February 2020, NASA selected four planetary science missions submitted to the Discovery Program for concept development. The Discovery Program is a competitive program that invites teams of scientists and engineers to design planetary science missions under a not-to-exceed cost-cap that further our understanding of the solar system and our place within it. The four selections include missions to explore Venus' atmosphere; Venus' surface; Jupiter's moon, Io; and Neptune's moon, Triton.¹¹

Launch of Mars 2020 Perseverance Rover Mission

NASA's Mars 2020 Perseverance rover launched on July 30, 2020, from Cape Canaveral Space Force Station in Florida. The Perseverance rover will seek out signs of past microscopic life on Mars, explore the geology of Jezero Crater, an ancient lakebed, and demonstrate key technologies that will help us prepare for further robotic and eventually human exploration of Mars. The rover will also be collecting well-documented, scientifically selected samples for potential future return through the Mars Sample Return Campaign. In addition to these objectives,

¹⁰ <https://www.nasa.gov/feature/jpl/comet-neowise-sizzles-as-it-slides-by-the-sun-providing-a-treat-for-observers>

¹¹ <https://www.nasa.gov/press-release/nasa-selects-four-possible-missions-to-study-the-secrets-of-the-solar-system>

Perseverance also carried a technology demonstration payload—the Ingenuity Mars Helicopter—that will attempt up to five powered, controlled flights. This demonstration mission will provide information to advance future human missions to Mars. The mission arrived at Mars in February 2021.¹²

Crustal and Time-Varying Magnetic Fields at the InSight Landing Site on Mars

NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission hosts the first magnetometer deployed to the Martian surface. In February 2020, scientists announced that its observations reveal a Martian crustal magnetic field ten times stronger than anticipated. The main source of the field is basement rocks estimated to be at least 3.9 billion years old that were likely magnetized by the ancient dynamo in the Martian core. Additional magnetic field variations discovered in InSight's magnetic data appear to be linked with ionospheric currents in the atmosphere between 120 km and 180 km above the planet's surface.¹³

MAVEN Spacecraft Observes Martian Atmospheric Motions in Middle Atmosphere

Images sent in August 2020 from NASA's Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft offered scientists the first insights into atmospheric motions in Mars' middle atmosphere. These observations indicate that Mars' middle atmosphere is influenced by a daily pattern of solar heating and impacted by the topography of Mars' large volcanic mountains. These circulation patterns of atmospheric gases help scientists better understand Mars' atmospheric conditions, as well as showing how atmospheric gases are transported around the planet and from the surface to the edge of space.¹⁴

Heliophysics

The energy from our Sun enables and sustains life on our home planet, while also producing radiation and magnetic energy that can impact that same life,

12 <https://www.nasa.gov/press-release/nasa-ula-launch-mars-2020-perseverance-rover-mission-to-red-planet>

13 <https://www.nature.com/articles/s41561-020-0537-x#citeas>

14 <https://www.nasa.gov/press-release/goddard/2020/mars-nightglow>

satellites, and planets' atmospheres. The Heliophysics Division studies the Sun and how it influences the very nature of interplanetary space—and, in turn, the atmospheres of planets and the technology that exists there. Solar activity can interfere with satellite electronics, communications, and GPS signals, and it can also impact the radiation fields that spacecraft travel through to get to the Moon, Mars, and other planets. Included below are four highlights from FY 2020:

Launch of Mission to Study Earth's Ionosphere

Launched in October 2019, NASA's Ionospheric Connection Explorer embarked on a unique mission to study the ionosphere, a region of space where space weather changes can disrupt communications and satellite orbits and increase radiation risks to astronauts. Previously, this region was difficult to observe, as spacecraft cannot travel within the low parts of the ionosphere, and balloons cannot travel high enough.¹⁵

Initial Data from Parker Solar Probe Reveal Details of Sun's Activities

Parker Solar Probe, which was launched in August 2018, is a first-of-its-kind mission to “touch” the Sun to understand how energy and heat move through the solar atmosphere, the corona, as well as what accelerates solar winds and energetic particles. Initial data results were published in December 2019, revealing details on how the Sun constantly ejects material and energy that can help scientists advance their understanding and prediction of space weather around Earth and explain aspects of how stars are created throughout the universe.¹⁶

Launch of Joint NASA-ESA Solar Mission

Solar Orbiter, a joint mission between ESA and NASA to study the Sun, was launched on February 9, 2020. The spacecraft carries six instruments to capture images of the Sun and its surroundings, as well as four instruments to monitor the environment around the spacecraft. In mid-June 2020, Solar Orbiter made its first close pass of the Sun, capturing the closest images of the Sun ever taken to that point and revealing new phenomena scientists have not been able to observe

15 <https://www.nasa.gov/press-release/nasa-spacecraft-launches-on-mission-to-explore-frontier-of-space>

16 <https://www.nasa.gov/feature/goddard/2019/nasas-parker-solar-probe-sheds-new-light-on-the-sun>

before, including “campfires,” small solar flare–type occurrences. Both agencies are committed to publicly sharing the data from this mission as they are transmitted, calibrated, and validated, with the first datasets released on September 30, 2020.¹⁷

New Space Environment Missions Selection

In August 2020, NASA selected five proposals for mission concept studies to better understand the dynamics of the Sun and the constantly changing near-Earth space environment. These studies include missions to expand our knowledge of Earth’s space weather system and its interactions with the magnetosphere, solar winds, the Sun’s corona, auroras, and the Sun’s poles. Investigators for the selected proposals are expected to conduct a nine-month mission concept study, at which point NASA will downselect no more than two proposals to go forward to launch.¹⁸

Astrophysics

The Astrophysics Division manages studies of the universe, seeking to better understand the creation and history of stars and galaxies, as well as our place within it. Astrophysics explores how planetary systems can form; how habitable environments, similar to our Earth, develop; and whether other worlds contain the signatures of life. Below are several significant highlights from FY 2020:

Hubble Discoveries

The Hubble Space Telescope, a revolutionary tool for modern astronomy, celebrated its 30th year in space in April 2020. Hubble has provided astronomers with key insights into our universe and our place in time and space. In FY 2020, Hubble data and images were used to make three significant discoveries!¹⁹

In October 2019, Hubble provided the best view to date of an interstellar comet from beyond our solar system. This discovery provides scientists with invaluable

17 <https://sci.esa.int/web/solar-orbiter/-/solar-orbiter-s-first-images-reveal-campfires-on-the-sun>; <https://sci.esa.int/web/solar-orbiter/-/solar-orbiter-releases-first-data-to-the-public>; <https://www.nasa.gov/press-release/nasa-esa-to-release-first-images-from-solar-orbiter-mission>

18 <https://www.nasa.gov/press-release/nasa-selects-proposals-for-new-space-environment-missions>

19 <https://science.nasa.gov/hubble-marks-30-years-space-tapestry-blazing-starbirth>

information about the chemical composition, structure, and dust characteristics of planetary objects born in an unknown star system.²⁰

That same month, scientists used Hubble data to make the most accurate measurements to date of how fast gas flows in and out of the Milky Way. Astronomers had previously determined that our galaxy undergoes a recycling process of galactic gas and had theorized there was an equilibrium of gas inflow and outflow. After evaluating ten years of ultraviolet data from Hubble, astronomers were able to determine that there is an excess of inflowing gas, the source of which remains a mystery. Though the Milky Way is the only galaxy for which we have a full accounting of gas inflow/outflow, this information can be used to better understand galaxies across the universe.²¹

In January 2020, astronomers, using Hubble data, found that dark matter can gather in clumps of smaller sizes than previously known, adding to the body of knowledge of the nature of dark matter. The significance of this discovery helps astronomers expand their understanding of fundamental physics and the nature of the universe.²²

Pulsar Mission Expands Our Understanding of the Remains of Exploded Stars

NASA's Neutron star Interior Composition ExploreR (NICER) is changing what scientists once knew about pulsars, the dense and whirling remains of exploded stars. In December 2019, scientists were able to use data captured by NICER to accurately measure both a pulsar's size and its mass, as well as create the first-ever map of hot spots on its surface, integral information to understanding how pulsars actually work. NICER was developed to precisely determine the masses and sizes of several pulsars, which in turn will help scientists understand the state of matter in the cores of neutron stars.²³

20 <https://www.nasa.gov/feature/goddard/2019/hubble-observes-1st-confirmed-interstellar-comet>

21 <https://www.nasa.gov/feature/goddard/2019/milky-way-raids-intergalactic-bank-accounts-hubble-study-finds>

22 <https://hubblesite.org/contents/news-releases/2020/news-2020-05>

23 <https://www.nasa.gov/feature/goddard/2019/nasa-s-nicer-delivers-best-ever-pulsar-measurements-1st-surface-map>

Spitzer Space Telescope End of Life

After more than 16 years of studying the universe in infrared light, NASA's Spitzer Space Telescope was decommissioned in January 2020. Launched in 2003, Spitzer was the most sensitive infrared telescope in history and provided a deeper view of the infrared cosmos, studying our own solar system, as well as star and planet formation, the evolution of galaxies, and the composition of interstellar dust. Among its most significant discoveries, Spitzer detected the largest number of terrestrial planets ever found orbiting a single star. In addition, the telescope discovered a previously unidentified ring around Saturn. All of Spitzer's data are publicly available, and scientists expect researchers will continue to make discoveries using these data.²⁴

Kepler Data Used to Discover an Earth-Sized Habitable Zone Planet

In April 2020, using early Kepler space telescope data, an international team of researchers discovered an Earth-sized exoplanet orbiting in its star's habitable zone, the area around a star where liquid water could exist on a planet. Of all the exoplanets Kepler has found, this one is the most similar to Earth in size and estimated temperature, leading scientists to speculate about the possibility of life as we know it on this or other similar planets.²⁵

NASA Missions Find First Possible "Survivor" Planet Orbiting White Dwarf Star

In September 2020, using NASA's Transiting Exoplanet Survey Satellite and the retired Spitzer Space Telescope, an international team of astronomers reported what may be the first intact planet found closely orbiting a white dwarf measuring only 40 percent larger than Earth. The white dwarf creation process starts when a Sun-like star runs out of energy, swelling to a much larger size and forming a cooler red giant star. Over time, this red giant ejects its outer layers of gas, losing up to 80 percent of its mass, with the remaining hot core becoming a white dwarf. This process typically leads to any nearby objects being engulfed and incinerated. This

²⁴ <https://www.nasa.gov/press-release/nasa-s-spitzer-space-telescope-ends-mission-of-astronomical-discovery>

²⁵ <https://www.nasa.gov/press-release/earth-size-habitable-zone-planet-found-hidden-in-early-nasa-kepler-data>

discovery provides a target for the James Webb Space Telescope, which will have a capability to detect water and carbon dioxide on distant planets.²⁶

Roman Space Telescope Reaches Key Development Milestone

The Nancy Grace Roman Space Telescope (Roman) reached a development milestone in September 2020 with the completion of its primary mirror, which will be used to collect and focus light from cosmic objects in space. This mirror will allow Roman to capture images in space with a field of view 100 times greater than that of the Hubble Space Telescope but with the same sensitivity and image quality. The telescope will help astronomers better understand dark energy, exoplanets, and infrared astrophysics, and it is expected to launch in the mid-2020s.²⁷

Biological and Physical Sciences

The Biological and Physical Sciences Division (BPSD) moved to the Science Mission Directorate in July 2020 from its previous home in the Human Exploration and Operations Mission Directorate. The division has a twofold mission: 1) to better understand how spaceflight affects living systems and prepare for future human exploration missions beyond low-Earth orbit and 2) to advance our understanding of physical phenomena in the microgravity environment and underlying space exploration technologies, such as power generation and storage, space propulsion, life-support systems, and environmental monitoring and control. BPSD's Space Biology research is focused on animal biology; cell and molecular biology; microbiology; plant biology; and developmental, reproductive, and evolutionary biology. Physical science research is focused on biophysics, combustion science, complex fluids, fluids physics, fundamental physics, and materials science.

In FY 2020, more than a dozen experiments focused on space biology and physical sciences were launched to the International Space Station onboard commercial vehicles, as a part of NASA's Commercial Resupply missions. These experiments are integral to understanding the microgravity environment and identifying ways

²⁶ <https://www.nasa.gov/press-release/nasa-missions-spy-first-possible-survivor-planet-hugging-white-dwarf-star>

²⁷ <https://www.nasa.gov/feature/goddard/2020/primary-mirror-for-nasas-roman-space-telescope-completed>

in which living organisms—plants, animals, and humans—can thrive in space-flight conditions.²⁸

More information about specific experiments and projects can be found in the Human Exploration and Operations Mission Directorate section of this report.

Exploration Science Strategy and Integration Office

In March 2020, the Exploration Science Strategy and Integration Office (ESSIO) was created within SMD to help develop and implement a strategy to enable robotic and human exploration of the Moon and beyond. In this capacity, ESSIO manages the Lunar Discovery and Exploration Program (LDEP) and the Commercial Lunar Payload Services (CLPS) initiative, both of which work toward strategically integrating our science and exploration goals. NASA's CLPS initiative leverages commercial capabilities and technology to deliver scientific instruments and technology demonstration missions to the Moon.

In FY 2020, ESSIO focused its efforts on seeking proposals for demonstration missions and awarding contracts to commercial partners for payload delivery services to the Moon, ahead of human exploration of the lunar surface. In April 2020, NASA published an RFI to gather ideas for potential scientific, exploration, and technology demonstration missions to the Moon through NASA's CLPS initiative²⁹ and received 238 responses from the broad lunar community. Through FY 2020, NASA selected three U.S. companies to deliver a total of 24 instruments to the lunar surface. These payloads will begin to answer priority scientific questions about planetary science, buy down risk associated with human expeditions to the Moon and demonstrate new technologies required for science and space exploration activities.³⁰

28 <https://www.nasa.gov/feature/spsra-northrup-grumman-crs-ng-12-experiments-and-payloads>; <https://www.nasa.gov/feature/space-life-and-physical-sciences-research-and-applications-mission-payloads-for-spacex-19>; <https://www.nasa.gov/feature/space-life-and-physical-sciences-research-and-applications-northrup-grumman-crs-13>; and <https://science.nasa.gov/news-article/space-life-and-physical-sciences-research-and-applications-spacex-20-experiments-and-payloads>

29 <https://science.nasa.gov/news-article/request-for-information-payloads-and-research-investigations-on-the-surface-of-the-moon>

30 <https://www.nasa.gov/press-release/nasa-awards-contract-to-deliver-science-tech-to-moon-ahead-of-human-missions>

Finally, in June 2020, NASA selected Astrobotic to deliver the Volatiles Investigating Polar Exploration Rover (VIPER) to one of the Moon's poles in late 2024. Astrobotic will deploy its Griffin Lander to deliver VIPER in order to collect data, including the location and concentration of ice, that will be used to inform a water resource map of the Moon, a first-of-its-kind effort. This data will also be used to identify potential landing sites for future human exploration of the Moon.³¹

James Webb Telescope Program Office

The James Webb Space Telescope (Webb) achieved two significant development milestones in FY 2020. In October 2019, Webb passed a critical deployment test milestone in preparing for its 2021 launch. Engineers and technicians fully deployed and tensioned each of the sunshield's five layers, putting the sunshield in the same position it will be in once in space. This was the first time the sunshield was deployed and tensioned by the spacecraft electronics and with the telescope positioned above it, indicating that the telescope and sunshield are interacting as designed and expected.³²

In March 2020, Webb fully deployed its primary mirror into the same position it will occupy in space, another integral milestone in final tests to prepare the observatory for its launch in 2021. This was the first of two deployment tests for the primary mirror, demonstrating that the spacecraft internal systems can command the telescope to fully extend and latch the primary mirror.³³ Webb launched in 2021.

Joint Agency Satellite Division

The Joint Agency Satellite Division, together with NOAA, manages the development and launch of reimbursable satellite programs, projects, and instruments. More information about these satellite programs can be found in the Department of Commerce chapter of this report.

31 <https://www.nasa.gov/press-release/nasa-selects-astrobotic-to-fly-water-hunting-rover-to-the-moon>

32 <https://www.nasa.gov/feature/goddard/2019/nasa-s-james-webb-space-telescope-clears-critical-sunshield-deployment-testing>

33 <https://www.nasa.gov/feature/goddard/2020/nasa-s-james-webb-space-telescope-full-mirror-deployment-a-success>

Aeronautics Research Mission Directorate

NASA's Aeronautics Research Mission Directorate (ARMD) personnel remained diligent and worked creatively during FY 2020, even while addressing the challenges and limitations of a global pandemic that impeded growth in the industry. Despite the hurdles, NASA Aeronautics persevered to accomplish its mission to explore advances in atmospheric flight. As shown by the work in 2020, ARMD continued to create solutions for an evolving industry that will lead to more lucrative economic growth and ensure the skies above the United States remain the safest and most advanced in the world.

With a wide-ranging research portfolio informed by a comprehensive Strategic Implementation Plan aimed at transforming aviation for the 21st century, NASA's flight team during FY 2020 focused on goals in four broad areas requiring scientific and engineering investigations:

- Enabling a new market in commercial supersonic air travel over land with the help of data gathered by the X-59 Quiet SuperSonic Technology (QueSST) airplane, which was under construction during 2020.
- Leading industry in developing the technology and systems to safely and responsibly improve the efficiency of the National Airspace System for existing commercial aviation users as well as new users such as Advanced Air Mobility (AAM) drones and other new aircraft to conduct missions including emergency response, civic resource management, package delivery, and passenger transportation.
- Ushering in the next generation of passenger-carrying aircraft with novel innovation in four main focuses: electrified aircraft propulsion, small-core gas turbines, transonic truss-braced wings, and composite manufacture at a high rate. The Electric Powertrain Flight Demonstration project was stood up during the past fiscal year to support research toward some of these goals, and progress was made demonstrating integration of more environmentally friendly technology on an all-electric general aviation-sized airplane, the X-57 Maxwell.

- Advancing innovation throughout government, industry, and academia, and growing the future aerospace workforce through university research and exploration of disruptive technologies.

In pursuing these goals and many others, NASA's team of experts joined their talents in partnership with aviation experts and organizations within government, industry, and academia.

Quiet Supersonic Flight Over Land

Project teams during 2020 made steady progress with the Low-Boom Flight Demonstration mission, which seeks to enable the possibility of boarding a commercial supersonic airliner and flying across the United States twice as fast as a traditional jetliner. To support this goal, NASA is building the X-59 airplane, whose unique appearance and technology are designed to turn loud sonic booms associated with faster-than-sound flight into barely noticeable sonic thumps. The X-59 will be flown above select U.S. communities to measure public response to its noise. The resulting data and statistics will be presented to regulators, who will then consider lifting the ban on supersonic flight over land that has been in place since 1973.

During 2020, assembly of NASA's X-59 QueSST aircraft made great strides at Lockheed Martin Aeronautics Company in Palmdale, California. Significant work was completed on its wings, cockpit, and other hardware. In addition, NASA received delivery of the F414-GE-100 engine for installation into the X-59.

As progress in construction of the X-59 continued, NASA engineers designed new systems to support the pilot's ability to fly the aircraft with limited forward visibility. The solution: the eXternal Vision System (XVS), which provides live camera views overlaid with flight simulator-like graphics. After successful in-flight tests, researchers tested the structural integrity of the XVS through a series of vibration tests.³⁴

³⁴ More information is available online at <https://www.nasa.gov/X59>; <https://www.nasa.gov/feature/nasa-takes-delivery-of-ge-jet-engine-for-x-59/>; <https://www.nasa.gov/aeroresearch/nasa-marks-continued-progress-on-x-59/>; <https://www.nasa.gov/aeroresearch/nasas-supersonic-x-59-assembly-team-marks-wing-milestone/>; and <https://www.nasa.gov/feature/langley/shaking-things-up-for-the-x-59-aircraft/>.

Advanced Air Mobility

As more emerging entrants, both commercial and recreational, continue to fill the skies and dominate discussions about the future of aviation, NASA Aeronautics in 2020 continued to lead the Nation in the area of Advanced Air Mobility (AAM) and has continued to prioritize the goal of laying the foundation for a safe, reliable, and intelligent National Airspace System in the future.

This leadership role took many forms in 2020, including offering an open invitation for public, private, and academic organizations to collaborate with NASA as members of the AAM Ecosystem Working Groups. The primary purpose of the working groups is to share input, information, and opinions that may help to accelerate the development of safe, high-volume AAM flight operations in the existing and anticipated future national airspace system.

A NASA patent for traffic management of Unmanned Aircraft System (UAS) vehicles was awarded the 2020 Government Invention of the Year. This technology, called “Unmanned Aerial System Traffic Management to Enable Civilian Low Altitude Goods and Service Delivery by UAS,” allows unmanned aerial systems to maintain safe and efficient operations for the delivery of goods and services.

NASA researchers conducted Unmanned Aircraft Systems flight tests of drone aircraft at Moffett Field at NASA’s Ames Research Center (Ames) in California. The purpose of the tests was to investigate the feasibility of a concept called Time-Based Conformance Monitoring. Conformance monitoring is an important task of air traffic controllers or traffic management services that will be implemented in the future to ensure aircraft are adhering to their assigned flight trajectories.

NASA’s team at the Airspace Operations Laboratory at Ames developed augmented reality software to make useful information about all kinds of vehicles in our skies, like drones, more widely available to those who need it. Whether for emergency response or managing air traffic, visualizing complex data through augmented reality makes it easier for people on the ground to be aware of the operations of the uncrewed vehicles that will increasingly populate our skies.³⁵

35 More information is available online at <https://nari.arc.nasa.gov/aam-portal/>; <https://www.nasa.gov/uam/>; <https://www.nasa.gov/ames/utm/>; <https://www.nasa.gov/feature/utm-awarded-2020-nasa-government-invention-of-the-year/>; and <https://www.nasa.gov/feature/ames/augmented-reality-air-traffic-management>.

Electrified Aircraft Propulsion

With global interest in reducing aviation's impact on the environment, NASA Aeronautics in 2020 contributed to understanding potential solutions with a research focus on developing technologies and systems that could be incorporated into future airplanes whose propulsion is powered by electricity. One key element of this research was centered on the X-57 Maxwell, which is designed to be NASA's first all-electric X-plane.

Significant progress was made in preparation for the X-57. NASA completed tasks for the X-57's functional ground testing, working toward taxi testing and first flight. Assembly and qualification tests began on two critical components: the electric cruise motors, which will power the X-57 in flight, and the future high-aspect-ratio wing that will fly on the aircraft in the X-57's final configuration. Advanced designs that will propel the X-57 underwent wind tunnel testing at NASA's Langley Research Center (Langley) in Virginia. These tests, which took place in the Langley Low-Speed Aeroacoustic Wind Tunnel over the course of two weeks, were conducted to gather valuable operational and performance data for flight conditions. These X-57 tests advanced NASA's effort to help set certification standards for electric aircraft of the future. NASA's primary goal for the X-57 is to share the electric-propulsion design, lessons learned, and airworthiness process with regulators as new electric aircraft markets begin to emerge. Knowledge gained from the X-57 already is being used by manufacturers of electric vehicles that will likely be used in an urban air mobility environment.³⁶

Additional Highlights from NASA ARMD's Programs

Advanced Air Vehicles Program

NASA research projects for gathering data on aircraft noise and testing an air traffic management digital communications tool flew aboard a Boeing 787 as part of the company's 2020 ecoDemonstrator program. Results from these flights

³⁶ More information is available online at https://www.nasa.gov/centers/armstrong/programs_projects/electric_propulsion/index.html; <https://www.nasa.gov/centers/armstrong/features/Progress-on-X-57-Cruise-Motors-and-Wing.html>; and <https://www.nasa.gov/aeroresearch/all-electric-x-57-propeller-designs-undergo-wind-tunnel-tests/>.

will help continuing development of technology to enable future aircraft designs and flight operations that will be quieter and more fuel efficient and will result in fewer delays.³⁷

Flying farther, faster, and with less fuel—these are among possible benefits of a major collaborative project that had its final review at the beginning of FY 2020. For the past five years, NASA partnered with academia, industry, and other government agencies to research advanced composite materials used in aerospace construction. Their focus was on reducing the time it takes to develop and certify composite materials and structures.³⁸

Aeronautical innovators at Ames assisted with the Mars helicopter Ingenuity. Some of the significant technical challenges to overcome were ensuring the vehicle could perform a controlled takeoff in the thin Martian atmosphere and designing the vehicle to survive bitterly cold Martian nights and to operate largely on its own since direct pilot control is not possible.³⁹

Airspace Operations and Safety Program

Under a partnership taking Urban Air Mobility (UAM) forward, researchers from Uber and Ames ran tests focused on identifying the kinds of data and information necessary for UAM, where multiple operators of sometimes passenger-sized vehicles will need to fly safely together in the airspace. The teams at Ames and Uber connected their computer systems and ran through different scenarios that UAM operators could encounter. NASA intends to collaborate with many partners and ensure airspace operations will meet the needs of multiple use cases and be interoperable with the Federal Aviation Administration's (FAA's) systems.⁴⁰

Two industry partners signed information exchange agreements with NASA during 2020 that will establish mutually beneficial relationships to accelerate AAM operations as part of NASA's AAM National Campaign. Both partners now join other industry partners to prepare for the first campaign beginning in 2022 with

37 <https://www.nasa.gov/aeroresearch/nasa-partners-with-boeing-on-test-flights-to-advance-aviation>

38 <https://www.nasa.gov/feature/langley/five-year-study-of-advanced-composites-enters-final-review>

39 <https://www.nasa.gov/aeroresearch/nasa-aeronautics-experts-help-prepare-ingenuity-to-fly-on-mars>

40 <https://www.nasa.gov/feature/ames/nasa-and-uber-test-system-for-future-urban-air-transport>

intent to assess operational safety scenarios focused on their respective automation and vehicle designs.⁴¹

The Airspace Technology Demonstration 2 (ATD-2) project focused on enabling the coordination of schedules by those who manage the movement of aircraft from an airport gate to a spot in the sky after taking off, where the airplanes can safely join with the overhead traffic. By more reliably predicting and scheduling an aircraft's pushback time to begin taxiing to the runway, traffic could be managed in a way that flights can take off without pausing to sit on a taxiway. In a partnership with American Airlines and Charlotte-Douglas International Airport, testing has shown that the extra time at the gate for those aircraft involved has run just shy of six minutes—time they would have spent waiting on a taxiway burning fuel and passengers' patience, as well as releasing emissions. So far, NASA has transferred to the FAA two of three planned packages of knowledge and technology from ATD-2's three phases for the FAA's continued evaluation, certification, and deployment.⁴²

At Langley, engineers laid the foundation for safe autonomous flight through a project called Pathfinder. Pathfinder takes the ideas from separate UAS Traffic Management projects and combines them into a single autonomous vehicle that communicates with other autonomous vehicles in the airspace during flight. Combined, these systems will decrease the risk of a drone flying near manned aircraft and over any people below. These projects and technologies are critical to decreasing risk while enabling UAS to have access to the national airspace system.⁴³

The Fatigue Countermeasures Lab at Ames studied the way fatigue affects people with complex tasks to perform. The realms for these tasks can be as diverse as aviation and spaceflight, NASA space mission operations, military settings, and the operation of self-driving cars. By learning how sleep, alertness, and circadian rhythms interact, the lab team explored solutions to help people manage fatigue and do their jobs safely.⁴⁴

41 <https://www.nasa.gov/centers/armstrong/features/two-industry-partners-join-advanced-air-mobility-project.html>

42 <https://www.nasa.gov/feature/nasa-showcases-benefits-of-air-traffic-management-tools>

43 <https://www.nasa.gov/feature/langley/blazing-the-trail-of-urban-traffic-management/>

44 <https://www.nasa.gov/ames/fatigue-countermeasures>

Integrated Aviation Systems Program

NASA's Unmanned Aircraft Systems Integration in the National Airspace System (UAS in the NAS) project concluded in September 2020 after nine years of successful work. The project identified, developed, and tested technologies and procedures to help make it possible for UAS to have routine access to the National Airspace System. In 2020, the Systems Integration and Operationalization demonstration activity completed two demonstrations under the UAS NAS project.⁴⁵

Transformative Aeronautics Concepts Program

As part of the University Leadership Initiative, NASA selected five teams led by university faculty and students to examine a range of technical areas in support of the Agency's aeronautics research goals and strategic research thrusts. During the next four years, the project will provide a total of \$38.2 million to the selected five teams led by the following universities: North Carolina Agricultural & Technical State University, Oklahoma State University, Stanford University, the University of Delaware, and the University of South Carolina.⁴⁶

NASA researchers across the country worked together with aerogels to develop a conformal antenna under the Conformal Lightweight Antenna Structures for Aeronautical Communications Technologies activity within the Convergent Aeronautics Solutions project. The team successfully completed five flight tests with four antenna configurations in a variety of flight altitudes, and the research outcomes and lessons learned have been documented to support aeronautics as more companies introduce their UAS.⁴⁷

NASA's aeronautical innovators invited university students to propose new research ideas that could help them solve some of the biggest technical challenges facing 21st-century aviation. Under the University Student Research Challenge (USRC), selected student teams were eligible to receive a grant from NASA worth up to \$80,000, depending on the scope of the proposed project and the ability of the team to raise a small portion of that total through crowdfunding. Each USRC

45 <https://www.nasa.gov/centers/armstrong/features/UAS-NAS-Research-Begins-New-Era.html> and <https://www.nasa.gov/centers/armstrong/features/NASA-Partners-Work-with-FAA-to-Develop-UAS-Road-Map.html>

46 <https://www.nasa.gov/press-release/nasa-looks-to-university-teams-to-advance-aviation-technology/>

47 <https://www.nasa.gov/centers/armstrong/features/aerogel-antenna.html>

proposal was required to describe a novel approach to one of ARMD's six major research thrusts.⁴⁸

NASA received delivery of an HQ-90 quadcopter aircraft at NASA's Armstrong Flight Research Center (Armstrong) in California. The aircraft will perform flight tests in a variety of scenarios using the Expandable Variable Autonomy Architecture (EVAA) software for the Resilient Autonomy project. EVAA software prioritizes human safety over preventing damage to property, and preventing damage is prioritized over the completion of the mission by following a set of programmed rules of behavior. These rules of behavior allow EVAA to better manage the mission intent of the flight while always maneuvering within the acceptable performance limits of the aircraft.⁴⁹

In 2020, NASA's Convergent Aeronautics Solutions project, which is designed to give researchers with innovative ideas a chance to prove if their idea is feasible, selected three teams to participate. One of them, called Scalable Traffic Management for Emergency Response Operations, or STEReO, began work on the tools needed to aid emergency responders in natural disasters such as wildfires and hurricanes. Drones (UAS) have great potential to assist emergency responders by making their interventions even faster, more targeted, and better able to adapt to changing circumstances. These vehicles and the systems that support them could multitask in unique ways. STEReO envisions a new ecosystem for emergency response that has three broad goals: reduce response times, scale up the role of aircraft, and provide operations that can adapt to rapidly changing conditions during a disaster.⁵⁰

NASA Aeronautics at Home

With the COVID-19 pandemic forcing students of all ages to stay in their homes to attend virtual schools and find something to do between classes, NASA's aeronautical educators offered a number of options online for kids and parents

48 <https://www.nasa.gov/aeroresearch/deadline-nears-for-university-student-research-opportunity/>

49 <https://www.nasa.gov/centers/armstrong/features/HQ-90-Arrives-at-AFRC.html> and <https://www.nasa.gov/centers/armstrong/features/resilient-autonomy-project-develops-evaa-software.html>

50 <https://www.nasa.gov/ames/stereo>

alike to stay busy, have fun using aviation-themed backgrounds during video calls, and learn something more about NASA's work to improve aviation and make air travel safer.⁵¹

Also, for National Aviation Day on August 19, 2020, NASA ARMD celebrated all things aviation by recognizing pilots and aviators everywhere, including those NASA pilots flying in support of projects, including the X-59 QueSST and X-57 Maxwell. The public was invited to record a selfie video on what they love about flying and post it to Twitter or Instagram with the hashtags #PilotsPerspective and #NationalAviationDay. Certain videos were shared on ARMD's Twitter and Instagram accounts. Our social media also featured pilots who work at NASA, whether flying is involved in their job or not.⁵²

51 Examples include: <https://www.nasa.gov/aero-at-home>; <https://www.nasa.gov/aero/coloring-pages/>; <https://www.nasa.gov/aero/virtualbackgrounds>; <https://www.nasa.gov/aeroresearch/resources/k-12>; and https://www.nasa.gov/connect/ebooks/aeronautics_ebooks_archive_1.html

52 <https://www.nasa.gov/aeroresearch/honoring-those-with-the-right-stuff-on-national-aviation-day>

Space Technology Mission Directorate

The Space Technology Mission Directorate (STMD) develops transformative space technologies that enhance the capabilities and reduce the cost of NASA, commercial, and other Government missions. Technology drives exploration of the Moon, Mars, and beyond. Space Technology investments in revolutionary, American-made technologies provide solutions on Earth and in space. STMD engages and inspires entrepreneurs, researchers, and innovators across the country to advance American leadership in space. NASA technology appears in nearly every corner of modern life.

In fiscal year (FY) 2020, STMD made significant progress toward NASA's Artemis and deep space missions. In order to enable and enhance the Agency's capabilities, investments focused in four strategic areas: 1) rapid, safe, and efficient space transportation (Go); 2) expanded access to diverse surface destinations (Land); 3) sustainable living and working farther from Earth (Live); and 4) transformative missions and discoveries (Explore).

In FY 2020, NASA's investments in space technology advanced capabilities for exploration, and new technology demonstrations, challenges, and partnerships helped solve complex challenges needed to fulfill the Agency's exploration goals.

In FY 2020, STMD had more than 1,400 active project activities, with more than 500 different industry partners and 150 different academic partners. In addition, STMD has partnered with 28 other government agencies or departments as well as 10 international organizations. In FY 2020, STMD evaluated over 3,700 proposals and funded over 900 new technology selections, amounting to more than \$500 million in award investments.

Lunar Surface Innovation Initiative

The Lunar Surface Innovation Initiative (LSII) got under way in FY 2020, aiming to spur the creation of novel technologies needed for lunar surface exploration and accelerate the technology readiness of key systems and components. LSII activities are implemented through a combination of unique in-house events, competitive programs, and public-private partnerships.

- In February, STMD kicked off its Lunar Surface Innovation Consortium (LSIC) with the Johns Hopkins Applied Physics Laboratory, which will team experts from academia, industry, and government to shape the technologies and systems needed to explore the surface of the Moon in new ways. The Consortium makes recommendations for a cohesive, executable strategy for developing and deploying technologies required for successful lunar surface exploration. In its first six months, over 160 organizations across the country have participated in LSIC monthly meetings; over 50 percent of the participants have not previously worked with STMD.
- In July, NASA announced its new lunar surface technology research (LuSTR) opportunity, seeking U.S. universities' ideas to advance technologies needed for sustainable operations on the Moon. In its inaugural year, LuSTR seeks proposals relating to in situ resource utilization and sustainable power systems. The maximum funding per grant is \$2 million over two years with awards announced in February 2021.
- LSII funded a public prize competition seeking designs for miniaturized payloads for future Moon missions. The “Honey, I Shrunk the NASA Payload” challenge sought instrument designs that could help support a sustained human lunar presence, demonstrate, and advance the use of resources found on the Moon, and enable new science. This ideation challenge received 132 entries from 29 countries. In total, NASA awarded \$160,000 across 14 different entries and recognized an additional three entries with an honorable mention award.⁵³
- Engineers have tested various configurations of a Moon-digging robot called RASSOR—short for Regolith Advanced Surface Systems Operations Robot—in a large lunar simulant sandbox at NASA's Kennedy Space Center. In May, NASA announced the winners of its RASSOR Bucket Drum Design Challenge (funded by LSII and managed by the NASA Tournament Lab), which challenged the public to help design a new bucket drum, the portion of the robot that captures the regolith and keeps it from falling out. Judges from Kennedy's Swamp Works, who developed

53 <https://www.nasa.gov/mini-moon-payload-designs>

RASSOR and have expertise in in situ resource utilization, reviewed more than 350 entries submitted by individuals from around the world.

The Perseverance Rover

NASA's Mars 2020 mission launched on July 30 on a United Launch Alliance Atlas V rocket from Cape Canaveral Air Force Station in Florida. The Perseverance rover reached the Red Planet in February 2021, with the tasks of seeking out signs of past microscopic life, exploring the diverse geology of Jezero Crater, and demonstrating key technologies that will help us prepare for future robotic and human exploration. The mission includes two landing instruments and two technology demonstrations funded by STMD:

- The Mars Entry, Descent and Landing Instrumentation (MEDLI) 2 is a next-generation sensor suite for entry, descent, and landing. It collected temperature and pressure measurements on the heat shield and backshell during entry and descent as the spacecraft slowed from 12,500 miles per hour to just under two miles per hour in six minutes.
- The Terrain Relative Navigation (TRN) system identified the safest landing spot and sent coordinates to the guidance and navigation computer, where the trajectory was set and executed. Using TRN, the Perseverance rover was able to land with far less risk in the harsh terrain of Jezero Crater, which had been identified by scientists as having more opportunities for science and discovery than other less hazardous landing sites.
- The Mars Environmental Dynamics Analyzer makes weather measurements, including on wind speed and direction, temperature and humidity, and also measures the amount and size of dust particles in the Martian atmosphere.
- The Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) is demonstrating a new, critical capability: making oxygen directly from the Martian atmosphere. This means access to air for breathing, but more importantly, the vast quantities of it needed to burn the fuel for rocket propellant. MOXIE is the first demonstration of its kind—the first test

of an in situ resource utilization technology to generate mission products with local resources—on another world.

Public-Private Partnerships

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

- On October 14, STMD announced its selection of 14 American companies, including several small businesses, as partners to develop a range of technologies that will help forge a path to sustainable Artemis operations on the Moon by the end of the decade. U.S. industry submitted the proposals to the fifth competitive Tipping Point solicitation, and the selections have an expected combined award value of more than \$370 million. STMD will negotiate with the companies to issue milestone-based firm-fixed-price contracts lasting for up to five years.

Technology Demonstration Missions

The Laser Communications 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, with significantly less mass and power. While other NASA efforts have used optical communications, this will be NASA's first relay system using optical entirely, giving NASA the opportunity to test this method of communications and learn valuable lessons from its implementation. Relay satellites create communications links between science and exploration missions and Earth, enabling these missions to transmit data to scientists and mission managers back home. In July 2020, the LCRD payload was installed and integrated on the U.S. Space Force Space Test Program Satellite 6 (STPSat-6) in preparation for its December 2021 launch. In August, NASA completed installing the second of two

state-of-the-art optical ground stations in Haleakala, Hawaii, that will collect data transmitted to Earth by LCRD.

In FY 2020, NASA continued its partnerships with Maxar Technologies and Made In Space, Inc., as part of work related to On-Orbit Servicing, Assembly and Manufacturing (OSAM)—the second phase of public-private partnerships focused on the development of robotic technologies to rapidly, efficiently, and autonomously manufacture and assemble hardware, components, and tools in space. The demonstrations will mature technologies with cross-cutting applications for government and commercial missions, including human exploration of the Moon and Mars and in-space construction of large telescopes.

- In July 2019, the OSAM-2 mission was funded to deploy and position in orbit a small spacecraft in 2023 that will 3D print two beams. One beam will extend nearly 33 feet from the side of the spacecraft and deploy a solar array surrogate, and one will extend nearly 20 feet from the other side of the spacecraft.
- The OSAM-1 technology demonstration was contracted in January of this year and passed an important, internal NASA milestone providing Agency-level approval for the team to begin implementation. The OSAM-1 spacecraft and the Space Infrastructure Dexterous Robot payload will refuel a satellite in space, assemble a communications antenna, and manufacture a beam. By demonstrating these capabilities, the mission is advancing never-before-tested technologies for use in future NASA missions.

The Evolvable Cryogenics project was focused on developing, integrating, and validating cryogenic fluid management technologies for future NASA mission needs. In November 2019, the team successfully completed their acoustic test series to simulate launch loads at the Plum Brook Test Facility using the Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER). SHIIVER is a cryogenic tank for testing technologies and methods for maintaining very cold liquid propellants to be used as fuel for Artemis and deep space missions. Additional SHIIVER tests completed in January 2020 demonstrated how the system performed after exposure to acoustic launch loads and matured the high vacuum multilayer insulation and vapor cooling system for large scale cryogenic tanks.

The Space Nuclear Technology portfolio focuses on advancing nuclear fission technology and system capabilities to meet space exploration mission needs. STMD is currently engaged in advancing technologies for both nuclear propulsion and fission surface power systems with U.S. Department of Energy support to meet lunar and Mars exploration goals. Solicitations were expected to be released in early FY 2021.

The Deep Space Atomic Clock (DSAC) launched in June 2019 aboard the SpaceX Falcon Heavy as part of the U.S. Air Force's Space Test Program (STP)-2 mission. The mission was to fly and validate a miniaturized, ultra-precise, mercury-ion atomic clock that is orders of magnitude more stable than today's best spacecraft clocks. DSAC completed its primary mission and has been extended for a year. While the team is working to make the clock more stable, its success so far is an important step toward a paradigm change in space navigation: making deep space vehicles that do not rely on Earth as much for navigation cues.

The Green Propellant Infusion Mission (GPIM) spacecraft also launched as part of the Air Force STP-2 mission in June 2019. In a little over a year in space, GPIM successfully proved that this never-before-used propellant and propulsion system work as intended, demonstrating that both are practical options for future missions. While in orbit, GPIM tested a monopropellant, called the Advanced Spacecraft Energetic Non-Toxic (ASCENT), and propulsion system, including the thrusters, tanks, and valves, by conducting a planned series of orbital maneuvers. Attitude-control maneuvers, the process of maintaining stable control of a satellite, and orbit lowering demonstrated the propellant's pre-mission projected performance, showing a 50 percent increase in gas mileage for the spacecraft compared to hydrazine.

Small Spacecraft Technology Program

Over the course of FY 2020, the Small Spacecraft Technology (SST) program; Advanced Space of Boulder, Colorado; Tyvak Nano-Satellite Systems of Irvine, California; and Stellar Exploration, Inc., of San Luis Obispo, California, continued to make progress on CAPSTONE, a microwave oven-sized CubeSat that will serve as the first spacecraft to test a unique, elliptical lunar orbit. As a

precursor for Gateway, a Moon-orbiting outpost that is part of the Artemis program, CAPSTONE will help reduce risk for future spacecraft by validating innovative navigation technologies and verifying the dynamics of this halo-shaped orbit. CAPSTONE represents a rapid lunar flight demonstration and is scheduled to launch in June 2022.

The Pathfinder Technology Demonstrator (PTD) project will test the operation of a variety of novel CubeSat technologies in low-Earth orbit, providing significant enhancements to the performance of these small and effective spacecraft. Each of the planned five PTD missions consists of a 6-unit, or 6U, CubeSat weighing approximately 25 pounds and comparable in size to a shoebox. The PTD-1 mission, slated for launch in late 2020 aboard a SpaceX Falcon 9 rocket, will demonstrate a propulsion system with a water-based propellant developed by Tethers Unlimited, Inc., in Bothell, Washington. The PTD-1 hardware and payload were delivered to KSC in November in preparation for a December launch.

In March 2020, the SST program announced its selection of nine university teams for its SmallSat Technology Partnerships initiative to mature new systems and capabilities to help pave the way for human and robotic lunar exploration. The technology development projects focus on three technical areas related to needs of Moon-bound missions: use of small spacecraft to help provide lunar communications and navigation services; small spacecraft propulsion for lunar missions and potential return of lunar samples using small spacecraft; and small spacecraft electrical power and thermal management systems tailored for the distant and harsh environment between Earth and the Moon.

Originally funded in April 2020 to mature CubeSat payloads through use of suborbital flight opportunities, the Payload Accelerator for CubeSat Endeavors (PACE) has payloads manifested on both suborbital and orbital flights in late 2020 and mid-2021 calendar year, respectively. Two PACE payloads, referred to as PACE-1, were scheduled for a high-altitude balloon flight in December 2020: the Advanced Developments Projects (ADP) avionics suite consisting of radio frequency communications, navigation, and attitude determination and control systems; and the Intrepid payload, a gamma-ray/neutron particle detector. PACE-1 was targeted for a June 2021 orbital flight. Both payloads were developed at NASA's Ames Research Center.

Initiated in December 2019, the V-R3x mission is a low-power, low-cost swarm of three IU spacecraft that will demonstrate autonomous networking and radio navigation processes that are key to reducing heavy reliance on ground-based infrastructure and increasing the autonomy of large swarms of spacecraft. Both sets of engineering and flight models were built over the course of 2020, and the mission was scheduled for an orbital launch in December 2020. V-R3x was also scheduled for a follow-on high-altitude balloon flight in February 2021 to demonstrate extensible swarm communication and navigation capabilities at >100,000 ft link distances with up to five nodes. The V-R3x mission is managed within the PACE project and is a collaboration with Stanford University.

Game Changing Development

SPLICE

The Safe & Precise Landing-Integrated Capabilities Evolution (SPLICE) project is a suite of precise landing and hazard-avoidance technologies. A combination of laser sensors, a camera, a high-speed computer, and sophisticated algorithms will give spacecraft the artificial eyes and analytical capability to find a designated landing area, identify potential hazards, and adjust course to the safest touchdown site. SPLICE will eventually make it possible for spacecraft to avoid boulders, craters, and more within landing areas half the size of a football field already targeted as relatively safe. Three of SPLICE's four main subsystems will have their first integrated test flight on a Blue Origin New Shepard rocket during an upcoming mission. As the rocket's booster returns to the ground, after reaching the boundary between Earth's atmosphere and space, SPLICE's terrain-relative navigation, navigation Doppler lidar, and descent and landing computer will run aboard the booster. Each will operate in the same way they will when approaching the surface of the Moon. The fourth major SPLICE component, a hazard detection lidar, will be tested in the future via ground and flight tests.

TALOS

The Thruster for the Advancement of Low-temperature Operation in Space (TALOS) project is developing small thrusters to reduce overall spacecraft mass

and power, which will reduce mission costs. The thrusters can make alterations in a spacecraft's flight path or altitude and can be used to enter orbit and descend to the surface of another world. They can also serve as main propulsion thrusters for landers. Through FY 2020, NASA and Frontier Aerospace performed roughly 60 hot fire tests on two main propulsion thrusters. The tests took place in a vacuum chamber that simulates the environment of space at Moog-ISP in Niagara Falls, New York. Engineers collected multiple data streams, including the combustion chamber's pressure and stability and the feed system's pressure and temperature, which delivers propellant from tanks to the thruster. The TALOS project performed engine qualification testing in 2020 and continued in early 2021 to ready the thruster design for use on Astrobotic's Peregrine lunar lander. Astrobotic is one of several American companies working with NASA to deliver science and technology to the lunar surface through the CLPS initiative, as part of the Artemis program.

Astrobee

The Astrobee project is a free-flying robotic system aboard the International Space Station that will help astronauts reduce time they spend on routine duties, leaving them to focus more on the things that only humans can do. Working autonomously or via remote control by astronauts, flight controllers, or researchers on the ground, the robots are designed to complete tasks such as taking inventory, documenting experiments conducted by astronauts with their built-in cameras, or working together to move cargo throughout the Station. Robots like Astrobee will play a significant part in the Agency's mission to return to the Moon under the Artemis program and other deep space missions by increasing astronaut productivity and helping maintain spacecraft when astronauts are not aboard. All three robots, Bumble, Honey, and Queen, were launched to the Space Station between 2018 and 2019. In June 2020, astronaut Chris Cassidy performed a series of tests on Honey to prepare for full commissioning, like its robotic teammate, Bumble. Soon, both will be ready to carry out tasks alongside astronauts on the Space Station.

PRIME-1

The Polar Resources Ice Mining Experiment-1 (PRIME-1) consists of a lunar drill called The Regolith and Ice Drill for Exploring New Terrain (TRIDENT), which can core out a hole roughly three feet deep on the lunar surface. The second part of the PRIME-1 technology suite is the modified mass spectrometer, called MSolo. Mass spectrometers are used to measure the composition or concentration of various elements in the atmosphere. In July 2020, NASA put out an RFP asking CLPS partners to submit bids to fly PRIME-1 to the Moon by December 2022 to help NASA search for ice at the Moon's South Pole.

A-PUFFER

The Autonomous Pop-Up Flat-Folding Explorer Robot (A-PUFFER) project was designed to scout regions on the Moon and gain intelligence about locations like hard-to-reach craters and narrow caves that may be difficult for astronauts to investigate on foot. In addition to larger wheels, each robot has an upgraded onboard computer with a wireless radio for communication and a stereo camera for sensing the environment in front of it. In February 2020, engineers began testing the upgraded A-PUFFER robots and their new capabilities. During the February testing, a team of three A-PUFFERs successfully trekked the sandy and rocky terrain of JPL's Mars Yard while simultaneously mapping the environment using sensors. Their maps were shared with a base station and merged into an integrated map of the Mars Yard. Together, this system demonstrates a capability that could robustly map parts of the Moon that have not been mapped before.

RAMPT

The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project is advancing development of an additive manufacturing technique to 3D print rocket engine parts using metal powder and lasers. The method, called blown powder directed energy deposition, could bring down costs and lead times for producing large, complex engine components like nozzles and combustion chambers. Prior developments in additive manufacturing did not have the large-scale capabilities this emerging technology provides. During the summer of 2020, the RAMPT team used the technique to produce one of the largest nozzles NASA has printed,

measuring 40 inches in diameter and standing 38 inches tall, with fully integrated cooling channels. This nozzle was fabricated in record time—just 30 days compared with nearly one year using traditional welding methods—and completion occurred a year earlier than scheduled due to the technology advancing rapidly.

BMGG

The Bulk Metallic Glass Gears (BMGG) project is developing special gears that can withstand the extreme temperatures experienced during missions to the Moon and beyond. The BMGG project team is creating material made of “metallic glass” for gearboxes that can function in and survive extreme cold environments without heating, which requires energy. Operations in cold and dim or dark environments are currently limited due to the amount of available power on a rover or lander. The BMGG unheated gearboxes will reduce the overall power needed for a rover or lander’s operations, such as pointing antennas and cameras, moving robotic arms, handling and analyzing samples, and moving (for a rover). The power saved with the BMGG gearbox could extend a mission or allow for more instruments. In FY 2020, the team tested the gears at NASA’s Jet Propulsion Laboratory (JPL), demonstrating that the gears can withstand impact and freezing temperatures. At JPL’s Environmental Test Laboratory, engineers mounted the motor and gearbox on a tunable beam designed to measure the response an item has to a shock, or forceful impact. The test simulated how the bulk metallic glass gears might behave when collecting a regolith sample during the lunar night—which spans roughly 14 days on Earth—or deploying a science instrument on an ocean world in our solar system.

MISSE-15

In June, STMD managed the selection of seven technology experiments, which will be tested on the ISS as part of the Materials International Space Station Experiment (MISSE)-15 mission. The experiments will be mounted on the exterior of the ISS to test the performance and durability of materials and devices—from polymers, energy-absorbing materials, radiation protection, and geopolymer lunar simulant to solar cell technologies—while exposed to the LEO space environment. Results of the on-orbit testing could enable Artemis missions through the study of

thermal and radiation shielding coatings and fabrics, lightweight materials for solar arrays and deployable structures, and more. The next call for MISSE experiments was planned for December 2020.

Flight Opportunities

In FY 2020, the Flight Opportunities program facilitated 44 tests of technology development payloads via flights with commercial suborbital providers, including three flights on rocket-powered vehicles, three high-altitude balloon flights, and eight flights on parabolic aircraft. U.S. commercial vendors providing flight services in the fiscal year included Black Sky Aerospace, Blue Origin, Masten Space Systems, Raven Aerostar, UP Aerospace, World View, and Zero Gravity Corporation.

- The 2020 Tech Flights solicitation sought promising space technology payloads for testing on commercial suborbital vehicles. This year's solicitation included new elements that allow researchers to participate in their technology testing aboard suborbital spacecraft and to add educational opportunities to their primary payload. Selections were scheduled to be announced in October 2020.
- Through Flight Opportunities, suborbital flights on commercial vehicles continue to provide valuable testing resources for NASA and industry. The program's technology team continues to identify and cultivate key innovations that could be essential for missions to the Moon and Mars. Several technologies selected for use on lunar landers developed under NASA's CLPS initiative have leveraged suborbital flights for testing. In addition, four of the companies providing landers for CLPS and three companies involved with development of human landing systems for the Artemis program have also leveraged suborbital flights for testing of their own innovations.
- In November 2019, UP Aerospace launched its SpaceLoft rocket on a flight funded by the company's NASA Tipping Point award, which was supported by Flight Opportunities. Several Flight Opportunities-supported payloads were also aboard, including the Affordable Vehicle

Avionics project from NASA's Ames Research Center and an autonomous flight termination system from NASA Kennedy.

- The Southwest Research Institute successfully demonstrated its miniature solar observatory—the Solar Instrument Pointing Platform—on a high-altitude balloon from World View in November 2019.
- Zero Gravity Corporation conducted eight flights in November 2019 enabling tests for a total of ten Flight Opportunities—supported technologies, all of which were tested on multiple flights.
- A variety of technologies were tested aboard Blue Origin's New Shepard rocket system in December 2019, including an experiment from the University of Florida to explore what happens to the genes of organisms as they travel from Earth to space and the Orbital Syngas Commodity Augmentation Reactor, a system from an Early Career Initiative team at NASA Kennedy, designed to convert space waste into valuable gases to address logistics challenges associated with long-duration space exploration.
- In July 2020, aroiseismometers from Sandia National Laboratory and JPL, designed for potential future infrasound investigations on Venus as well as other planetary bodies, were flight tested on balloons from Raven Aerostar.
- In September 2020, Psionic tested its navigation doppler lidar technology aboard Masten Space System's vertical takeoff/vertical landing system called Xodiac. Psionic licensed this technology from NASA in 2016 and continues to collaborate with NASA's Langley Research Center to advance the technology for both space and terrestrial applications.
- Also in September, the Aerospace Corporation tested a technology for rapid calibration of space solar cells aboard a high-altitude balloon from Blacksky Aerospace, the second flight in a series of iterative suborbital tests.

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

NASA's SBIR/STTR programs invested more than \$211 million in small businesses in FY 2020. Specifically, 351 SBIR and 58 STTR Phase I proposals were

awarded to 312 U.S. small businesses to establish the scientific, technical, and commercial feasibility of each proposed innovation. This investment totaled more than \$51 million.

- In addition, the program made 140 SBIR and 21 STTR Phase II awards, valued at over \$120 million, to further expand upon prior Phase I work.
- The program ran a pilot for Phase II Sequential Awards to Advance Moon to Mars Objectives. Phase II Sequential awards are an opportunity for firms who have developed promising technology during their first Phase II contract to win a second Phase II award to continue the work. On July 8, NASA announced four small businesses were selected to receive contracts totaling \$17 million. On September 3, NASA selected an additional three small businesses to receive contracts totaling \$12 million. The selected businesses will mature various lunar-focused technologies related to in situ resource utilization, laser communications, and other high-impact technologies for use on the Moon.
- Through the Phase II Extended/Expanded program, 37 proposals were selected to have their Phase II-E option exercised for \$9.6 million in SBIR/STTR funding, which was matched from, and in some cases exceeded by, investors outside the program (other NASA programs, other government agencies, and commercial investors, among others).
- The Civilian Commercialization Readiness Pilot Program, an additional funding opportunity designed to accelerate the transition of SBIR- and STTR-funded technologies to commercialization, resulted in seven selections for a total of \$4.2 million in SBIR/STTR investment matched by an equal amount from outside investors.
- Additionally, 78 Phase III awards were made, leveraging over \$35 million in non-SBIR/STTR funding.

The program took a number of proactive steps to address the needs of the small business research and development community during the coronavirus pandemic.

- Provided provisional acceptance of deliverables to pay for work performed on existing contracts while NASA Centers are operating remotely.
- For Phase I, reduced time between selection and first payment from five months to two months.

- Extended the 2020 Solicitation Phase I due date this spring by one month—from March 20 to April 20—to give firms more time to prepare their proposals. With this delay, we saw a 14 percent increase in proposals this year and streamlined internal processes so as not to delay funding by the full month.
- The 2021 solicitation has been accelerated to make another funding opportunity available sooner. It will open November 9 as opposed to the typical January release.

A current focus of the SBIR/STTR program is working with small businesses on their research and development to contribute to NASA's lunar and Mars exploration goals. In FY 2020, NASA announced a number of partnerships with SBIR/STTR award recipients whose technologies have been selected for a lunar mission or could have direct applications. A few examples include the following:

- In June, Astrobotic, a small business based in Philadelphia, was selected to deliver NASA's Volatiles Investigating Polar Exploration Rover, otherwise known as VIPER, to the South Pole of the Moon by late 2023. The lunar landers were developed by Astrobotic in part with SBIR/STTR awards.
- Another SBIR/STTR company, Honeybee Robotics, based in Altadena, California, is one of the providers of the instruments that will fly on VIPER.
- An additional SBIR/STTR company was selected under CLPS to provide delivery services to the lunar surface to support the use of the Moon as a proving ground for systems and technologies that will enable humans to explore Mars. Masten Space Systems' \$75.9 million award includes end-to-end services for delivery of the instruments, including payload integration, launch from Earth, landing on the Moon's surface, and operation for at least 12 days.

Space Technology Research Grants (STRG)

Since its inception in FY 2011, STRG has funded exciting space technology research via 773 grants at 118 universities across 45 states and one U.S. territory. In FY 2020, NASA made 14 Early Stage Innovations awards, nine Early Career

Faculty awards, and 63 NASA Space Technology Research Fellowship awards; there are currently more than 300 active awards, including four Space Technology Research Institutes.

NASA Innovative Advanced Concepts (NIAC)

In FY 2020, NIAC awarded 16 Phase I awards, six Phase II awards, and one Phase III award across industry, academia, and NASA Centers, while completing twelve 2019 Phase I studies and nine 2018 Phase II studies with three approved no-cost extensions.

NIAC announced its FY 2020 Phase I, II, and III award selections in April. The program funded 16 new concepts and seven studies that had previously received at least one NIAC grant with a combined award value of \$7 million to determine the feasibility of early stage technologies that could go on to change what is possible here on Earth and in the far reaches of space. Fellows' studies include mapping asteroids and other small bodies in the solar system with hopping probes, making on-demand pharmaceuticals in space, and extracting water on the Moon. Several of the concepts could inform capabilities relevant to the Artemis program.

JPL, under a grant from NIAC, facilitated a citizen science, public competition to seek ideas for a mechanical obstacle avoidance sensor that could be incorporated into a possible future Venus rover. On July 6, the winners of the "Exploring Hell: Avoiding Obstacles on a Clockwork Rover" were announced, featuring three novel designs and a number of honorable mentions. In all, 572 entries from a mix of teams and individuals were submitted from 82 countries, with ideas that ranged from systems of rollers to detect hazards to oversized fenders that would snap the rover backward should it hit a boulder.

World Book, Inc., developed a book series called *Out of This World*, featuring stories about the lives and scientific work of NIAC researchers. In 2020, World Book began offering virtual access to all eight e-books free of charge as part of the "NASA@Home" activities and to support educators, parents, and students during the novel coronavirus pandemic.

In June, the NIAC 2021 Phase I solicitation was released, seeking proposals for early stage feasibility studies of visionary concepts that address national

government and commercial aerospace goals. Concepts are solicited from any field of study that offer a radically different approach or disruptive innovation that may significantly enhance or enable new human or robotic science and exploration missions. The 2021 Phase II and Phase III calls for proposals were planned for release in December 2020.

On September 22–24, NIAC held its first virtual symposium on Livestream. Fellows introduced their multidisciplinary research to a broad global audience with concepts covering a wide range of innovations in a diverse range of sciences. Exciting keynote presentations were given from experts in aeronautics and advanced technologies, and further information was discussed regarding the latest news about NIAC's exciting progress and plans.

Prizes and Challenges

The Prizes and Challenges portfolio supports the use of public competitions and crowdsourcing as tools to advance NASA R&D and serve other mission needs. It includes Centennial Challenges, which stimulate research and technology solutions to support NASA missions and inspire new national aerospace capabilities through public prize competitions. It also includes the NASA Tournament Lab (NTL), which enables employees at NASA and other U.S. Federal agencies to use crowdsourcing approaches to procure novel ideas or solutions to serve R&D and others efforts in support of the NASA mission.

In FY 2020, NASA opened 35 crowdsourcing and challenge projects using NTL capabilities, including several challenges supporting Artemis-related exploration activities. Some of these competitions derived from a competitive internal solicitation for ideas to further NASA goals. NTL also launched 25 projects using an internal crowdsourcing platform, NASA@WORK. In April, the Prizes and Challenges team coordinated an Agencywide call for ideas on the platform to help the Nation with the unprecedented challenge of COVID-19. This call fostered cross-Center collaboration and tapped into the skill, energy, and power in NASA's workforce.

- NASA innovators put forward concepts for sensors that can improve the detection of the COVID-19 virus in the environment or a viral infection

in a person. NASA is working with the National Institutes of Health and other external partners to develop at least one of these concepts.

- Many submissions involved the use of 3D printing capabilities at various NASA Centers. These ideas helped inform the Agency COVID-19 response team's outlined approach to Center-specific efforts, including the formation of Center-level NASA COVID-19 3D Printing Response teams.
- Ames is funding early work on a few monitoring and prediction projects relevant to COVID-19 that also have other applications.
- Additional ideas from the NASA@WORK challenge were also pursued through the International Space Apps COVID-19 Challenge hackathon May 30–31, which encouraged people around the world to leverage NASA and other space agencies' Earth science data to improve monitoring and prediction of the virus spread and impacts.

In FY 2020, NASA continued facilitating several ongoing Centennial Challenges and launched one new challenge:

- The Watts on the Moon Challenge, phase 1, opened on September 25, 2020. This challenge complements ongoing NASA lunar power generation technology projects by focusing on technologies to distribute, manage, and store energy generated by different sources. The public competition will award up to \$500,000 for the first phase, in which participants will design a flexible and robust system capable of addressing one or more of three hypothetical mission activities similar to a real lunar mission. If the first phase yields promising concepts, then a second, system development and demonstration phase will be open with up to \$4.5 million in available cash prizes.
- The purpose of the \$1 million CO₂ Conversion Challenge is to convert carbon dioxide into sugars, such as glucose, as a step to creating mission-critical resources. Such technologies will enable the manufacture of products using local, indigenous resources on Mars and Earth by using waste and atmospheric carbon dioxide as a resource. Phase 2 of the competition launched in September 2019 and seeks to award up to \$750,000 to the top three teams that demonstrate operational systems. Due to COVID-19,

the submission deadline for Phase 2 was extended to December 2020 and winners were expected to be announced in April 2021.

- The Vascular Tissue Challenge is a \$500,000 competition to create thick, vascularized human organ tissue in an in vitro environment to advance research and benefit medicine on long-duration missions and on Earth. This challenge is ongoing, with teams working to develop functional tissues for a liver, pancreas, heart, muscle, kidney, and/or lungs. Due to COVID-19, the deadline was extended for teams to attempt to complete development of the tissue and prove that they can keep the tissue viable and functional for 30 days. Awards were expected to be made to the first three teams to achieve the goals by March 2021.
- The Qualification Round of Phase 2 of the \$1 million virtual Space Robotics Challenge closed in September 2020. The competition focuses on advancing robotics software and autonomous capabilities for space exploration missions on the surface of distant planets or moons. Phase 2 Qualification Round winners were scheduled to be announced in January 2021. The Competition Round was to run January–July 2021, with awards made in early FY 2022.

Early Career Initiative

Our Early Career Initiative (ECI) provides the best and brightest of NASA's early career technologists with hands-on technology development opportunities. The initiative aims to invigorate NASA's technological base and best practices by partnering early career NASA leaders with external innovators. Started as a pilot effort in 2014, the ECI is now a formalized and a growing effort, one that has become a wellspring of innovation to help shape our future missions to the Moon and Mars.

The opportunity is publicized through chief technologists at NASA Centers via an annual call for proposals in March. Once applications are submitted, an evaluation team scores the proposals, and selections are usually announced in August. In FY 2020, seven projects were chosen:

- Development of a Thermal Control System to Survive the Lunar Night

- Extractor for Chemical Analysis of Lipid Biomarkers in Regolith
- In-space Assembly of Perovskite Solar Cells for Very Large Arrays
- Joint Augmented Reality Visual Informatics System, an Exploration Extravehicular Mobility Unit
- Mobile Frequency-Modulated Continuous-Wave Light Detection and Radar System for Lunar Surface Terrain-Mapping and Navigation
- Modular and Reconfigurable Manipulation System for Autonomous In-space Assembly
- Molten Regolith Electrolysis starter device

STEM Engagement

In FY 2020, STMD invested in and supported a variety of Science, Technology, Engineering, and Mathematics (STEM) Engagement activities, products, and opportunities to connect the academic community with NASA space technology. Based on the NASA Strategy for STEM Engagement (2020–2023), STMD focused on efforts to create unique opportunities for students to contribute to mission-driven work and to engage diverse groups of students in STEM.

- In February 2020, the Breakthrough, Innovative and Game-changing (BIG) Idea Challenge, in partnership with the Space Grant project, announced nearly \$1 million in awards to eight university teams to build sample lunar payloads and demonstrate new ways to study the Moon's polar regions. STMD worked with the Office of STEM Engagement (OSTEM) to continue our cost-sharing partnership with Space Grant for the BIG Idea Challenge 2021, announced in July 2020. This challenge offers awards, ranging from \$50,000 to \$180,000, to university teams to propose solutions for lunar dust mitigation technologies. In 2020, BIG Idea Challenge worked with OSTEM to stand up NASA's Artemis Student Challenges, a community of activities focused on the Artemis generation. BIG Idea Challenge is sponsored by the Game Changing Development Program and managed by the National Institute of Aerospace.
- Additionally, STMD committed nearly \$400,000 to four universities through the Artemis Student Challenges Opportunity competitive

solicitation: University of Illinois, Urbana-Champaign; University of Colorado, Boulder; University of Hawaii, Honolulu; and University of Washington, Seattle. Announced in May 2020, selected projects will introduce students to topics and technologies critical to the success of the Artemis program.

- In partnership with NASA's Minority University Research and Education Project (MUREP), the MUREP Space Technology Artemis Research (M-STAR) activity was established to strengthen and develop the research capacity and infrastructure of U.S. Minority Serving Institutions and Historically Black Colleges and Universities in areas of strategic importance and value to STMD's missions and technology focus areas. In August 2020, M-STAR awarded nearly \$604,000 in cooperative agreements to 15 universities for 16 projects that will support the advancement of technologies needed for the Agency's Artemis program.
- As part of NASA's celebration of the 50th anniversary of Earth Day, STMD collaborated with the National Park Service to issue its new Junior Ranger Space Tech Explorer activity sheets, focused on space technology and its connection to life on Earth. The activities were included in NASA@Home and STEM@Home initiatives and were released in Spanish in honor of Hispanic Heritage Month.

Technology Transfer

The Technology Transfer program worked with engineers and scientists to develop and improve existing technology and get it into the hands of businesses and the public for the widest possible impact in response to the coronavirus global pandemic:

- JPL developed the Ventilator Intervention Technology Accessible Locally, or VITAL, prototype, designed to avoid using any of the same parts as traditional ventilators. By fall, the design had been licensed by dozens of companies, and one in Brazil was already manufacturing them. At NASA's Johnson Space Center, engineers modified a design for an Orion ventilator to create one that uses human power and that can be

3D printed. It can be used to keep a patient alive for hours and is aimed particularly to help in developing countries where access to electronic ventilators can be limited.

- NASA's Glenn Research Center continued a collaboration with a local Ohio company on its portable fogger, which can sterilize surfaces. With expert consultation from JPL and Glenn, the company updated their design to better address airborne contaminants. NASA Glenn also worked with Cleveland's university hospitals to develop new methods and technologies for decontaminating personal protective equipment.
- For some COVID-19 patients who do need supplemental oxygen but not ventilators, an oxygen hood can be beneficial. A task force, led by NASA Armstrong and including several outside partners, was charged with developing a low-cost, easily made, and more robust helmet, without impacting the supply chain.

This year dozens of licenses were signed for the VITAL ventilator, but beyond that, the Technology Transfer program far exceeded its goals for licensing and software usage agreements. In fact, this year was the highest single year total of licenses in the program's history. In FY 2020, the program signed 171 new licenses and 4,616 new Software Usage Agreements.

Also in FY 2020, the Technology Transfer program took over the Regional Economic Development program, centralized it, and refocused it to better engage with entrepreneurial communities across the United States, with the aim of fostering startup ecosystems, assisting companies with product development, and connecting well-positioned entrepreneurs with NASA technologies. Technology Transfer teamed up with FedTech this summer for an eight-week training with entrepreneurs on commercializing NASA technology. The winning entrepreneurial team created a new company and is now seeking a license for a NASA alloy to build better tires.

As part of virtual in-reach to encourage NASA innovators to disclose their inventions, the Technology Transfer program launched a new Inventor's Hall of Fame web page, featuring more than 30 of NASA's most prolific and most impactful inventors, with new inductees to be added every year.

iTech

Through iTech, STMD discovers and quickly assesses technologies that could help NASA accomplish future missions. This initiative connects innovators with experts who provide valuable technical feedback and with investors who could provide resources to help propel the technologies forward. In FY 2020, iTech hosted two cycles of competition: Cycle I focused on artificial intelligence and machine learning, biotechnology, system autonomy, advanced manufacturing, and x-factor innovations; Cycle II focused on power generation/energy, integrated photonics, advanced engineering materials, miniaturized systems, and x-factor innovations. The program hosted numerous virtual “Ignite the Night” events throughout the year, leading up to its two virtual forums in October 2020.

DEPARTMENT OF DEFENSE

DOD

Aeronautics

Rotorcraft

Army

During FY 2020, Army Aviation supported multiple deployments in U.S. Central Command, U.S. European Command, and U.S. Indo-Pacific Command. While supporting these deployments, aviation formations conducted home station training for their assigned Divisions and Brigade Combat Teams focused on large-scale combat operations to support humanitarian assistance and disaster relief efforts and prepared for other contingencies.

In FY 2020, the Army continued its modernization efforts across the entire aviation fleet. Rotary-wing aircraft fielding of the AH-64E Apache, HH/UH-60M Black Hawk, CH-47F Chinook, UH-60V Black Hawk, and UH-72A/B Lakota ensure that Army aircraft provide capability for decades to come. Unmanned Aircraft Systems (UAS) modernization includes improvements to the MQ-1C Gray Eagle and the RQ-7B Shadow, supporting enhanced manned-unmanned teaming. As the Army modernizes its current fleet of rotary-wing aircraft and UAS, it looks to the future with Future Vertical Lift (FVL) initiatives. The FVL Cross-Functional Team works closely with industry and is already integrating new technologies into the current force.

Program Executive Office (PEO) Aviation's Apache Helicopter Program Manager accepted the 300th AH-64E aircraft from the Boeing Company, and it will be assigned to the 82nd Combat Aviation Brigade, Fort Bragg, North Carolina.



Fielding throughout U.S. Army Forces Command (FORSCOM) will continue in FY 2021 and beyond. In support of the continued fielding of the helicopter, a contract modification was awarded to Boeing fully funding Lot 9, which includes 48 AH-64E remanufactured aircraft and 12 AH-64E new build aircraft. The Army Threat Systems Management Office conducted the AH-64E Version 6 Cyber Assessment, marking the conclusion of Follow-On Test and Evaluation II. AH-64E Version 6 delivers quality and capability improvements, designed and equipped with an open systems architecture including the latest communications, navigation, sensor, and weapon systems. The E-model has multiple upgrades from its predecessors, such as the improved Modernized Target Acquisition Designation Sight/Pilot Night Vision System, which includes a new integrated infrared laser that allows for easier target designation and enhanced infrared imagery capabilities. The AH-64E Version 6 also provides Manned/Un-Manned Teaming Extended, which allows video from 62 offboard sensors to be seen by the flight crew and allows for control of the MQ-1C Gray Eagle and RQ-7B Shadow UAS.

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

The CH-47F Chinook is the Army's only heavy-lift cargo helicopter supporting combat and other critical operations. The Army completed the final fielding of CH-47F Block I aircraft to United States Army Forces Command units and United States Army South units in FY 2020. Development of the CH-47F Block II aircraft continues to provide an option for future modernization of the cargo fleet when that decision is required.

PEO Aviation's Aviation Mission Systems and Architecture Project Office and the Aviation Ground Support Equipment Product Office successfully completed

Aircraft Notebook (ACN) training and fielding to the U.S. Army Rotary Wing fleet. ACN replaced the Unit Level Logistics System–Aviation (Enhanced) system and began integrating within Global Combat Support System–Army Increment 2 in mid-2020. ACN provides a common logistics information system for Army Aviation, streamlines user experience, improves record keeping, and provides the ability to view aircraft availability in near-real time across the fleet. To date, more than 26,500 soldiers and civilians have been trained to use ACN and more than 9,000 pieces of computer equipment converted.

Future Vertical Lift

The Future Vertical Lift (FVL) Cross-Functional Team (CFT) is an Army-led, multi-service initiative, focused on enhancing vertical lift dominance through affordable next-generation assets that provide increased reach, protection, lethality, agility, and mission flexibility. This initiative focuses on addressing aviation capability gaps against peer and near-peer competitors. The following four lines of effort address these gaps: Future Attack Reconnaissance Aircraft (FARA), Future Long Range Assault Aircraft (FLRAA), Future Tactical Unmanned Aerial Systems (FTUAS), and Air Launched Effects (ALE) and the Modular Open System Architecture (MOSA). This year, four FTUAS industry partners are participating in “Buy, Try, Inform” demonstrations within active component Brigade Combat Teams to inform user requirements. The first of these demonstrations at the 1st Infantry Division was completed in October 2020, and the remaining four demonstrations continued through early 2021.

Project Convergence (PC) is the Army Futures Command’s annual capstone exercise designed to aggressively advance and integrate the Army’s contributions to the Joint All Domain Operations concept. This Joint demonstration and experimentation effort ensures that the Army can rapidly and continuously integrate and converge effects across all domains—air, land, sea, space, and cyberspace—to overmatch our adversaries in competition and in conflict. Over the course of the seven-week PC 20 demonstration in August and September, the FVL CFT conducted onsite experimentation, integration, and collaboration at Yuma Proving Ground, totaling more than 400 flight hours and 107 sorties and achieving 127 technical objectives. The synchronization of a surrogate FARA platform, three

Gray Eagles, and six ALEs during multiple peer-on-peer vignettes substantiated the Army's ability to extend an air-ground mesh network across 60 kilometers and deliver Long Range Precision Fires in support of Joint Force reconnaissance, surveillance, target acquisition, and radar defense penetration objectives. These demonstrations created cross-domain synergies with space, air, and ground assets and proved the ability of the FARA ecosystem to be decisive in the lower tier of the air domain. The FVL CFT captured valuable lessons and observations that they will incorporate into future ecosystem requirements. Initial planning tasks are already under way for PC 21, set to occur in October 2021.

In March 2020 PEO Aviation announced the downselect from four to two vendors in both the FARA CP and FLRAA programs. These remaining industry partners will participate in Competitive Development and Risk Reduction activities as they build aircraft prototypes for initial flight testing scheduled for FY 2023. The Vice Chief of Staff of the Army approved the FLRAA Abbreviated-Capability Development Document (A-CDD) in October 2020, and PEO Aviation expects to release a draft Request for Proposal (RFP) to industry in December 2020. The FARA CP A-CDD went to the Army Requirements Oversight Council (AROC) for consideration in January 2021. Both FARA and FLRAA are scheduled for a First Unit Equipped (FUE) in 2028.

Navy

The U.S. Navy (USN) CH-53K Super Stallion program provides nearly three times the external lift capacity of the CH-53E, a mission radius of up to 200 nautical miles, and the lift and range to support the future Marine Air Ground Task Force. Flight test operations continued throughout 2020 at Naval Air Station Patuxent River.

The VH-92 Presidential Helicopter Replacement program continued production with the award of LRIP Lot 2 for six operational aircraft in March 2020.

The V-22 Osprey has been in production for several years, with more than 400 aircraft delivered to the U.S. Marine Corps (USMC), Air Force, United States Special Operations Command, the USN, and the Government of Japan. This tiltrotor aircraft provides unique capabilities to the warfighter, combining the flexibility of a helicopter with the speed and range of a fixed-wing aircraft. In

addition to the wide range of missions that the aircraft can currently support, new capabilities continue to be developed. Upgrades that enable the aircraft to meet the USN carrier onboard delivery requirements are complete with the associated Development Test commencing in the second quarter and the Operational Test planned for 2021.

The Navy has delivered over 555 domestic MH-60 helicopters and transitioned all Helicopter Sea Combat and Helicopter Maritime Strike squadrons to the MH-60R/S. Due to high operational demand and evolving warfighter needs, the program has initiated a Service Life Assessment intended to evaluate requirements for a Service Life Extension. These efforts will improve mission systems/sensors, recapitalize current MH-60 investments to pace the threat, and extend the life of MH-60 until the Navy migrates to the Future Vertical Lift-Maritime Strike platform.

Fixed Wing

Navy

The P-3C to the P-8A active-duty squadron fleet transition was completed this year. Ninety-nine of 119 P-8A aircraft have been delivered to the U.S. Navy and 12 aircraft were delivered to the Royal Australian Air Force under a cooperative agreement. The FMS United Kingdom program has taken delivery of two of nine P-8A aircraft.

The E-2D Advanced Hawkeye (AHE) Program has delivered 45 aircraft to date. The United States Navy awarded a Multi-Year Procurement Contract in April 2019 to build 24 E-2D AHE aircraft. A modification to that contract was made in September 2019 to add the procurement of nine Japan Foreign Military Sales E-2D AHE aircraft. A July 2019 Program of Record (POR) Requirements Review Board validated the requirement to procure a total of 86 E-2D AHE aircraft, up from the prior 75 aircraft POR. Upgrades to the platform continue as the Navy plans to release Delta System/Software Configuration build 3 in the third quarter of FY 2020, allowing the E-2D AHE to outpace the evolving threat.

The F/A-18 & EA-18G Program consistently maintained and exceeded the Secretary of Defense's mandate of 80 percent Mission Capability for E/F/G

throughout FY 2020. Artifacts and lessons learned were provided to the Naval Aviation Enterprise for institutionalization across multiple platforms and organizations. Full funding was provided to Boeing for year two of the FY 2019–awarded multi-year contract, obligating \$1.23 billion of APN-1 for Lot 44.

Unmanned Aircraft System

Army

The MQ-1C Gray Eagle Extended Range Unmanned Aircraft System (UAS) successfully completed a follow-on operational test and evaluation, the third major MQ-1C operational test. The test results indicated the MQ-1C Gray Eagle Extended Range aircraft is operationally suitable with a combat availability of greater than 80 percent. The fifth Gray Eagle full rate production contract was awarded to procure 30 Gray Eagle Extended Range Aircraft, 30 Satellite Air Data Terminals, two Universal Ground Data Terminals, government-furnished equipment repairs/maintenance, and associated program management. This contract completed the Gray Eagle Army acquisition objective of 204 aircraft. Additional contract actions will be to replace attrited air vehicles. The MQ-1C provides the Warfighter with dedicated, assured, multi-mission unmanned aircraft system capabilities with the extended range variation providing nearly 50 percent greater endurance. The Army began experimenting on a Future Tactical Unmanned Aircraft Systems initiative that will eventually replace the RQ-7V2 Shadows in Brigade Combat Teams as soon as FY 2025. Currently Shadows are assigned to all Brigade Combat Teams, Special Forces Groups, and Combat Aviation Brigades.

Navy

The MQ-4C Triton (formerly Broad Area Maritime Surveillance UAS) will develop maritime capable UAS for operational deployment by providing persistent maritime Intelligence, Surveillance, and Reconnaissance (ISR) services. Along with the P-8A Poseidon, the MQ-4C Triton UAS is an integral part of the Maritime Patrol and Reconnaissance Force family of systems and will provide combat information to operational and tactical users such as the Expeditionary Strike Group, Carrier Strike Group, and Joint Forces Maritime Component Commander.

Developmental testing on the baseline capability was completed in October 2017, and Early Operational Capability was reached in January 2020. The upgraded multiple intelligence capability is on track to support the maritime Intelligence, Surveillance, Reconnaissance, and Targeting transition plan in FY 2022.

The MQ-8 Fire Scout UAS program provides real-time and non-real-time ISR data to tactical users without the use of manned aircraft or reliance on limited joint theater or national assets. An MQ-8 system is composed of air vehicles (MQ-8B/MQ-8C), a Mission Control Station, Tactical Control System software, a Tactical Common Data Link, a UAV Common Automatic Recovery System for takeoffs and landings, payloads (electro-optical/infrared/laser designator-range finder, Automated Information System [AIS], voice communications relay, radar, mine countermeasures, and other specialty payloads), and associated spares and support equipment. Fire Scout radar (MQ-8C) provides a 240-degree instantaneous field of view and a range of digital modes to include Maritime Surveillance, Synthetic Aperture, Inverse Synthetic Aperture, weather detection, and a ground moving target indicator. The MQ-8 launches and recovers vertically and can operate from all suitably equipped air capable ships. Fire Scout is the first platform to successfully receive Cybersafe Certification. In addition, MQ-8 has completed Risk Management Framework certifications.

The MQ-25 program is rapidly developing an unmanned capability to embark on CVNs (aircraft carriers with nuclear propulsion) as part of the Carrier Air Wing (CVW) to conduct aerial refueling as a primary mission and provide ISR capability as a secondary mission. MQ-25 extends CVW mission effectiveness range, partially mitigates the current Carrier Strike Group organic ISR shortfall, and fills the future CVW-tanker gap, mitigating Strike Fighter shortfall and preserving F/A-18E/F fatigue life. MQ-25 will achieve this through the use of a carrier-suitable, semi-autonomous (man-in-the-loop, air vehicle executes preplanned missions) UAS (provided by the Air System segment) and controlled through existing C4I networks from the control systems integrated into the CVNs. MQ-25 will initially be integrated aboard Nimitz-class aircraft carriers, followed by Ford-class. The combined Government/Industry team will use modern processes and advanced technology, such as Model Based Systems Engineering and embedded teaming, to keep the program on track to be the fastest contract award-to-IOC of any modern major

aviation program. To date, T1 has flown 12 flights total, encompassing 27.8 flight hours. T1 recently completed modifications in support of MQ-25 requirements and will return to test flights in the first quarter of FY 2021. A Gate 6/Configuration Steering Board and System Design Review were successfully conducted in March 2020. Following the System Design Review, the program exercised the options for three System Demonstration Test Article (SDTA) air vehicles.

The RQ-21A Blackjack provides runway-independent, persistent maritime and land-based tactical Reconnaissance, Surveillance, and Target Acquisition (RSTA) data collection, dissemination, and communications relay capabilities to the warfighter. The RQ-21A carries an EO/IR payload with a laser rangefinder and IR pointer. For the United States Marine Corps, the RQ-21A Blackjack provides Marine Expeditionary Force and subordinate commands with a dedicated ISR system capable of operating from both L-class ships and remote austere locations ashore delivering intelligence products directly to the tactical commander in real time. For the Navy, the RQ-21A provides persistent RSTA support for tactical maneuver decisions and unit-level force defense/force protection for Navy ships, Marine Corps forces ashore, and Navy Special Warfare Units. USMC and NSW production deliveries are complete, and Full Operational Capability was declared in FY 2020. The systems continue to receive evolving capability upgrades to include EO/IR turret and radar and signals payloads. The Blackjack system now has more than 16,000 operational flight hours.

Weapons

Army

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

precision munition for our UAS. These smaller precision weapons will increase lethality and provide more flexibility in targeting.

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

In February 2020, the AROC approved a Directed Requirement (DR) to field the Spike Non-Line of Sight (NLOS) missile to our highest priority theaters in order to satisfy two COCOM Operational Needs Statements and close one of Army Aviation's identified Large Scale Combat Operations gaps. Spike NLOS is an interim Long Range Precision Munition (LRPM) solution that possesses the range and many capabilities required for Army Aviation to be successful against peer adversaries in conflict. Testing and federation efforts will begin by the Apache Program Management office and the Aviation Technology Development Directorate in early 2021, with the goal of fielding a limited number of systems in priority theaters by 2023. The FVL CFT will conduct a competitive shoot-off in 2022 that will inform the LRPM Program of Record.

Flight Test Patriot-27 Event 2 (FTP-27 E2): The Joint Functional Component Command Integrated Missile Defense J8 Directorate has been working closely with the Missile Defense Agency (MDA) in test planning and execution of new Ballistic Missile Defense System capabilities that will enhance regional BMD in all theaters. The MDA, in conjunction with the Army, executed Flight Test Patriot-27 Event 2 (FTP-27 E2) at the White Sands Missile Range and Fort Wingate, New Mexico. FTP-27 E2 was a demonstration of Patriot Launch on Remote using Terminal High Altitude Area Defense (THAAD) AN/TPY-2 Terminal Mode (TM) track and discrimination data. The Black Dagger short-range ballistic missile target was launched from Fort Wingate and flew a nominal trajectory. The AN/TPY-2 TM radar detected, tracked, and provided discrimination data to the Patriot battery. The battery received the data from THAAD, developed a firing solution based on remote data, and fired two PAC-3 MSE missiles.

Ballistic and Hypersonic Test Support: On October 2, 2019, the Reagan Test Site (RTS), located at U.S. Army Garrison–Kwajalein Island, successfully supported Air Force Global Strike Command’s Minuteman III Glory Trip 232 operational test mission. The launch was initiated from Vandenberg Air Force Base, California, and impacted at RTS within the Kwajalein Missile Impact Scoring System. Glory Trip tests demonstrate the capability of the U.S. intercontinental ballistic missile system.

On March 19, 2020, the RTS located at U.S. Army Garrison–Kwajalein Island supported the successful test of the Army and Navy jointly developed hypersonic glide body. Information from the test will inform the Department of Defense’s (DOD’s) hypersonic technology development. MDA monitored and gathered tracking data from the flight experiment that will inform its ongoing development of systems designed to defend against adversary hypersonic weapons. The event was a major milestone toward the goal of fielding hypersonic defense against hypersonic warfighting capabilities in the early- to mid-2020s. RTS provides test support capabilities found nowhere else in the world and is the Nation’s only long-range capable test range.

Navy

During FY 2020, the Department of the Navy continued to mature its long-range Cruise Missile Strategy. Key developmental and sustainment tenets of this strategy include 1) demilitarization of Tomahawk Land Attack/Block III; 2) support of Tactical Tomahawk (TACTOM)/Block IV recertification program, and development/fielding of new Block V capabilities through integration of modernization and obsolescence upgrades to TACTOM during a midlife recertification program (which extends the missile service life an additional 15 years); 3) continued fielding of the Long-Range Anti-Ship Missile (LRASM) as the Offensive Anti-Surface Warfare/Increment 1 material solution to meet near- to mid-term anti-access Anti-Surface Warfare threats; and 4) development of follow-on Next Generation Strike Capability (NGSC) weapons to address future threats and targets in time to replace or update legacy weapons while bringing next-generation technologies into the Navy’s standoff conventional strike capabilities. NGSC includes capabilities to counter long-term anti-surface warfare threats and a surface- and

subsurface-launched Next Generation Land Attack Weapon (NGLAW) to initially complement, and then replace, legacy land attack cruise missile weapon systems.

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

LRASM shifted focus from initial development and fielding to obsolescence management as components within the baseline system required replacement. Modest improvements in performance are expected as well.

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

The Advanced Precision Kill Weapon System (APKWS) guidance kit transforms an unguided 2.75-inch (70-millimeter) rocket into a precision-guided rocket, giving warfighters a low-cost surgical strike capability. The APKWS rocket redefines precision by hitting the target with pinpoint accuracy and minimal collateral damage. The rocket has been proven in combat for ten years. The Advanced Precision Kill Weapon System continued its high level of reliability and lethality as this weapon has become one of the key weapons in the current fight against the Islamic State (known variously as ISIS and ISIL). The Navy has delivered 40,000 APKWS guidance kits to date to Navy/Marine, Air Force, Army, and Foreign Military Sales customers. Efforts are under way to develop a Single Variant guidance kit to replace separate Rotary Wing and Fixed Wing versions, increase fleet logistical flexibility, and address component part obsolescence.

Aviation Survivability Equipment

Army

Aviation Survivability Equipment (ASE) is essential to providing force protection for aircraft against emerging advanced threats. Nowhere is this more evident than in the Concept of Operations (CONOPS) for FVL in Multi-Domain Operations (MDO). Therefore, while we continue to maintain capable ASE systems in the current fleet and develop advanced capabilities to counter an ever-evolving array of threat systems, we are viewing the future of ASE through an FVL lens. The Common Missile Warning System (CMWS) continues to provide the Army's fleet with infrared (IR) threat detection with the primary focus on Man-Portable Air Defense Systems (MANPADS). CMWS employs a range of expendable countermeasures on all platforms with the addition of the Advanced Threat IR Countermeasure system on CH-47s to defeat incoming MANPADS. Army Aviation has begun receiving production systems of the Common Infrared Countermeasure and the initial component deliveries of the Limited Interim Missile Warning System, a directed requirement increment intended as a rapid capability insertion for improved protection of Army helicopters. Army Aviation is also developing requirements for the next-generation ASE systems with an eye toward both FVL and the current fleet. Those advanced capabilities have to protect our aircraft and crews against a range of advanced MANPADS as well as vehicle-borne systems that include radar, laser, and various passively cued systems. FVL efforts provide the ASE program office with a unique opportunity to assess offerings from FVL competitors in addition to ongoing developmental programs.

In the area of radio frequency (RF) systems, the Army completed the validation and verification of the APR-39D(V)2 Radar Warning Receiver and began its fielding. APR-39D(V)2 is a bridging capability while we continue development of the APR-39E(V)2, Modernized Radar Warning Receiver. Along with advances in detection capabilities, the Army is also advancing its threat defeat capabilities with the development of a family of Advanced Airborne Expendable Countermeasures and is pursuing opportunities to accelerate active RF Countermeasures capabilities. Production of an improved counter-RF expendable (Chaff) is expected to field to the force in 2024. The fielding of upgraded Chaff and Electronic Countermeasures

will coincide with the improved detection initiatives, with an eye toward implementation in FVL platforms as well as the current fleet. MDO requirements will continue to drive Army Aviation science and technology efforts to develop follow-on systems that are able to detect and defeat a threat system regardless of its targeting and guidance systems, propulsion means, or warhead type.

Propulsion

Army

The Army continues its development of the Improved Turbine Engine (ITE), a 3,000-shaft-horsepower engine designed to power FARA and replace the current GE 701D engine that powers the AH-64 and UH-60 airframes. The ITE is critical to the FARA program and supports the Army's Multi-Domain Operations (MDO) concept with increased reach and lethality in its enduring aircraft fleet, specifically through lower fuel consumption, higher shaft horsepower, improved sustainability and growth margins, and improved performance at 6,000 feet pressure altitude and 95°F. Having already achieved Program Milestone B and an approved Acquisition Program Baseline (APB), the PEO Aviation, Aviation Turbine Engines Project Office successfully completed engine fit checks in both the AH-64 and UH-60 and Critical Design Reviews (CDR) in 2020. The first engine to test was scheduled for delivery to the Army in mid-2021, and current projections indicate that the Army will achieve Milestone C and aircraft qualifications on the FARA CP, AH-64, and UH-60 in FY 2024.

Space

Army

Army Astronauts

Colonel (Dr.) Andrew R. Morgan, U.S. Army, launched onboard the Soyuz MS-13 spacecraft from the Baikonur Cosmodrome in southern Kazakhstan on July 20, 2019, to the International Space Station (ISS) as a flight engineer for Expeditions 60, 61, and 62. When his 272-day mission ended on April 17, 2020,

it established COL Morgan as the record holder of the longest-duration single spaceflight mission by a currently serving active duty military officer. COL Morgan conducted seven spacewalks, totaling 45 hours and 48 minutes, four of which were to improve and extend the life of the Station's Alpha Magnetic Spectrometer as it looked for evidence of dark matter in the universe. He established another record for the most spacewalks conducted by a U.S. astronaut in a single spaceflight, tying the Russian cosmonaut record. COL Morgan's extended stay in space increased the space community's body of knowledge about how the human body responds to long-duration spaceflight through the various investigations he supported, including the Fluid Shifts study.

Lieutenant Colonel Frank Rubio, U.S. Army, completed his astronaut candidate training and on January 10, 2020, earned the designation of NASA astronaut. His class of 11 new astronauts are slated for NASA's Artemis program.

SpaceX Training with Industry

In FY 2020, the Army sent its second Space Operations Officer to SpaceX as part of its Training with Industry (TWI) fellowship program. TWI is a work-experience training program designed to imbed selected officers with industry leaders. This exposure gives officers insight into current commercial industry technology processes, business practices, corporate structures and cultures, and various management techniques. During his fellowship with SpaceX, Captain J. Cupit served as a mission integration engineer on the Commercial Crew Program (CCP) Mission Management Team, and his efforts were crucial in the successful launch of the Commercial Crew Demonstration 2 (Demo-2) spacecraft, which restored America's human spaceflight capability. He played a pivotal role in the certification of the CCP Demo-2 Dragon spacecraft, which made history on May 30, 2020, when it successfully launched two NASA astronauts, Robert Behnken and Douglas Hurley, into space and docked with the ISS the following day. Cupit worked with SpaceX and NASA engineers to negotiate the testing, qualification, and approval of all Demo-2 Dragon change tickets, qualification test plans and reports, and final verification reviews for over 1,000 components. He held daily meetings with NASA technical leads to resolve issues with the qualification of the Demo-2 Dragon vehicle. Additionally, while working with the CCP Mission Management Team,

he was certified as a Mission Control Operator and participated in Crew/Operator Training events in preparation for the Demo-2 Dragon Launch. He also contributed to the certification of the In-Flight Abort Test, which SpaceX and NASA conducted to validate the emergency abort capabilities of the Dragon Capsule and its ability to separate from the Falcon-9 rocket. SpaceX management hand-picked Cupit to serve on SpaceX's Proposal Team to assist in writing the company's lunar HLS proposal. He developed and wrote the Collaboration Plan and multiple technical sections to establish partnerships between SpaceX and NASA to advance technical designs for returning U.S. astronauts to the Moon. His work directly contributed to SpaceX being awarded the contract for HLS. Jointly, with the HLS certification lead, Cupit created certification and NASA interface processes for the new program while leveraging crew program lessons learned, maximizing efficiency, significantly improving communication flow between SpaceX and NASA, and reducing internal team administration burden.

Support to Human Space Flight Operations

SpaceX's Demo-2 was the first crewed test flight of the Crew Dragon spacecraft. The spacecraft, named Endeavour, launched on May 30, 2020, and carried NASA astronauts Douglas Hurley and Robert Behnken to the ISS. Demo-2 was intended to complete the validation of crewed spaceflight operations using SpaceX hardware and to receive human-rating certification for the spacecraft, including astronaut testing of Crew Dragon capabilities on orbit. During the return of Demo-2 on August 2, 2020, precautionary Search and Rescue (SAR) forces were postured at primary and secondary splashdown locations. The SAR aircraft and vessels employ Friendly Force Tracking/Blue Force Tracking (FFT/BFT) systems that provide near-real-time location and status of the SAR assets. All of the SAR FFT/BFT systems are provisioned to the SMDC Force Tracking Mission Management Center (FT-MMC) in Colorado Springs, where the tracking data are managed and disseminated to the USNORTHCOM Common Operational Picture and the other tactical displays providing commanders with command-and-control capabilities and situational awareness of SAR forces.

History of the Transfer of the Army's Space Mission to NASA

In July 2020, NASA celebrated the 60th anniversary of the George C. Marshall Space Flight Center located on Redstone Arsenal. This anniversary also marked a significant milestone in the Army space program. On July 1, 1960, the first day of fiscal year 1961, the core of the Army Ballistic Missile Agency/Army Ordnance and Missile Command transferred to NASA, becoming the Marshall Space Flight Center.

Air Force

Environmental Monitoring

The Weather System Follow-on (WSF) environmental satellite system follows a two-phased acquisition approach that places the Compact Ocean Wind Vector Radiometer (COWVR) technology demonstration on the ISS via the 2021 installation of the Space Test Program–H8 (STP-H8). The COWVR demonstration is intended to mature the technology and develop ground-processing algorithms. The WSF–Microwave (WSF-M) program will collect critical observations on Ocean Surface Vector Winds and Tropical Cyclone Intensity. WSF-M is the planned replacement for the legacy WindSat mission as well as the Special Sensor Microwave Imager/Sounder sensors, which fly on the Defense Meteorological Satellite Program (DMSP) satellites. The first of up to two WSF-M satellites is in development, having achieved acquisition Milestone-B in May 2020 and initial launch capability in late 2023.

The Electro-optical/infrared Weather System (EWS, formerly WSF-E) prototyping activities were conducted among competing vendors starting in spring of 2020 that will lead to downselect in early 2021 for prototype launches in 2022 and 2023. EWS will satisfy DOD's two highest-priority Space Based Environmental Monitoring (SBEM) sensing needs from the family of systems' "early-morning" orbit–Cloud Characterization and Theater Weather Imagery. The initial launch capability for EWS that will begin replacement of DMSP is scheduled for 2025.

Beginning in 2018, the Air Force and NOAA conducted various technical interchanges, site surveys, and planning activities for the Electro-optical/infrared Weather System-Geostationary (EWS-G, formerly WSF-G). The intended

purpose of EWS-G is to provide persistent weather monitoring of the CENTCOM Area of Responsibility from a dedicated U.S. geostationary SBEM satellite before Europe's Meteosat-8 reaches its projected end of mission. A remote ground station in Western Australia became operational in late 2019, supporting tracking, telemetry, and control for EWS-G. EWS-G reached Initial Operational Capability in September 2020, providing timely and reliable SBEM capabilities to CENTCOM.

The Space Situational Awareness Environmental Monitoring (SSAEM) program is a technology demonstration project to support the international Constellation Observing System for Meteorology, Ionosphere and Climate 2 (COSMIC-2) mission. The SSAEM program provides the acquisition, development, and launch/on-orbit support of 18 space/terrestrial weather sensors to COSMIC-2 in coordination with National Oceanic and Atmospheric Administration (NOAA) and Taiwan's National Space Organization (NSPO). COSMIC-2, launched in 2019, consists of six satellites in an equatorial, low-Earth orbit with three SSAEM sensors in each spacecraft. Final orbital placement of the six satellites occurred throughout FY 2020. The sensor types are Tri-Global Navigation Satellite System Radio Occultation System, Ion Velocity Meter, and Radio Frequency Beacon. The SSAEM sensors will observe ionospheric density, equatorial ionospheric scintillation, and electric field to provide additional space meteorological data to improve forecast capabilities and improve warfighter navigation/communication capabilities over the next five years.

Missile Warning/Attack Assessment

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

The SBIRS GEO-5 and GEO-6 satellites are in production and are meeting cost and schedule objectives. In FY 2020, SBIRS GEO-5 entered space vehicle final testing and SBIRS GEO-6 began space vehicle integration and test activities.

The Space Force is taking projected threats seriously and focusing investments on maturing resilient technologies. The Space Force approved acquisition strategies

for the Next Generation Overhead Persistent Infrared (Next-Gen OPIR) space and ground segments to rapidly prototype these new resilient capabilities. The space segment will replenish the SBIRS constellation by delivering five resilient and survivable Missile Warning Satellites (three GEO and two Polar Orbit), with the first GEO Satellite to be delivered by FY 2025. In FY 2020, the GEO program completed Preliminary Design Reviews for two infrared sensor providers slated for the satellite's main mission payload. In addition, the Polar program conducted a successful System Requirements Review in March 2020.

The ground segment, Future Operationally Resilient Ground Evolution (FORGE), is developing a cyber-secure open OPIR mission framework capable of hosting applications and providing services to process mission data for missile warning, missile defense, battlespace awareness, and technical intelligence mission areas. In FY 2020, FORGE awarded a contract to develop the mission data application framework and successfully demonstrated the capability to command and control an SBIRS Highly Elliptical Orbit payload.

Positioning, Navigation, and Timing (PNT)

The GPS program celebrated its 25th anniversary this year of providing uninterrupted PNT data, free of charge, to users worldwide. GPS has been operational since July 1995. The success of the GPS program can be reflected in the total number of GPS receivers produced to date, estimated at more than four billion worldwide. The first three GPS III satellite launches occurred in December 2018, August 2019, and June 2020, with the fourth planned for the first quarter of FY 2021. These launches are ushering in the next generation of GPS technology with significant enhancements to the current constellation, including higher-power military signals, new civilian signals, and hosted search-and-rescue payloads. GPS III satellites five through ten are in various stages of production with the next launch scheduled in July 2021.

The GPS III Follow-on (GPS IIIF) was approved to enter into the Production and Deployment phase. GPS IIIF will provide 22 satellites with an eightfold increase in anti-jam performance over current GPS satellites.

Satellite Communications (SATCOM)

The Advanced Extremely High Frequency (AEHF) system is a joint-service satellite communications system that provides global, survivable, secure, protected, and jam-resistant communications for high-priority military ground, sea, and air assets. Five on-orbit AEHF satellites augment the existing Milstar constellation, providing protected satellite communications for strategic users. The sixth, and final, AEHF satellite launched March 26, 2020, and was planned to transition to operations in October 2020.

The Evolved Strategic SATCOM (ESS) program is the disaggregated strategic communications follow-on to the AEHF program. The ESS space segment was designated a Middle Tier of Acquisition (MTA) Rapid Prototyping Activity, which reduces the ESS schedule to deliver the first satellite available for launch by approximately two years as compared to a traditional DOD 5000.02 acquisition. Three rapid prototyping contracts were awarded in the Fall of 2020. The simultaneous prototyping by three vendors will drive competition that will strengthen the industrial base for the follow-on build, integrate and test, and delivery contract.

The Protected Tactical SATCOM (PTS) program is the disaggregated tactical communications follow-on to the AEHF program. PTS will provide worldwide, beyond-line-of-sight, anti-jam, low-probability-of-intercept communications to tactical warfighters in both benign and contested environments. Designated as an MTA Rapid Prototyping Activity, PTS will develop two prototype payloads. The Rapid Prototyping activity reduces the PTS schedule to deliver two prototype payloads by three years as compared to a traditional DOD 5000.02 acquisition. Using Other Transaction Authorities, Northrop Grumman, Boeing, and Lockheed Martin received prototype payload development awards in February 2020.

The Protected Tactical Enterprise Service (PTES) is a ground system that will provide anti-jam protection via a Wideband Global Satellite Communications system to tactical warfighters currently unable to operate through interference in anti-access/area denial operational environments. PTES is an MTA, Rapid Prototyping Activity pursuing a prototype capability in the Pacific Theater in early FY 2022. The Post-Software Build #1 Decision Review was accomplished in July 2020.

The Enhanced Polar System (EPS) program, with two hosted payloads on orbit and a ground Control and Planning Segment (CAPS), were accepted for

operational use on November 19, 2019. EPS replaces the Interim Polar System to ensure that critical protected communications requirements above 65 degrees north latitude are satisfied for joint forces. The Space Force is procuring two replenishment EPS payloads, the Enhanced Polar System-Recapitalization (EPS-R), to prevent a MILSATCOM mission gap in the polar region in the 2025 timeframe. These EPS-R payloads will be hosted on a Space Norway satellite, promoting U.S. policy of strengthening international partnerships, and has the potential for saving the U.S. Government \$900 million in costs. The EPS-R payload delta-CDR was successfully completed in October 2019, and the CAPS CDR supporting EPS-R was successfully completed in June 2020.

The Wideband Global Satellite Communications (SATCOM) (WGS) system provides bandwidth to support Unified Combatant Commanders, military services, other DOD agencies, and international partners. The space segment operates in the X-band and Ka-band with flexible connectivity between bands and coverage areas to support and connect users operating worldwide. The WGS satellite program consists of eleven satellites with ten currently on orbit. WGS-10 successfully passed operational acceptance on November 19, 2019. The WGS program office definitized the firm-fixed-price contract for production of WGS-11+ in February 2020. Additionally, the WGS program office successfully completed Preliminary Design Review for WGS-11+ in July 2020.

The United States Space Force Commercial SATCOM Office (SFCSCO) was established under Air Force Space Command (AFSPC) in December 2018 and was transferred to the United States Space Force (USSF) upon its establishment in December 2019. SFCSCO procures Commercial SATCOM (COMSATCOM) for DOD by managing more than 90 active customer contracts, leveraging 40 COMSATCOM providers. SFCSCO delivers unlimited access to the global commercial Iridium Satellite Constellation, providing airtime, secure voice, and secure data services for DOD, all Federal agencies, state and local governments, and foreign partners (FVEY and NATO). SFCSCO also delivers COMSATCOM capabilities through standard and custom contracts including transponder capacity, managed services, and custom solutions.

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. All 84 planned FAB-T Command Post Terminals are now on contract, 33 terminals have been delivered, 18 terminals have been installed, and 14 are in operational use.

Space Access

The National Security Space Launch (NSSL) program continues to successfully place satellites into orbit. There were three launches during FY 2020: United Launch Alliance (ULA) successfully launched two National Security Space (NSS) launches, and SpaceX launched one.

(Launch Date, Launch Vehicle Configuration, Payload)

- March 26, 2020, Atlas V (551), Advanced Extremely High Frequency (AEHF)-6
- June 30, 2020, Falcon 9 Upgrade, Global Positioning System (GPS) III-3
- May 17, 2020, Atlas V (501), United States Space Force (USSF)-7

On August 12, 2020, the U.S. Space Force's Space and Missile Systems Center, in partnership with the National Reconnaissance Office's Office of Space Launch, competitively awarded two firm-fixed-price, indefinite delivery requirement contracts to ULA and SpaceX that will provide reliable, innovative, and affordable launch services for NSS missions. The Phase 2 Launch Service Procurement was a full-and-open best-value-tradeoff competition. This award marks the culmination of an innovative acquisition strategy that also used Other Transaction Authority investments made via public-private partnerships in Rocket Propulsion Systems (awarded February 2016) and Launch Service Agreements (awarded October 2018) to end reliance on Russian engines and leverage launch industry innovation.

Since 2016, the Department of the Air Force has actively engaged in evaluating reusable launch systems and establishing common standards consistent with NSSL Mission Assurance standards. The successful launch of GPS III-3 on June 30, 2020—the first NSSL mission to recover flight hardware for future use—returned \$9.5 million to U.S. taxpayers with no overall change to the mission risk and obtained valuable reuse data.

The Department of the Air Force and SpaceX reached an agreement to reuse a SpaceX Falcon 9 booster for GPS III-5 (and GPS III-6, if the contract option is exercised). Combined with the booster recovery contract modifications, the Falcon 9 booster reuse agreements provide \$52.7 million in cash savings.

Rocket Systems Launch Program: The Space Force's Rocket Systems Launch Program (RSLP) continues to provide a low barrier for new entry launch vehicles, enabling a diverse vendor pool consisting of both large and small businesses with a mixture of mature and emerging launch providers. Examples include the April 2020 launch services award to VOX Space for the STP-S28 mission and the July 2020 award to Northrop Grumman to support a tactically responsive mission. RSLP also continues with its STP-27RM Monolith mission—the first Rocket Lab launch from the United States—planned for spring 2021 from Wallops Flight Facility, Virginia.

Launch Ranges: Range modernization efforts continued in FY 2020 with architectural overhauls at the Eastern and Western Ranges with sustainment engineering and modification projects to address cybersecurity issues, obsolescent technology, and diminishing vendor concerns. Range subsystems modernization continued with telemetry, radar, and command site instrumentation and associated software to ensure mission reliability, maintainability, and availability. In July 2020, the modernized Cape 1B Command Destruct Antenna operationally supported a launch for the first time, in support of the NASA Mars Perseverance launch from Cape Canaveral Air Force Station (CCAFS). The upgraded antennas enable ground control to send a destruct command to errant launch vehicles to ensure public safety, while safeguarding against inadvertent destruct commands to nominal launch vehicles. The modernization replaced obsolete and unsustainable equipment, upgraded communications, and enabled use of the NSA's latest encryption systems. This critical capability was operationally accepted on May 7, 2020, as part of the Eastern Range Command Destruct Modernization project at CCAFS.

Additionally, Eastern and Western Range Network Modernization continued with upgrades for mission communications core to provide automated routing versus manual range reconfiguration, centralized network management across the IP network, increased bandwidth enabling transport of range data now and in the future, and opportunities to modernize information assurance.

Space Rapid Capabilities Office: The Space Rapid Capabilities Office (SpRCO) mission focuses on developing and delivering operationally dominant space capabilities in support of national defense as directed by the Secretary of the Air Force through a Board of Directors (BoD). The BoD is chaired by the Secretary of the Air Force with membership that includes the Chief of Space Operations; Commander of U.S. Space Command; Assistant Secretary of the Air Force for Acquisition, Technology and Logistics; Under Secretary of Defense for Acquisition and Sustainment; and Under Secretary of Defense for Research and Engineering. Through the BoD, the SpRCO has been assigned and is executing programs that fill critical portions of the Space Warfighting CONOPS as defined by the Commander of U.S. Space Command. The SpRCO continues to develop partnerships with other government organizations, industry, academia, and federally funded research and development centers to aid in the rapid development and delivery of U.S. space capabilities at the speed of warfighting relevance.

Space Control

The Counter Communications System (CCS) provides expeditionary, deployable, and reversible counter-space effects applicable across the full spectrum of conflict. CCS denies adversary satellite communications in an area of conflict. CCS is a key piece of DOD's space control strategy and has been in operation since 2004 with the fielding of three Increment 10.0 systems. To date, CCS has gone through two subsequent preplanned product improvements and delivered 16 CCS Increment 10.2 systems. The Space Force declared it had reached initial operational capability with the CCS Block 10.2 on March 9, 2020, and 16 CCS Block 10.2 have been fielded and operating at Peterson Space Force Base, Colorado; Vandenberg Space Force Base, California; Cape Canaveral Space Force Station, Florida; and other deployed locations outside the continental United States.

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. The SSDP completed efforts resulting in the delivery and implementation of

specific cyber and materiel solutions to emergent capability needs. These include the following:

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

The Space C2 system will provide a collaborative environment that will enhance and modernize SDA and Battle Management Command and Control capabilities; create decision-relevant views of the space environment; rapidly detect, track, and characterize objects of interest; identify/exploit traditional and nontraditional sources; perform space threat analysis; and enable efficient distribution of data across the Space Surveillance Network. In FY 2020, the Space C2 program delivered key capabilities for theater support and protect-and-defend missions.

Space Domain Awareness

Adversary nations are fielding sophisticated space weapons at a pace our legacy SDA and C2 systems cannot currently match. To address the rapidly expanding threats to the space enterprise, the Space C2 program will allow the Space Force to command and control space control and SDA forces by integrating data for commanders. SDA will be an integral tool to help commanders develop courses

of action to address threats to critical space assets. The program's new acquisitions approach is an innovative, agile development, security, and operations (DevSecOps) effort, linking users with developers to deliver improved and prioritized capabilities to operators on a recurring basis. This pivots future SDA and C2 development efforts to a user-driven, rapid-delivery approach leveraging best practices in digital engineering to defeat an advancing threat.

Space Fence site 1 was delivered in FY 2020 and provides un-cued surveillance of small objects and satellites primarily in low-Earth orbit (LEO) (primary mission), as well as medium-Earth orbit (MEO) and geosynchronous-Earth orbit (GEO) (secondary mission), to provide spaceflight safety, early detection, custody of threats, and awareness to satellite operators in the human spaceflight regime. Space Fence is a high-capacity radar in the Space Surveillance Network (SSN) and provides extensive updates to the space catalog, delivers increased sensitivity for new object discovery, and delivers optimum orbital coverage, including coverage of much lower inclinations of orbiting objects. Space Fence greatly increases the ability to understand the space domain battlespace and inform warfighter decisions. The increased sensitivity, coupled with increased computing capabilities of the Joint Space Operations Center Mission System, improves understanding of the space operating environment and associated threats.

The acquisition strategy implemented Better Buying Power—cost, capability, and design trade studies, prototyping, and risk reduction in the System Development and Preliminary Design Review phases. Current efforts are focused on interim contractor support, software patches, and cybersecurity testing.

Deep Space Advanced Radar Concept (DARC) is a ground-based Space Domain Awareness radar system that detects, tracks, and maintains custody of deep space objects 24/7. Two transmit and five receive antennas were built on White Sands Missile Range as part of the DARC demonstration prototype.

Satellite Control Network: Satellite Control Network upgrades continued in FY 2020 by transferring two Remote Tracking Station Block Change Hybrids to operations at Hawaii and Vandenberg Air Force Base, California. These upgrades updated the core electronics to current internet standards while adding automation. The antennas were refurbished with the upgrade. Additionally, two prototype

demonstrations showed antenna technologies that support multiple satellite contacts simultaneously from one antenna.

Robert J. Collier Trophy: The Department of the Air Force's X-37B spaceplane, a reusable, multipurpose system that operates without an onboard crew, won the prestigious Robert J. Collier Trophy August 13, 2020, for advancing technology that pushes "the boundaries of flight and space exploration." The X-37B provides the Department of the Air Force the ability to conduct experiments and perform other functions in Earth orbit.

"The X-37B team win of the 2019 National Aeronautic Association, Robert J. Collier Trophy exemplifies the kind of lean, agile, and innovative technological development our nation needs to secure its interests," said General John "Jay" Raymond, U.S. Space Force Chief of Space Operations.

"Underscoring the importance of space to the nation, the Collier Trophy celebrates the record-setting mission of the X-37B," Secretary of the Air Force Barbara Barrett said. "Most Americans use space daily for navigation, information, and communication. Sophisticated and uncrewed, the X-37B advances reusable spaceplane technologies and operates experiments in space that are returned for further examination on Earth."

In all, the spaceplane has flown six missions since being launched for the first time on April 22, 2010. In 2019 the X-37B set a new 780-day on-orbit endurance record and completed an overflight of the United States, using Federal Aviation Administration airspace, before landing at NASA's Kennedy Space Center. That mission broke the previous on-orbit record of 718 days that also was held by the X-37B. In all, the program has logged more than 2,865 days and travelled more than 1 billion miles on orbit.

Space Development Agency

The Space Development Agency (SDA) orchestrates the development and fielding of DOD's future threat-driven National Defense Space Architecture (NDSA), a resilient military sensing and data transport capability via a proliferated space architecture primarily in LEO.

Per the administration's guidance, SDA acts as a constructive disruptor within DOD for space acquisition and delivery of advanced space-based capabilities for the warfighter. The Space Development Agency's model solves the *Innovator's Dilemma*¹ problem by allowing disruption to improve upon our current architecture while ensuring the current mission is not compromised. To achieve this mission, SDA uses novel approaches to accelerate the development and fielding of military space capabilities necessary to ensure U.S. technological and military advantage in space for national defense. SDA has demonstrated the capacity to accelerate DOD acquisition processes through the release of two Broad Agency Announcements (BAAs) and four RFPs, as well as the award of seven contracts for space hardware since the Agency's initial appropriation of funds in early CY 2020. SDA employs a spiral development approach to elicit warfighter needs and develop and field new defense space capabilities in two-year tranches, or capability increments, with Tranche 0 launching at the end of CY 2022 and Tranche 1 launching at the end of FY 2024. SDA's first major contract awards for space vehicle acquisition—the Tranche 0 Transport and Tracking Layers—each went from solicitation publication through the award of multiple contracts in less than 120 days.

SDA is focused on the eight essential capabilities described in the August 2018 *Final Report on Organizational and Management Structure for the National Security Space Components of the Department of Defense*.² These capabilities include

- (1) Persistent global surveillance for advanced missile targeting;
- (2) Indications, warning, targeting, and tracking for defense against advanced missile threats;
- (3) Alternate PNT for a GPS-denied environment;
- (4) Global and near-real time space situational awareness;
- (5) Development of deterrent capability;
- (6) Responsive, resilient, common ground-based space support infrastructure (e.g., ground stations and launch capability);

1 Christensen, C. M. (2016). *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston: Harvard Business Review Press.

2 Department of Defense. (2018). *Final Report on Organizational and Management Structure for the National Security Space Components of the Department of Defense*.

- (7) Cross-domain, networked, node-independent battle management command, control, and communications, including nuclear command, control, and communications; and
- (8) Highly-scaled, low-latency, persistent, artificial-intelligence-enabled global surveillance.

SDA will not necessarily develop and field all capabilities of the NDSA but rather form mission partnerships across the Department to orchestrate these efforts, fill gaps in capabilities, and provide the integrated architecture.

Science and Technology

SDA is interested in both broad technology vectors as well as specific, implementable solutions. As the NDSA matures, measurable advances are needed in

- **Global Real-Time Access** including, but not limited to, advanced alternate PNT and advanced communication encryption;
- **Comprehensive Space-Based Sensing** including, but not limited to, hybrid missile tracking architectures and all-weather custody of time-sensitive ground targets;
- **Advanced Processing and Trusted Autonomy** including, but not limited to, software frameworks that enable on-orbit updates and distributed onboard processing; and
- **Resilient Support and Seamless Interoperability** including, but not limited to, architecture-wide digital engineering and interfaces/standards supporting multi-vendor/industry-wide solutions.

The Naval Research Laboratory is under contract with SDA to develop a hardware-in-the-loop/software-in-the-loop testbed for integration and interoperability testing of space vehicles and payloads developed by multiple vendors for the NDSA. This testbed will enable integration testing of optical-intersatellite link (OISL) implementations to ensure that space communications systems developed by different vendors are able to transmit, receive, and process data via optical intersatellite links prior to placing the space vehicles on orbit.

Missile Warning/Missile Tracking/Missile Defense

The NDSA Tracking Layer will provide global indications, warning, tracking, and targeting of advanced missile threats, including hypersonic missile systems. The Tracking Layer will include both wide field of view (WFOV) and medium field of view (MFOV) OPIR satellites. WFOV OPIR sensors are employed to maximize threat missile detection coverage and will cue MFOV OPIR sensors to form target tracks with greater precision for dissemination to advanced U.S. weapons systems. Tranche 0 of the NDSA Tracking Layer will include eight WFOV OPIR satellites. MFOV OPIR capabilities will be derived from MDA's Hypersonic and Ballistic Tracking Space Sensor prototype program and incorporated into future SDA Tracking Layer tranches. Tranche 0 will provide advanced missile threat detection and tracking capabilities with periodic regional coverage. If funded, SDA plans to incrementally improve the coverage of threat missile detection and tracking capabilities in subsequent tranches, with persistent regional coverage in Tranche 1 and persistent global coverage by Tranche 2.

Satellite Communications (SATCOM)

The NDSA Transport Layer will provide assured, resilient, low-latency military data and connectivity worldwide to a full range of warfighter applications. On August 31, 2020, less than four months after releasing the Tranche 0 Transport Layer RFP, SDA awarded firm-fixed-price contracts to teams led by Lockheed Martin and York Space Systems for the design, development, and launch of a total of 20 space vehicles at an average cost of just \$14 million per satellite, including non-recurring engineering costs. These space vehicles will be delivered for launch in less than two years, and once in orbit will connect to one another and to ground terminals via OISLs, which employ free space optical communication to provide secure, low-latency, wideband connectivity. Six of the 20 satellites will also have Link 16 transmit and receive capabilities to provide real-time dissemination of threat missile tracks and time-critical targeting data to warfighting platforms via tactical data link.

Modernization of our defense space capabilities and architecture will require contributions from a robust and collaborative multi-vendor enterprise. To promote the interoperability of future space-based communications systems, SDA

released the open SDA OISL Standard on June 4, 2020, which specifies the NDSA Transport Layer's optical communications interface.

Space Situational Awareness

There have been recent increases in the level of activity in the region of space extending beyond geosynchronous orbit to lunar ranges. SDA awarded two contracts for the performance of space situational awareness architecture studies to identify effective strategies for persistent observation and deterrence of hostile behavior in this cislunar environment.

FEDERAL AVIATION ADMINISTRATION

FAA

The mission of the U.S. Department of Transportation's (DOT's) Federal Aviation Administration (FAA) is to provide the safest, most efficient aerospace system in the world. We strive to reach the next level of safety and efficiency and to demonstrate global leadership in how we safely integrate new users and technologies into our aviation system.

FAA in Action: COVID-19 Pandemic

The global spread of Coronavirus Disease 2019 (COVID-19) resulted in a dramatic decrease in the movement of people, within the United States as well as across international borders. In an attempt to reduce the spread of the virus, governments around the globe implemented various measures, including limiting cross-border travel, limiting the size of crowds, employing social distancing measures, using personal protective equipment (PPE), and placing restrictions on certain sectors of their economies.

The COVID-19 pandemic dramatically altered the aviation industry. In response, the FAA adjusted operations to better support our Nation's needs, the aviation industry, and the safety of the FAA workforce.

In spring 2020, passenger aircraft traffic dropped 96 percent.¹ This drop in traffic and associated revenues significantly impacted the industry. Through legislation,

¹ FAA Fiscal Year 2020 Performance and Accountability Report (FAA FY 2020 PAR), available at https://www.faa.gov/sites/faa.gov/files/about/plans_reports/2020_PAR.pdf (accessed July 25, 2022).



including the Coronavirus Aid, Relief, and Economic Security (CARES) Act, and issuances of exemptions and other types of relief, the Federal Government kept airports open and aircraft flying. Since the beginning of the pandemic, the FAA has played an important role in safeguarding the National Airspace System (NAS).

Protecting the NAS

The DOT, including the FAA, carried out important roles in leading the COVID-19 pandemic response in the aviation sector and the wider transportation industry. With the passage of the CARES Act, the FAA took the lead in deploying to 3,229 airport sponsors a \$10 billion aid program designed to preserve America's airports. Due to the dramatic decline in passenger air travel, sources of airport revenue declined rapidly. To prevent these airports from shutting down, the FAA developed a first-of-its-kind grant program to ensure that public-use airports of all sizes had the necessary funds to stay open and operational.

Airports are but one segment of the NAS. Air carriers, while remaining operational, significantly reduced aircraft fleets due to dramatic decreases in passenger demand. Operators were forced to take aircraft out of service and the FAA quickly had to develop a strategy for safely parking more than 2,000 aircraft without impacting ongoing airport operations.

During the early stages of the pandemic, the composition of air travel quickly changed. Cargo traffic surpassed passenger travel² due to the need to transport large amounts of PPE and other medical materials and equipment across the country. To safely meet this critical need, the FAA issued, in a timely manner, numerous grants of exemptions and imposed certain terms, conditions, limitations, and mitigations to ensure that operations did not adversely impact safety. The FAA, in conjunction with the Federal Emergency Management Agency, coordinated and facilitated the distribution of 87 million cloth face coverings to all 14 CFR part 139 certificated airports with air carrier service.

The relief the FAA granted enabled air carriers to transport cargo in empty passenger aircraft and allowed certain general aviation operators to assist with the movement of critical infrastructure and medical supplies. To further support the

2 FAA FY 2020 PAR.

transport of critical materials, the FAA granted relief from applicable regulations to enable the use of unmanned aircraft systems in novel ways, such as to deliver medical tests and medical supplies.

At the same time, the FAA continued its mission to provide the safest air transportation system in the world. In the summer of 2020, the FAA began working to address the multitude of safety, logistics, and coordination issues related to ensuring the safe, efficient, and expeditious distribution of anticipated COVID-19 vaccines by air. The FAA collaborated with air carriers, pharmaceutical manufacturers, and Federal government agencies to ensure safe and easy air transport of vaccines once they were approved for use.

The FAA also worked closely with the Commercial Aviation Safety Team to identify quickly the safety hazards unique to COVID-19, disseminate this information to our international partners, and begin the process of developing mitigations to help offset some of the effects of these hazards on the aviation industry and its operations.

Early in the COVID-19 pandemic, holders of airman medical certificates began to experience difficulty obtaining required medical examinations. The FAA quickly developed a policy to extend medical certifications while maintaining safety standards. The FAA then reviewed each case to verify the individual was medically safe to continue performing safety-sensitive duties.

Protecting FAA Employees

Just as airports, air carriers, and other operators kept operating, so did the FAA. Air traffic controllers and other safety professionals perform critical work in managing traffic across the Nation's skies as well as ensuring the safety of the flying public. The FAA's Airport Certification and Safety inspectors also continued to work during this time to perform oversight of airport operators and airfield safety. To protect this critical workforce, the FAA took extraordinary steps to ensure the safety of its employees.

The FAA first ensured that only employees whose responsibilities required them to work from the office were required to do so. This policy lowered the population density in FAA buildings to the minimum necessary and protected critical workers.

The FAA proceeded to modify staffing patterns to protect its workforce further and ensure continuity of operations. At larger facilities, the FAA created separate pods of controllers who did not interact with each other; thus, if an individual in one pod contracted COVID-19, other pods would not be affected. If one pod was unable to work due to COVID-19 exposure, another pod could take over its shift.

Finally, the FAA adopted DOT procedures that allowed the FAA to swiftly separate employees exposed to COVID-19 from other employees. In the first month, the agency closed affected facilities for several days while it planned and executed cleaning. The agency worked with its janitorial contractors to enhance routine cleaning protocols and to have hospital-grade services on call to disinfect facilities where employees with presumed or confirmed COVID-19 cases had been present.

Now, cleaning can be completed in a few hours, generally during an overnight shift. During that time, the agency might shift operations to an adjacent facility, a contingency site, or a sterile area of the same building. Additionally, the FAA supplied PPE to all FAA facilities to ensure that the critical work of managing the Nation's air traffic could continue.

Social distancing guidelines forced the FAA to rethink and re-engineer how it conducts some of its work. Many of the FAA's activities, including continuity of aircraft inspections, installation of air traffic control equipment, and public meetings, typically necessitate some degree of face-to-face interaction.

The FAA had to adapt quickly to perform some of these critical activities remotely. Safety personnel deployed high-definition cameras to conduct certain types of inspections of aircraft. Similar techniques aided inspectors in conducting oversight over commercial space launches. For example, FAA inspectors in the United States safely oversaw multiple rocket launches in New Zealand.

Major Accomplishments

Commercial Space

The United States returned to crewed space flights in FY 2020. On May 30, 2020, astronauts Bob Behnken and Doug Hurley launched to the International Space Station aboard the SpaceX Crew Dragon capsule. The event marked the first

time a private company launched astronauts into orbit and the first time in nine years NASA astronauts launched from U.S. soil on a U.S.-built vehicle. Although it did not license this demonstration mission, the FAA worked closely with NASA from the beginning of this effort to ensure that commercial crew providers design, build, and operate their vehicles while focusing on public safety.

Commercial space operations in FY 2020 saw a record-breaking 31 launches and two reentries. To further support commercial space activities, the FAA promulgated a rule to enhance public safety during launch and reentry operations while keeping pace with an increasingly complex and diverse commercial space transportation industry (14 CFR part 450). The new rulemaking arose from a directive of the National Space Council to protect public safety while encouraging American leadership in space commerce. Further, as the FAA implements the new rule it will do so with strong emphasis on environmental and stakeholder engagement priorities.

The rule eliminates obsolete requirements, replaces most prescriptive requirements with performance-based criteria, and reduces duplicative regulations. The rule will also establish a single set of licensing and safety regulations for several types of commercial space operations and vehicles so that one license may support multiple launches and reentries at multiple locations.

Data Communications

The FAA moved forward with the en route high-altitude phase of the Data Communications (Data Comm) program. The FAA controls high-altitude traffic through a network of 21 Air Route Traffic Control Centers (ARTCCs) with Frequency Protected Air-Ground Voice Communications. The joint FAA and industry team overcame many challenges and achieved full operational capability at Kansas City and Indianapolis ARTCCs in November 2019. Following the January 2020 decision to deploy Data Comm at the remaining ARTCCs, training and testing commenced at those facilities. The Washington ARTCC achieved 24/7 operations in March 2020. Unfortunately, the COVID-19 pandemic subsequently caused the FAA to pause all training and testing activities at the remaining facilities. Once facility restrictions are removed, the FAA will complete the ARTCC deployment as efficiently and safely as possible.

A supplement to Frequency Protected Air-Ground Voice Communications, Data Comm enables controllers to digitally text flight clearance and reroute instructions to multiple aircraft at once. Without Data Comm, a controller reads the route of flight to the pilot over a voice radio. Then the pilot is required to read those instructions back to the controller to confirm the pilot fully comprehends those directions, and then the pilot manually enters the clearance. The longer the flight, the more complicated the readback, which increases the possibility of error. With Data Comm, air traffic can issue an entire route of flight with a single data transmission. Data Comm reduces readback errors and the communication time between controllers and pilots, reducing gate delays and taxi-out times and thereby improving the overall efficiency of the system.

Sound frequency engineering protections through Data Comm are useful in flight because they provide a protected digital link between ground automation and flight deck avionics in aircraft cockpits. Using the data link, a controller can open the menu, click on an aircraft, update waypoints, and more. When plans change, pilots can accept route revisions as many times as necessary during flight and on the ground.

Data Comm is deployed at 62 airport towers and has saved more than 2.47 million minutes of radio time between controllers and pilots and more than 1.75 million minutes of airspace-user time. It has reduced carbon dioxide emissions by more than 20.31 million kilograms and prevented more than 134,000 readback errors.

Aircraft manufacturers, various general aviation manufacturers, avionics equipment manufacturers, and more than 100 domestic and international operators participate in Data Comm. To date, 6,000 domestic, international, and general aviation aircraft are equipped to use Data Comm; and pilots, passengers, and the aviation system are reaping the benefits.

Notice to Air Missions (formerly known as Notice to Airmen) Modernization

Notice to Air Missions (NOTAMs) provide pilots, operators, and aircrews with essential information regarding unanticipated or temporary changes to services, components, or hazards in the NAS that could affect a flight from completing as planned. As many pilots will attest, critical safety information provided in

DELIVERING NEXTGEN CAPABILITIES		
	Past Practices	NextGen Capabilities
 Communications	Controllers communicate only by voice to each individual aircraft	In addition to voice communications, controllers communicate via computer (digital messages) to multiple aircraft at a time, which increases efficiency and improves safety by reducing misunderstandings
 Aircraft Routes	Flight paths are limited by reliance on ground-based navigation infrastructure	Aircraft can follow more efficient flight paths that use GPS navigation, reducing delays, fuel burn, and carbon emissions
 Aircraft Spacing	Controllers manage air traffic by maintaining specific distances between aircraft	Controllers can strategically manage the flow of air traffic using the expected position of aircraft throughout intended flight paths, improving the safety and efficiency of the national airspace
 Information	Air traffic controllers and users of the national airspace (such as commercial airlines) do not have access to the same information to inform their decisions	Information (including weather and flight status) is shared between the FAA and the users of the national airspace, allowing collaborative decision-making and improving the efficiency and predictability of the flow of air traffic



NOTAMs can be challenging to understand because the notices appear in all capital letters, using abbreviations, keywords, and shorthand. In recent years, Federal legislation has mandated the FAA update its NOTAM system. Specifically, the 2012 “Pilot’s Bill of Rights” (PL 112-153), as amended by the FAA Reauthorization Act of 2018 (PL 115-254), requires the FAA modernize its NOTAM system by creating a sole repository in a “public central location to maintain and archive all NOTAMs...in a manner that is Internet-accessible, machine-readable, and searchable.” Pub. L. 115-254 § 394(b). The legislation also requires the FAA “to apply filters so that pilots can prioritize critical flight safety information.” Pub. L. 112-153 § 3(a)(2).

In response to these safety concerns and legislative mandates, the FAA embarked upon the NOTAM Modernization initiative in 2019 to create a single system for entering, processing, and retrieving all NOTAM data, and improving

access to and use of safety-critical information for pilots and other users of the NAS. The NOTAM Modernization will implement internationally recognized standards for formatting NOTAMs. This will make NOTAMs easier to understand and will improve the ability to sort, filter, and prioritize NOTAMs. The initiative will also overhaul the system's hardware and software to improve the reliability and performance of this safety-critical service.

To date, the NOTAM Modernization initiative has resulted in several improvements to NOTAMs, including

- aligning the NOTAM governance and operations offices with Aeronautical Information Services to create a single authority for all aeronautical information with the power to standardize and ensure compliance with FAA Orders and International Civil Aviation Organization (ICAO) requirements;
- retiring redundant and outdated sources of NOTAM information, including the Pilotweb website and the Notice to Air Mission Publication (NTAP), thereby reducing the number of places pilots need to check for NOTAMs;
- implementing a cloud-based data connection to the NOTAM system that makes it easier to connect to NOTAM data via the FAA's System Wide Information Management infrastructure; and
- charting and canceling more than 400 permanent (PERM) NOTAMs, removing them from the NOTAM system and reducing the number of NOTAMs pilots need to read during a pre-flight briefing.

In addition, NOTAM Modernization has made improvements to related aeronautical information, including synchronizing route data (particularly preferred routes and coded departure routes) across various FAA systems and removing redundant or outdated NOTAM-related information in the Chart Supplements.

Automatic Dependent Surveillance-Broadcast Equipage

As the FAA successfully continues to deploy major Next Generation Air Transportation System (NextGen) programs, it is shifting its focus to operationalizing the benefits of these programs for the flying public. For example, Automatic

Dependent Surveillance-Broadcast (ADS-B), which uses GPS technology to determine the precise location of aircraft, not only helps meet new needs expected with the predicted increase in air traffic in the coming years, but also creates the opportunity for future operational benefits.

Compared to radar, ADS-B provides more accurate aircraft monitoring and expanded coverage of the skies. ADS-B enables controllers to allow aircraft to fly closer together safely, thereby increasing the capacity of the NAS when high demand exists. However, this is possible only if aircraft utilizing specific airspace within the NAS are equipped with ADS-B. As of January 1, 2020, aircraft flying in most controlled airspace must be equipped with ADS-B Out unless otherwise authorized by air traffic control.

All U.S. air carrier fleets use aircraft that are now equipped with ADS-B Out. General aviation operators that need regular access to controlled airspace also are largely equipped with ADS-B-Out, and aircraft needing only occasional access are continuing to become equipped. To promote ADS-B equipage, the FAA continues to work with the aviation community to establish action plans, as needed, to resolve any remaining equipage challenges.

Shortly after the ADS-B equipage rule took effect on January 1, 2020, the FAA started using ADS-B to reduce separation standards from five nautical miles to three nautical miles in en route airspace below 23,000 feet at Washington and Boston ARTCCs.

Unmanned Aircraft Systems Integration

FAA regulations provide for safe crewed and uncrewed aircraft operations. Current regulations for small Unmanned Aircraft Systems (UAS), or drones, permit certain routine civil operations the FAA considers to be low risk. Operators seeking to conduct other operations, such as flying beyond a pilot's visual line of sight, must obtain a waiver from the applicability of certain regulations. Prior to beginning operations, UAS operators seeking to operate UAS in controlled airspace must request an authorization from the FAA. These requests are equivalent to operators filing flight plans for crewed aircraft prior to taking off. The requests

allow the FAA to ensure the airspace is available and safe for the operator to use. Certain operations may require both a waiver and an authorization.

The FAA worked with nine state, local, and Tribal governments through the UAS Integration Pilot Program (IPP). These organizations, known as Lead Participants, partnered with private industry to explore the further safe integration of drone operations into the NAS. Over the program's duration, which began in 2018 and continued through FY 2020, the FAA enabled multiple novel operations within current regulations by issuing grants of exemption, operational waivers, and airspace authorizations.

The IPP generated opportunities for a variety of novel operations to occur. For example, UPS Flight Forward and Wing Aviation (an air delivery service subsidiary of Alphabet) earned the distinction of becoming the United States' first FAA-certified air carriers authorized to conduct UAS package deliveries. In addition, part of the North Carolina Department of Transportation IPP team, UPS Flight Forward; and Matternet, a drone manufacturer, conducted routine medical package delivery with UAS over the WakeMed medical campus in Raleigh, North Carolina. This dramatically reduced delivery times for medical samples.

The insurance company State Farm, a member of the Virginia IPP team, operated UAS over people and beyond visual line of sight of the pilot leveraging visual observers to conduct damage assessments following natural disasters. Conducting such operations with UAS increased the area that the operator can quickly survey and reduces the cost to do so. These successful operations led to a nationwide waiver that also covers pre-damage assessments.

The Choctaw Nation of Oklahoma gained a direct economic benefit by using UAS to inspect pecan trees. These inspections allowed the Choctaw Nation to determine that seemingly diseased trees had healthy crops in their upper levels. This improved the crop yield for those trees by 200 percent.

The Chula Vista Police Department, which is part of the San Diego IPP team, uses drones successfully to enhance the safety of its police officers and the overall community by giving first responders an early assessment when they respond to 911 calls. For the first 1,000 missions, this system reduced average on-scene response time from 6 minutes to 2.2 minutes for priority calls.

At the Memphis Airport, FedEx enhanced the efficiency and safety of its aircraft inspection process by replacing manual visual inspection by maintenance technicians with UAS inspection. Using drones reduced aircraft inspection times from three hours to 20 minutes and improved employee safety and data collection.

By the fall of 2020, the Lead Participants had conducted approximately 21,000 flight operations and tests for mission types that included medical and other package delivery, infrastructure inspections, crowd surveillance, newsgathering, post-hurricane damage assessments, and law enforcement response. These partnerships and novel operations help advance policy development and enable more complex routine drone operations.

In addition to the success under the IPP, the FAA performed research on applications that would be beneficial to an airport operator. There are several objectives for this research, which include determining benefits and limitations, minimum performance specifications, and standards for using UAS in each application. In FY 2020, the FAA completed UAS obstruction analysis testing at McCormick County Airport, South Carolina, to understand the benefits and limitations of using UAS to conduct obstruction surveys. The FAA also completed initial UAS perimeter security testing at Cape May County Airport, New Jersey, to look at perimeter surveillance applications using UAS. The results from this research will allow the FAA to develop necessary guidance for airport operators on how to safely and effectively use UAS for airport applications.

Airport Safety and Infrastructure Investment

In June 2015, the FAA unveiled the national Runway Incursion Mitigation (RIM) program to identify and mitigate risk factors that might contribute to runway incursions at specific airports. Runway incursions occur when an aircraft, vehicle, or person enters the protected area of an airport designated for aircraft landings and takeoffs. Risk factors contributing to runway incursions include unclear taxiway markings, airport signage, and more complex issues, such as the runway or taxiway layout.

Through collection and review of data, RIM identifies specific airport areas with risk factors that could contribute to a runway incursion. The program has an

inventory of these airport locations where runway incursions occurred frequently and worked with the airport sponsors to develop mitigation strategies.

As of September 2020, the RIM program decreased runway incursions by 77 percent in total at 58 locations that previously had 674 runway incursions.

More broadly, the Airport Improvement Program (AIP) provides grants for infrastructure investments at airports across the country and mitigates safety risks at RIM locations. In FY 2020, the FAA issued 1,866 AIP and Supplemental Discretionary Program grants, totaling \$4.3 billion, to 1,508 airports. These grants fund infrastructure projects to meet the needs of airports in support of safety, capacity, standards, planning, and environmental mitigation.

The FAA William J. Hughes Technical Center

The William J. Hughes Technical Center in Atlantic City, New Jersey, is the Nation's premier air transportation system laboratory. Its professional and diverse 4,500-person-strong workforce and vast array of world-class laboratories provide a state-of-the-art environment that enables research, engineering, development, testing, and evaluation of advanced aviation technologies. These combined assets deliver NextGen operational capabilities that modernize the NAS. The Technical Center provided quality test and evaluation services across 75 acquisition programs and delivered more than 130 test products in FY 2020.

In response to the COVID-19 pandemic, the Technical Center's resident Second-Level Engineering groups worked together to issue guidance for disinfecting NAS equipment and a temporary safe reduction of periodic maintenance tasks to help foster social distancing at NAS facilities. The groups also provided guidance for continued testing of critical NAS modifications while maintaining a safe, socially distanced environment at Technical Center lab facilities. The following focus areas are key to attaining the Technical Center's goals: advancing aviation technology, cultivating a qualified aviation workforce of the future, capitalizing on partnerships and outreach with other government agencies and private parties involved with aviation, and advancing core work that supports the three aforementioned focus areas.

To improve air traffic operations and increase the overall predictability of traffic, the Technical Center continues to support the development of Trajectory Based

Operations (TBO). TBO is an air traffic management concept that enhances strategic planning of aircraft flows to reduce capacity-to-demand imbalances in the NAS and provides tools to air traffic management personnel and controllers to help expedite aircraft movement between origin and destination airports.

Through improved strategic planning and management of traffic flows, TBO helps reduce reactive decision making and use of static miles-in-trail restrictions. In support of this important initiative, the Technical Center established a TBO Integrated Test Environment (TITE) that combines resources and tools at the Technical Center with partner agency capabilities. The TITE includes multiple hardware and software systems, prototypes, and network topologies (arrangement of elements in a communications network) that will enable the FAA to test, evaluate, and develop TBO.

In support of other research and development efforts to advance aviation technology, the Technical Center staff continued testing of alternative non-fluorinated fire-fighting foam products in the Aircraft Rescue and Firefighting Test Facility. This research responds to high-priority congressional direction to identify and enable replacements for Aqueous Film Forming Foam (AFFF) products presently in use in aircraft rescue and firefighting. Since January 2020, the facility has worked with the Department of the Navy, and the Department of Defense at large, to develop a Military Specification for PFAS-free AFFF products.

The National Airport Pavement test facility also conducted testing of emerging and sustainable pavement technologies. This research is focused on improving current processes using recycled aggregate as well as new materials including warm-mix asphalt and low-carbon concrete in an effort to reduce the amount of embodied carbon during the lifecycle of airport pavements.

The Technical Center established a new Cooperative Research and Development Agreement with Seattle-based magniX, a creator of electric propulsion systems for aviation, to advance the understanding of safety risks and hazards associated with electric-powered aircraft. This agreement enables a key partnership for government-industry collaboration to advance understanding, maturation, and adoption of a new aircraft propulsion technology with reduced potential for polluting.

In addition, the Technical Center, along with the Departments of Defense (DOD) and Homeland Security (DHS), conducted a series of aviation cyber risk

reduction flight tests with military and FAA aircraft. This was a joint interagency effort to mitigate data confidentiality, integrity, and availability vulnerabilities that puts at risk operational safety, security, and mission success on the ground and in the air to help inform policy, rulemaking, training, and regulations and allow for the appropriate use of tactics, techniques, and procedures in the aviation ecosystem.

Finally, Technical Center operations significantly enhanced the FAA's environmental performance by implementing innovative Thermal Conducting Heating (TCH) technology to accelerate remediation of spilled jet fuel contamination of groundwater. The TCH technology works by heating large areas of soil to 100 degrees Celsius, thus boiling away hazardous chemicals contaminating the ground water. The hazardous vapors created from the heating are captured and burned to eliminate any hazardous chemicals or further releases to the environment. The 15-year reduction in cleanup costs presents the agency with a cost avoidance of more than \$10 million.

The Technical Center's research, engineering, development, test, and evaluation capabilities remain essential to the continued advancement of technologies that improve aviation, the environment, and our lives.

Mike Monroney Aeronautical Center

The Mike Monroney Aeronautical Center (MMAC) in Oklahoma City, Oklahoma, is home to more than 6,000 FAA employees and contractors, performing mission-critical activities to support a diverse customer base, including more than 35 Federal agencies in addition to the FAA. The MMAC delivers unique functions, including technical training; centralized supply chain management and field site services, such as maintenance, repair, overhaul, and distribution; financial management shared services and information technology support across government; aviation medical and human factors research; and registration of the Nation's civil aircraft and certification of airmen.

In 2020, MMAC staff successfully met the unprecedented challenge of continuation of services while working primarily remotely. In response to the COVID-19 pandemic, 75 percent of the MMAC's employees and contractors quickly transitioned to full-time telework. Other notable FY 2020 accomplishments include

the achievement of \$51 million in cost savings and avoidance by implementing streamlined processes and renegotiating contracts, process automation, utilities management, and workforce management improvements. As part of its ISO-9001 re-certification audit, MMAC also achieved level 5 (maturity level) for management control—level 5 is considered best-in-class across industry.

MMAC Facility Management provides facility-related services and maintenance for MMAC's 137 buildings and 3.4 million square feet of industrial, administrative, and laboratory space. In FY 2020, this organization oversaw the MMAC COVID-19 response team, enabling 2,000 employees to safely continue working on-site; achieved \$590,000 cost avoidance in energy costs; and completed 119 construction projects, valued at \$11.5 million, across the MMAC campus.

The FAA Academy develops and delivers technical training that enables the FAA workforce to maintain and safely operate the NAS. In FY 2020, the FAA Academy recorded more than 50,000 participant course completions, successfully transitioned numerous courses to a variety of virtual learning platforms, and virtually trained more than 3,500 participants.

The Logistics Center is the FAA's centralized maintenance, repair, and overhaul provider for the NAS. In FY 2020, the Logistics Center completed more than 1,630 on-site restorations to ensure continued operations of the airspace system; tested and repaired more than 36,000 critical NAS parts; distributed more than 610,000 parts across the NAS; and sourced, purchased, and distributed 1.7 million items of COVID-19 critical PPE and sanitation supplies worth \$12.3 million.

The Enterprise Services Center delivers financial and technology services to 35 Federal agencies, processing millions of financial transactions. The organization's FY 2020 accomplishments include continued reduction in aggregate costs, reducing pricing to below FY 2017 levels, thereby creating more value for its customers and providing \$3.7 million in rebates to customers over the past two years; saving more than \$2.4 million through centralized management of FAA cellular services and equipment; collaborating with the Technical Center to increase remote access capability from 12,500 to 36,000 users; processing more than \$56.6 billion in grant payments for DOD, with 100 percent paid on time; processing 101,779 travel vouchers across DOT with more than 95 percent on time; and processing 351,925 cash receipts and 42,608 accounts receivable invoices across DOT.

The FAA Civil Aerospace Medical Institute (CAMI) located at the MMAC is the medical certification, medical/human factors research, education, and occupational medicine wing of the Office of Aerospace Medicine which is an integral part of the FAA Aviation Safety (AVS) organization. Its mission is to assure civil aerospace safety through excellence in medical certification, research, and educational programs. CAMI is one of the premier civil aerospace medical organizations in the world. CAMI's programs focus on the safety of pilots, flight attendants, air traffic controllers, passengers, and the entire human support system that embraces civil aerospace transportation. CAMI's certification, research, and education programs help to prevent accidents from human causes, make cabins safer for passengers, and prepare pilots and flight attendants for post-accident survival. CAMI supports national and international programs to promote interaction between aerospace medicine professionals while enabling the exchange of scientific information and promoting the FAA's leading role in civil aerospace medicine worldwide. CAMI personnel are pioneering new technologies and scientific developments that will lead to new global safety standards as innovations are translated into aerospace operations.

Environment and Energy Research and Development

The FAA's Office of Environment and Energy continued its work to understand, manage, and reduce the environmental impacts of aviation through research, technological innovation, policy, and outreach to benefit the public. These efforts contribute to the overarching vision to minimize the environmental impact on aviation growth by achieving quiet, clean, and efficient air transportation. The ability to manage this growth partly depends on the extent to which the effects of noise and emissions are addressed. These efforts are contributing to the United States Aviation Climate Action Plan,³ which describes a whole-of-government approach to put the sector on a path toward achieving net-zero emissions by 2050. Further, FAA, alongside our colleagues at the Office of the Secretary of Transportation, are working with others across the Government under the SAF Grand Challenge

3 <https://www.faa.gov/sustainability/aviation-climate-action-plan>

to develop a comprehensive strategy for scaling up sustainable aviation fuels (SAF) production.⁴

To support its work, the Office of Environment and Energy maintains a robust research and development program to address issues that focus on reducing the impacts of noise and emissions. This research program supports several well-known initiatives at the forefront of efforts to reduce the environmental impacts of aviation:

- The FAA and industry work together through the **Continuous Lower Energy Emissions and Noise (CLEEN) program** to develop technologies that enable manufacturers to create aircraft and engines with lower noise and emissions and improved fuel efficiency.⁵
- **The Aviation Sustainability Center (ASCENT)**, also known as the FAA Center of Excellence for Alternative Jet Fuels and Environment, is where the FAA works with leading universities to improve our understanding of the impacts of noise and emissions on the public and use that knowledge to develop innovative solutions to reduce those impacts. ASCENT is also at the forefront of efforts to develop sustainable aviation fuels.⁶
- **The Commercial Aviation Alternative Fuels Initiative (CAAFI)**, enables the FAA to engage with the commercial aviation and emerging alternative fuels industries to advance the development and deployment of sustainable aviation fuels.⁷

The Office of Environment and Energy and our research partners had several recent notable successes:

- The Office advanced the FAA's understanding of the noise and emissions produced by supersonic aircraft and UAS, as well as means to reduce these impacts through aircraft design and operational procedures. This improved knowledge is enabling the development of regulations to facilitate the introduction of these new entrants into the NAS.

4 <https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge>

5 <http://www.faa.gov/go/cleen>

6 <https://ascent.aero>

7 <http://caafi.org>

- Through the CLEEN Program, Boeing was able to demonstrate structurally efficient wing technologies and General Electric advanced an integrated aircraft power system designed to support future “more-electric” aircraft architectures. These technologies improve fuel efficiency and complement other CLEEN technologies that are reducing noise and emissions.
- The Office also facilitated the public release of the Aviation Environmental Design Tool (AEDT) version 3b software, which includes improved aircraft performance and takeoff modeling capabilities. This new model allows users across the globe to assess accurately the impacts of advanced aircraft operations, such as those being developed as part of NextGen.⁸
- ASTM International approved the D4054 Fast Track Annex for alternative jet fuels. This new Annex expedites the approval of new sustainable aviation fuels that have reduced environmental impacts, and reduced costs and are drop-in compatible with the current fleet of aircraft.
- ASCENT researchers continued to expand and foster the development of knowledge and understanding in a wide range of fields and have documented their work in more than 100 publications and conference presentations.⁹

The FAA conducts these activities in close cooperation with other U.S. Federal agencies, including NASA; the Departments of Defense, Energy, and Agriculture; and international partners, such as Transport Canada. They are also being used extensively to support U.S. decision making in domestic and international venues, such as the ICAO Committee on Aviation Environmental Protection, for the development of airworthiness standards for aircraft noise and emissions.

⁸ <https://aedt.faa.gov/>

⁹ Information on the research results from ASCENT is available at <https://ascent.aero/general-public-resources/>.

DEPARTMENT OF COMMERCE

DOC

During FY 2020, the Department of Commerce (DOC) continued to prioritize Strategic Objective 1.1, “Expand Commercial Space Activities.” In furtherance of the objective, the Department continued to revitalize the Office of Space Commerce (OSC), participated in the National Space Council to advance American leadership in commercial space activities, supported innovative American space companies to transform traditional space markets and create new ones, developed new capabilities to provide space situational awareness data and services to the public, drove and implemented regulatory change, promoted space weather and Earth weather innovation, and deepened understanding of global space economy trends.

National Oceanic and Atmospheric Administration

In FY 2020, NOAA’s satellites remained as critical as ever, monitoring the wildland fires in the western United States (witnessing the most burned acres on record); hurricanes in the Gulf of Mexico and the Atlantic and Pacific oceans (2020 being the most active Atlantic season on record); flooding for Federal, state, and local governments; and the second hottest year on record. Twenty-four-hour global coverage from NOAA’s satellites provides the public and partners, such as the National Weather Service, with a continuous stream of information used to prepare for events impacting our weather, oceans, and climate. NOAA manages and operates geostationary environmental satellites and low-Earth orbiting satellites, as well as a deep space satellite for space weather monitoring and forecasting.



In FY 2020, NOAA involved the National Weather Service's Space Weather Prediction Center to help DOC address Space Policy Directive-3. Given the exponential growth of the commercial satellite industry and accelerated pace of innovation of these companies, satellite companies are assuming more risk and in turn, becoming more vulnerable to minor space weather events.

In FY 2020, NOAA advanced its efforts to partner with commercial space firms on weather innovation. NOAA released its assessment of the Commercial Weather Data Pilot Round 2 and issued a solicitation in support of its first commercial radio occultation satellite data buy purchase in support of operational weather forecasting. NOAA made contract awards to engage the commercial sector in producing new concepts for NOAA's future space-based observation architecture and solicited ideas for future commercial data pilots. NOAA also participated in a new Working Group for Interagency Coordination of Commercial Weather Data to pursue common approaches across the government to purchasing space-based commercial weather data.

Below is a summary of major accomplishments regarding new NOAA and partner satellite assets in FY 2020.

Geostationary Satellites

NOAA's newest Geostationary Operational Environmental Satellites, known as the GOES-R Series, are providing advanced imagery and atmospheric measurements of Earth's Western Hemisphere, real-time mapping of lightning activity, and improved monitoring of solar activity and space weather. 2020 was the first full year to see the new GOES-R capabilities deployed in both the GOES-East and West locations. Together, these two satellites provide continuous, real-time observation of hurricanes, thunderstorms, snow, ice, fog, damaging winds, fire, and other severe weather conditions across the Americas and Atlantic and Pacific Oceans.

The GOES satellites provided imagery and critical information about the record-setting 30 Atlantic basin tropical storms observed in 2020, including the 12 storms that struck the United States. They also supported emergency responders controlling extreme wildfires in the western states and farmers dealing with \$7 billion of

damage from a derecho wind storm. The GOES space weather instruments helped to confirm the start of a new solar cycle and monitored intensifying solar activity.

NOAA initiated planning for the Geostationary Extended Observations (GeoXO) satellites, the next-generation program to follow GOES-R. The program team conducted multiple workshops and surveys to gather user needs, performed industry and internal studies to assess satellite and instrument concepts, and finalized the recommended observations and satellite constellation. GeoXO is planning its first launch in 2032 to maintain the continuity of geostationary imagery and data.

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

- GOES West (GOES-S/GOES-17), March 1, 2018
- GOES East (GOES-R/GOES-16), November 19, 2016
- GOES-15 (on-orbit backup), March 4, 2010
- GOES-14 (on-orbit backup), June 27, 2009

Low-Earth Orbiting Satellites

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

These satellites also play a fundamental role in response and planning for extreme weather. Their sounding instruments (the Advanced Technology Microwave Sounder and the Cross-track Infrared Sounder) were crucial in providing data on the path, intensity, and structure of hurricanes during one of the most intense hurricane seasons in history. And in a record-setting wildfire season in the western United States, JPSS Active Fire products and Day/Night band imagery from the Visible Infrared Imaging Radiometer Suite (VIIRS) were important tools for emergency responders, providing a reliable source of data over a wide range to help direct resources and response teams when needed.

Meanwhile, the High Resolution Rapid Refresh (HRRR) Smoke Model remains invaluable in tracking smoke from fires often thousands of miles away. Now operational at NOAA's National Centers for Environmental Prediction (NCEP) as of December 2, 2020, HRRR-Smoke simulates the behavior of wildfire smoke, predicting the amount of smoke produced, the direction it will travel and its plume height. This can provide important information on harmful particulates for air quality managers as well as flight visibility for aviation forecasters and flight operators.

VIIRS flood detection continues to play a significant role in providing flood extent information. In 2020, this included monitoring the spring ice break-up in Alaska and Canada, where restrictions caused impacts on traditional river ice monitoring programs. In addition, because floods are common and widespread throughout the world, knowledge of the extent of the flood can play a role in knowing which population areas are most vulnerable, especially with the added complication of the pandemic changing previous evacuation plans. Flood products, long proven valuable to the National Weather Service, are also helping internationally, providing an important tool for natural disaster response.

The Vegetation Health Index (VHI) model used NOAA-20 data to show crop health around the globe. In 2020, the U.S. Department of Agriculture relied on this data to develop estimates of crop production in more than 120 growing regions in 35 countries. These estimates informed decisions about planting, food prices, and foreign market exports, all of which play an important role in food security. The VHI model also informed the U.S. Drought Monitor map.

In 2020, when other methods of data collection may have been affected or limited by COVID-19 restrictions, the combination of the Suomi NPP and NOAA-20 satellites flying 50 minutes apart provided a steady stream of critical data and products to users. The Ozone Mapping Profiler Suite (OMPS) and VIIRS instruments were able to remotely measure reductions in nitrogen oxide as automobile use declined and have shown reduced activity in the changed density of nighttime lights. In short, the JPSS satellites allowed for lower latency data and increased global coverage for numerical weather models, forecast applications, and emergency response.

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) follow-on COSMIC-2/FORMOSAT-7 constellation provides precision

radio occultation soundings to support improved numerical weather prediction model forecasts. The program is being conducted under an agreement between the American Institute in Taiwan (AIT) and the Taipei Economic and Cultural Representative Office (TECRO) in the United States, for which NOAA is AIT's designated representative, and the Taiwan National Space Organization is TECRO's designated representative. The mission consists of six satellites designed to improve weather forecasts and space weather monitoring via state-of-the-art instruments that provide improved precision and performance, as well as five times the number of measurement capabilities, with near-real-time numerical weather prediction. By measuring the bending due to refraction of Global Navigation Satellite System (GNSS) signals through Earth's atmosphere, the COSMIC-2 satellites provide meteorologists with information such as temperature, pressure, density, and water vapor, which will help meteorologists better observe, study, and forecast severe storms. Temperature measurements derived from radio occultation are very accurate and are well-suited to help scientists understand long-term climate changes. Additionally, the COSMIC-2 GNSS receivers are sensitive to space weather effects on the ionosphere that can cause regional and local disruption of radio communications and affect accuracy of GNSS readings.

Since the launch of the six COSMIC-2/FORMOSAT-7 satellites on June 25, 2019, the joint program has commissioned the satellites and transitioned them incrementally to their operational orbital positions over the course of 19 months. The program has been calibrating and validating the data. The neutral atmosphere data have been in use operationally by the U.S. National Weather Service, the Taiwan Central Weather Bureau, and global weather forecast centers since the spring of 2020. COSMIC-2/FORMOSAT-7 data proved to be a valuable new data resource during the active Atlantic hurricane season in 2020. As the calibration and validation of the space weather data products have progressed, the products have been released incrementally.

The Argos Advanced Data Collection System (A-DCS) is a data collection and relay program that provides global coverage and platform location services dedicated to studying and protecting the environment. The Argos system supports a wide variety of applications, including environmental monitoring, marine fisheries applications, and maritime security applications. The Argos system consists of DCS

instruments that are hosted on polar-orbiting satellites operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the Indian Space Research Organisation, and NOAA in three Sun-synchronous orbits that ensure timely reporting at all latitudes. The current DCS instruments on the NOAA polar-orbiting satellites (NOAA-15, -18, -19) are operating well beyond their design life. To provide continuity of service, NOAA, under an international agreement with the French space agency CNES, is providing accommodation for the next Argos DCS payload (Argos-4) on a commercial spacecraft using a U.S. Space Force Hosted Payload Solutions contract. In 2018, a delivery order was awarded to General Atomics to integrate and launch the Argos-4 payload on the Orbital Test Bed-3 spacecraft by October 10, 2022. In 2020, General Atomics completed the host spacecraft Critical Design Review, and received the Argos-4 instrument from CNES for integration into the spacecraft during 2021.

Metop is a series of three polar-orbiting meteorological satellites that form the space segment component of the overall EUMETSAT Polar System. The Metop series satellites are part of a joint commitment between NOAA and EUMETSAT to fly complementary polar-orbiting satellites. EUMETSAT covers the morning orbit and NOAA covers the afternoon orbit. The third in the Metop series, Metop-C, which launched on November 7, 2018, is a new polar-orbiting satellite that helps improve complex weather forecasts and models as well as long-term climate assessments. This satellite works together with its predecessors (Metop-A and -B), as well as Suomi-NPP, NOAA-20, and NOAA legacy satellites, to collect more precise weather data as we continue to improve forecast errors from combined satellite observations incorporated into models. NOAA supplied four of the 13 instruments onboard the satellite, including two microwave sensors that measure global atmospheric temperature, humidity, and sea ice, as well as a visible/infrared radiometer that delivers imagery of clouds, oceans, ice, and land surfaces. The last instrument is the Space Environment Monitor (SEM), which monitors space plasma and radiation around the spacecraft. Additionally, the satellite's instruments provide new and improved observations to the National Weather Service on atmospheric aerosols, soil moisture, greenhouse gases such as carbon dioxide and methane, and radio occultation soundings that deliver enhanced vertical temperature and humidity profiles of the atmosphere. The launch was a collaborative

effort between NOAA, NASA, and international partners at EUMETSAT and the European Space Agency.

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

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

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

- Jason-CS/Sentinel 6, November 21, 2020
- COSMIC-2, June 25, 2019
- Metop-C, November 6, 2018
- Jason-3, January 17, 2016
- Metop-B, September 19, 2012
- Metop-A, October 19, 2006

Deep Space (Lagrange Point–1) Satellites

Geomagnetic storms are major disturbances of Earth's magnetosphere caused by shock waves in the solar wind. Geomagnetic storms are the costliest type of space weather events as they can cause widespread damage to power grids, satellites, and communication and navigation systems. The Deep Space Climate Observatory mission is NOAA's first operational deep space mission. The satellite has become America's primary warning system for solar magnetic storms and solar wind data while giving Earth scientists a unique vantage point for studies of the planet's atmosphere and climate.

As part of NOAA's Space Weather Follow On (SWFO) Program, NOAA is partnering with the Naval Research Laboratory (NRL) to build two Compact Coronagraph (CCOR) instruments for future space weather observations. In FY 2019, NRL's CCOR completed its Critical Design Review, which affirmed that the design meets requirements and is ready to proceed with full-scale fabrication,

assembly, integration, and testing. In FY 2020, NOAA continued assembly of the first CCOR (CCOR-1) and initiated work on a second (CCOR-2). The first CCOR will be integrated onto the GOES-U spacecraft, which is planned for launch in 2024. NOAA is developing the SWFO-L1 mission, which will include CCOR-2 and a suite of in situ instrumentation to monitor the solar wind. SWFO-L1 will launch as a rideshare with NASA's Interstellar Mapping and Acceleration Probe for positioning at the Lagrange-1 point.

In FY 2020, NOAA, using NASA as its acquisition agent, put all the SWFO L-1 instruments and spacecraft bus on contract. In FY 2021, NOAA put the Command and Control element of the ground segment on contract and continued to work to place the SWFO Antenna Network on contract in FY 2021.

Office of Space Commerce

The Office of Space Commerce (OSC) led a Department-wide campaign to advance space industry engagement and advocacy, regulatory streamlining, and policy development and implementation. The Office's staffing expanded via cross-bureau assignments and contractor hires. The Secretary of Commerce testified before Congress and supported legislative proposals in support of the expansion and elevation of the Office of Space Commerce. The Department sponsored a congressionally mandated, independent study by the National Academy of Public Administration that reaffirmed the Office of Space Commerce as the best-suited agency to provide space situational awareness support to commercial and civil space operations.

The Department made significant strides in preparation for its future role providing space situational awareness (SSA) to commercial operators as directed by Space Policy Directive-3. In addition to the efforts mentioned above, the Department established the first instantiation of its cloud-based platform to disseminate public SSA data; maintained a continuous DOC presence in the Department of Defense's (DOD's) existing SSA operations center; promoted rules and standards for space safety and signed a declaration of intent to cooperate with the French space agency Centre national d'études spatiales (CNES) on SSA matters; and engaged industry in continuous dialogue about these efforts.

The Secretary of Commerce participated in the May 2020 meeting of the National Space Council, where he announced the publication of new remote sensing licensing rules. The Office of Space Commerce prepared responses to three National Space Council tasks to the Secretary, supported the Deputy Secretary in National Space Council decision processes, and represented DOC at other White House deliberations on space issues, including involvement in several White House interagency working groups. Such deliberations led to the release of Presidential Executive Orders on “Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services” and “Encouraging International Support for the Recovery and Use of Space Resources,” Space Policy Directive-5 (“Cybersecurity Principles for Space Systems”), a strategy paper on Moon/Mars development, the Artemis Accords for lunar cooperation, and other documents. The Department also participated in international engagements led by the National Space Council, including the U.S.-Japan Comprehensive Dialogue on Space.

DOC engaged in continuous dialogue with U.S. space companies to understand and support their business needs. The Secretary hosted an event on American space startups and how the government can leverage their innovation. The Secretary visited and participated in ribbon-cutting ceremonies for innovative space companies. The International Trade Administration’s SelectUSA program successfully attracted foreign space firms to open facilities in the United States. The Economic Development Administration issued a matching grant for development of a space innovation hub in Maine. The U.S. Patent and Trademark Office (USPTO) supported intellectual property protection that supported innovation and drove technological progress to help transform traditional space markets and create new markets. DOC made plans to host the second annual Space Enterprise Summit at USPTO, but the event was postponed to 2021 due to the pandemic.

Through NOAA, DOC published its final rule streamlining the licensing of commercial remote sensing satellite systems, significantly improving U.S. industry competitiveness and fulfilling the President’s direction under Space Policy Directive-2. Through the Bureau of Industry and Security and the Office of Space Commerce, DOC continued efforts to protect the transfer of sensitive technologies while streamlining export control regulations to ensure they do not unnecessarily

hamper international business. Through the National Telecommunications and Information Administration, DOC took actions to oppose and seek a stay on the Federal Communications Commission's (FCC's) order authorizing terrestrial wireless operations that would cause harmful interference to GPS users. DOC participated in the U.S. coordination with other nations and the United Nations to promote common approaches to the authorization and supervision of private activities in space.

The Commerce Department's Bureau of Economic Analysis released preliminary statistics at the end of 2020 that measured the contributions of space-related industries to the overall U.S. economy after gathering feedback from space stakeholders in industry and academia.

During FY 2020, the Department continued to participate in the national management of the GPS as a member of the National Executive Committee for Space-Based Positioning, Navigation, and Timing. The Office of Space Commerce continued to host the physical offices of the Committee as well as the <http://www.gps.gov> website, which remained the leading source of online information about GPS.

Space Weather Prediction Center

NOAA's Space Weather Prediction Center (SWPC), located in Boulder, CO, provides 24/7 impact-based decision support services through timely and accurate operational space weather forecasts, watches, warnings, alerts, and real-time space weather monitoring for the Federal government, civilian, and commercial sectors, exclusive of the responsibilities of the Secretary of Defense. SWPC ensures continuous improvement of operational space weather services, utilizing partnerships, as appropriate, with the research community, including academia and the private sector, and relevant agencies to develop, validate, test, and transition new technologies, observation platforms, and models from research-to-operations and from operations-to-research. SWPC provides the research community with operational needs, including information on model and tool performance, observation gaps, and other areas for improvement.

In FY 2020, the National Weather Service headquarters and SWPC worked with the OSC to include space weather in OSC's efforts to track satellites and debris in space and provide conjunction forecasts for space operators as directed by Space Policy Directive-3. Space weather data was also the first dataset included in the Open Architecture Data Repository (OADR) prototype for commercial space situational awareness. Through National Weather Service headquarters, OSC also facilitated a Cooperative Research and Development Agreement between SWPC and the University of Texas to advance space traffic coordination and collision avoidance support services.

National Institute of Standards and Technology

In FY 2020, the National Institute of Standards and Technology (NIST) continued to provide wide-ranging contributions to the aerospace industry, academia, and Federal agencies with the research, standards, products, services, and guidance needed to advance the President's aeronautics and space agenda.

NIST's primary contributions were calibrations, technology development, and standards development, which are expanded upon below.

Advanced Manufacturing for Aerospace Applications

In FY 2020, NIST used measurement expertise in mass, force, networking, and other areas to partner with multiple industrial aerospace corporations. In addition to providing calibration support, NIST's broad portfolio in advanced manufacturing helped aerospace manufacturing companies address needs in many sectors, including additive manufacturing, collaborative robotics, smart manufacturing, cybersecurity in manufacturing environments, supply-chain logistics, and large-scale manufacturing.

A project is currently under way for NIST to deliver measurement science that will establish the foundation for qualification of machines, processes, and parts used in advanced manufacturing (AM) at reduced cost. Machines and processes used to produce critical components for defense, aerospace, and medical applications must first be formally qualified to demonstrate that a machine or process

will function as expected. Currently no AM machines or processes are qualified for critical defense or aerospace applications. NIST's excellence in measurement science and its standing as a neutral third party with a broad public forum make it the ideal place to develop test methods and protocols, provide reference data, and establish minimum requirements needed to achieve lower costs and more rapid qualification.

NIST contributed to workshops with the FAA, DOD, NASA, and aerospace industry representatives to identify approaches for qualification and certification of additive manufacturing materials, processes, and parts for use in load-bearing and mission-critical applications.

NIST research addressed safety standards for robotic manipulators and automated guided vehicles (i.e., mobile platforms) and measurement science to enable new capabilities for collaborative robotics of interest to aerospace manufacturers.

NIST has an ongoing engagement with aerospace companies to identify technical issues and to define requirements for industrial wireless networking, cybersecurity in manufacturing environments, and prognostics and health management for manufacturing systems. As one example, NIST and the Boeing Company collaborate on standards development for prognostics and health management (PHM) through the ASME PHM Subcommittee.

Much of NIST's support for the aerospace supply chain came with interactions through the suppliers themselves. In FY 2020, the Hollings Manufacturing Extension Partnership (MEP) National Network engaged in 314 projects with 184 individual manufacturing clients designated with an aerospace North American Industry Classification System (NAICS) number 3364. The MEP post-project, a follow-up survey of aerospace NAICS companies, revealed that MEP services had resulted in the creation or retention of 2,639 aerospace jobs, over \$46 million in new sales, over \$291 million in retained sales, over \$73 million in new investment, and over \$20 million in cost savings.

Aerospace Systems and Supplies

NIST's contributions to the manufacturing sector were complemented with support for the design, development, and calibration of aerospace systems and supplies.

Contributions included collaborative robotics, material development for advanced applications, fuel development, weapons calibrations, and thrust calibrations.

In support of materials development and selection, NIST researchers developed a new, interactive spreadsheet that will help the U.S. military extinguish aircraft and vehicle fires using the latest environmentally friendly chemicals. The spreadsheet has improved functionality and additional fluids compared to the previous program, and links to NIST's REFPROP database containing properties of many additional fire-suppressing chemicals and mixtures.

Aerospace Communications

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

NIST is developing chip-scale acceleration-measurement devices that could provide backup navigation systems when GPS fails. NIST is also pioneering radically new designs for gyroscopes that use extremely small clouds of trapped atoms to detect miniscule directional and rotational changes simultaneously in three dimensions. Such devices could enable accurate navigation for aircraft by giving them a way to stay on course when no visual or electronic guidance system is available. GPS relies on a network of satellites sending out signals timed by atomic clocks. The GPS receivers in aircraft need their own onboard timing source to ensure that their reception is precisely synchronized with the GPS, and chip-scale atomic clocks being developed by NIST can provide dramatically improved accuracy for that task.

Calibrations and Sensor Development for Satellites

NIST contributed to satellite and other space hardware in both technology development and measurement calibration.

A NIST team pioneered a revolutionary optomechanical accelerometer that uses a microscale optical cavity to detect the extremely small motion of a mechanical resonator caused by an acceleration. This sensor is designed to be intrinsically

self-calibrating, thereby avoiding the need for periodic calibrations and expensive calibration equipment. Accurate accelerometers are critically important for navigational guidance in satellites and spacecraft, particularly when GPS service fails or is unavailable.

NASA-built CubeSats—small boxy satellites with dimensions as small as 10 centimeters on a side—are already using NIST on a Chip technology: bolometers that measure the power of electromagnetic radiation, specifically the irradiance of the Sun. The final frontier promises to be a major growth area for quantum-based, chip-scale measurement equipment.

In collaboration with researchers from the Naval Research Lab, NIST evaluated a new approach to calibrating solar cells intended to power satellites and other spacecraft. The current accepted approach involves aircraft flying high in the atmosphere; the laboratory-based method developed by NIST matched data from an aircraft-based calibration and could provide developers of photovoltaics for space applications with a significantly more convenient method of assessing performance.

In support of satellite and related missions, NIST provided calibration services and research to enable the aerospace industry and Government agencies to obtain temperature, pressure, vacuum, humidity, and leak thermodynamic measurements traceable to international standards. Calibrations provided traceability to maintain quality systems, to maintain process control, and to qualify instrumentation for flight and space travel. Industries that rely on this unique calibration capability include U.S. aerospace manufacturers, who need to know if their plane materials and designs will be able to withstand the massive forces that occur on takeoff and during flight.

Support for Extraterrestrial Research

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

NIST researchers designed a non-image telescope used to measure the spectral irradiance of the Moon, known as the Airborne LUnar Spectral Irradiance

(air-LUSI) system. In collaboration with NASA, the telescope was integrated into a wing pod of an ER-2 research aircraft to measure spectral irradiance during flight and has successfully flown seven times. NIST will use the data collected to develop a new SI-traceable dataset of lunar spectral irradiance, allowing the Moon to be used as an on-orbit absolute calibration source, leading to more effective and accurate climate and Earth's weather changes and better data integration from different satellite sources. The air-LUSI preliminary data are currently undergoing evaluation by NIST scientists and end-users.

International Trade Administration

The Commerce Department's International Trade Administration (ITA) Office of Transportation and Machinery (OTM) participates in multiple fora regarding the operations and industry development of UAS. OTM participates in the interagency UAS Executive Committee, which addresses UAS policy issues. OTM participates in the UAS Security Senior Steering Group (UAS Security SSG), which implements policy initiatives derived from the Executive Committee. OTM provides industry perspective through the SSG and participates in a working group to address testing and evaluation of counter-UAS systems to be operated by the U.S. Government. OTM also participates in the UAS Standards Collaborative (UASSC) hosted by the American National Standards Institute. The UASSC coordinates the development of standards and conformity assessment programs needed to facilitate the safe integration of UAS into the U.S. National Airspace System. Within these groups, OTM provides industry's perspective on wide-area inspection, international coordination, and adaptability to foster the growth of the UAS market worldwide.

Throughout the year, OTM organized and led five meetings of ITAC 1. The Committee provides advice to the Secretary of Commerce and the U.S. Trade Representative on aerospace-related trade policy issues. This year, the Committee provided advisory opinions to the Secretary of Commerce and the U.S. Trade Representative concerning the U.S.-Kenya and U.S.-United Kingdom free trade agreement negotiations, negotiations with the Government of China, the United States-Mexico-Canada Agreement, the World Trade Organization (WTO)

Aircraft Subsidies case, U.S.-India trade, U.S. trade with Brazil, and European Union (EU) defense policies that impact U.S. aerospace trade with Europe.

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

ITA's Office of Finance and Insurance Industries 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.

The 2001 ASU continued to function as intended, but the steep drop in aircraft demand resulting from the contraction of air travel due to the COVID-19 pandemic prompted signatories to consider whether temporary changes were warranted to provide liquidity to airline buyers. Export credit financing levels—already at record lows due to unrelated interruptions in U.S. and European support for aircraft from 2016 to 2019—remained low as airlines sought to delay deliveries and postpone purchases. Signatories will monitor the demand for air travel and availability of commercial aircraft financing in considering further temporary ASU adjustments.

As a member of the U.S. delegation, ITA helped ensure that the interests of the industry were addressed during the ASU negotiations, continued to monitor implementation, and participated in negotiations of potential ASU adjustments. ITA also worked closely with interagency partners to monitor conditions in the aircraft finance market and supported EXIM Bank's initiatives to provide enhanced financing to the aerospace industry and its supply chain.

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

ITA continued to play an important role in promoting U.S. aerospace trade interests as the industry faced mounting competition from abroad. ITA participated in and organized trade events and provided advocacy to support U.S. companies in international aerospace competitions, including commercial sales for aircraft, helicopters, airport construction, communications, remote sensing satellites, commercial projects, and air traffic management projects. At the close of FY 2020, ITA's Advocacy Center had 27 active space-related cases with a total project value of \$6.6 billion and U.S. export content of \$6.2 billion. At the same time, the Advocacy Center had 568 active cases in the aerospace and defense sectors.

ITA's Export Assistance Center in Middletown, Connecticut, hosted a series of webinars on the space sector. The first was launched in June 2020 in coordination with Congressman Joe Courtney (CT2) and was a 12-month follow-up from the successful May 2019 International Space Trade Summit. Congressman Courtney moderated the webinar, which featured space industry experts Major General Stephen Whiting, Deputy Commander, HQ, U.S. Space Force, and Mr. Kevin O'Connell, Director, Office of Space Commerce, Commerce Department. The speakers provided important updates regarding their respective agencies, current opportunities and challenges to the space sector, comments regarding the commercial crew launches to the International Space Station, and information on foreign space activities. More than 320 individuals registered for the call, including mostly small- to medium-sized enterprises.

In FY 2020, ITA organized and supported the Commerce Department's participation in the Dubai and Singapore Air Shows and arranged senior-level meetings with foreign government and industry officials as well as U.S. industry executives. Through a Strategic Partnership with Kallman Worldwide, ITA hosted numerous educational briefings at the shows to help small- and medium-sized businesses enter foreign markets. Additionally, ITA/OTM met with numerous U.S. and

foreign government and industry officials to discuss ongoing policy issues impacting the competitiveness of U.S. industry. Unfortunately, all other international aerospace trade shows were canceled through the rest of the fiscal year due to COVID restrictions.

Industry and Trade Promotion

ITA's Global Aerospace and Defense Team (Global Team) recorded approximately 207 Written Impact Narratives (WIN) in FY 2020. A WIN is an organizational metric that showcases ITA's contribution to a company's success. These include ITA and particularly Commercial Service personnel-impacted deals with small- and medium-sized companies, as well as larger corporations such as Bell Helicopter, Boeing, General Dynamics, Lockheed Martin, and United Technologies Corporation.

The Global Team held approximately 3,000 counseling sessions with over 2,000 U.S. aerospace companies, helping them to resolve international trade issues, identify new export markets, and develop strategies for entering those markets.

COVID-19 impacted the ability of the Global Team to participate "in person" at most shows, but the team pivoted to provide virtual services. Prior to the pandemic's impact, team members provided one-on-one counseling sessions, individualized business-to-business meetings with international business partners, and export counseling services to U.S. exhibitors at the Dubai Air Show and the Singapore Air Show. ITA trade show support generated trade leads for participating companies, allowing them to enter or expand their exports to international markets. Virtually, the Global Team conducted numerous webinars for U.S. businesses, covering topics such as export controls, advocacy, Mexico's airport infrastructure, defense sales, and regional market entry strategies for Singapore, Taiwan, Japan, India, Norway, Denmark, and France. Approximately 1,100 companies registered for these virtual events.

Bureau of Industry and Security

During FY 2020, the Bureau of Industry and Security (BIS) continued to support export control reform efforts as they relate to the transfer of jurisdiction of certain items from the U.S. Munitions List to the Commerce Control List. Throughout the fiscal year, the Departments of State and Commerce, in coordination with other interagency partners, reviewed public comments on the spacecraft and related items enumerated and described therein submitted in response to published notices of proposed rulemaking. The feedback received has informed ongoing interagency discussions on streamlining export control regulations for both the U.S. commercial space industry and those of international partners. Consistent with the objectives of Space Policy Directive-2, the Departments of State and Commerce seek to bolster the U.S. commercial space sector by lowering the administrative burden, decreasing regulatory compliance costs, and increasing U.S. exports. BIS also participated in the Transportation Technical Advisory Committee discussions, which include aerospace-related topics such as controls on emerging technology for national security reasons in coordination with international export control partners.

DEPARTMENT OF THE INTERIOR

DOI

Remotely sensed data and derived information contribute substantially to mission-critical work across the Department of the Interior (DOI). This section highlights a sampling 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. In FY 2020, the USGS manages the Landsat satellite series and a web-enabled archive of global Landsat imagery that dates back to 1972. Landsat represents the world's longest continuously acquired collection of spaceborne moderate-resolution land remote sensing data, and the entire archive became available to the public at no charge in December 2008. The USGS also distributes aerial photography through the National Map. The USGS archives and distributes historical aerial photography; light detection and ranging (lidar) data; declassified imagery; hyperspectral imagery; data collected by UAS; and imagery from a variety of Government, foreign, and commercial satellites. These data were used for a wide variety of applications, such as mineral resource development; monitoring the health of U.S. and global ecosystems; land-use change; emergency response; and assessments of natural hazards such as fires, hurricanes, earthquakes, volcanic eruptions, droughts, and floods.



Advancing a 3D Burn Severity Mapping Capacity

Research by the Fire Science Team at the Earth Resources Observation and Science (EROS) Center explores how a 3D characterization of burn severity can be integrated into operational mapping programs. Burn severity mapping is commonly informed by changes in vegetation spectral response; the Monitoring Trends in Burn Severity program, for instance, relies on pre- and post-fire Landsat image pairs to delineate and characterize fire severity. However, satellite-derived spectral response conveys limited information about changes in vegetation structure because it only represents the uppermost layer of the canopy. Structural changes in the vegetation understory, in particular, may be obscured. In contrast, lidar data penetrate the canopy and record the 3D structure of all vegetation layers. A comparison of pre- and post-fire lidar data can thus supply information about fire-caused structural changes. The complementary information derived from lidar and multispectral data can provide a more complete picture of the fuel load and burn severity on the landscape. The objective is to learn how pre- and post-fire vegetation structure and burn severity are correlated. This correlation will depend on a series of factors including vegetation/forest type, severity of burn, time of data acquisition, and data acquisition specifications.

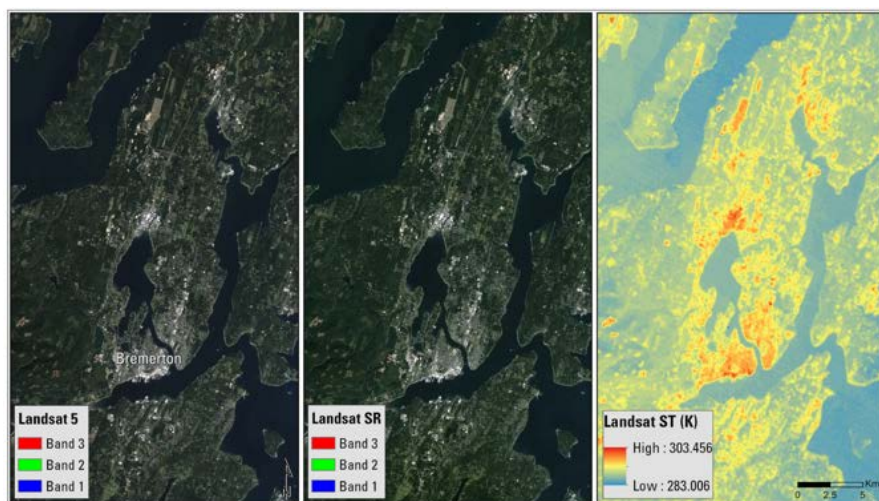
A multi-scale research plan focusing on the Legion Lake Fire, which burned more than 54,000 acres in the Black Hills of South Dakota, is being implemented to explore this approach. Field-based composite burn index, ground-based lidar, as well as UAS-based imagery and space-based observations are being used to explore how vegetation structure is impacted by fire from the plot level to landscape and regional levels. The plot-level observations provide very detailed but highly localized data, which are useful in building initial models. The space-based observations provide data to derive regionally consistent and comprehensive assessments of 3D burn severity. The UAS data serve as an important bridge across observation and mapping scales. Knowing how observations, correlations, and errors vary over spatial scales is critical to developing actionable science products. As the work expands, having the UAS capacity to strategically collect targeted data (e.g., before and after a prescribed burn) will be immensely valuable for advancing 3D burn severity mapping.

Advancing Interoperability of the Global Landsat Archive

Landsat Collection 2 marks the second major reprocessing event of the USGS Landsat archive since 2016, resulting in several data product improvements that harness recent advancements in data processing, algorithm development, and data access and distribution capabilities. Collection 2 became available to the public December 2020 via EarthExplorer. The USGS Landsat no-cost open data policy has continued since its inception in 2008. Collection 2 includes Landsat Level-1 data for all sensors since 1972; and for the first time, it also includes global Level-2 surface reflectance and surface temperature scene-based products from 1982 to the present. Landsat Collection 2

- is a substantial improvement in the absolute geolocation accuracy of the global ground reference dataset—improving the interoperability of the global Landsat archive spatially and temporally and with Europe’s Copernicus Sentinel-2 mission;
- has updated global digital elevation modeling sources; and
- is processed and accessible from a commercial cloud-based environment.

The USGS implemented a Collections-based Landsat archive structure in 2016 in recognition of the need for consistent Landsat 1–8 sensor data and in anticipation of future periodic reprocessing of the archive to reflect new sensor



An example of Landsat Collection 2 Surface Reflectance and Surface Temperature of the Bremerton, Washington, region, derived from Landsat 5 data acquired on October 6, 2010.

calibration and geolocation knowledge. Current Collection 1–based products, such as Landsat 8 and Landsat 7 Level-1, U.S. Landsat Analysis Ready Data, and Level-3 Science Products, will continue to be generated and remain available for at least one year after Collection 2 is publicly released. The Landsat Collection 2 web page provides summaries of the characteristics of Landsat Collection 2 Level-1 and Level-2 data products.¹

Alaska Statewide Interferometric Synthetic Aperture Radar Elevation Data and Satellite Imagery Status

The 3D Elevation Program (3DEP) effort to acquire new statewide Alaska elevation data is complete. The goal of 3DEP is to complete acquisition of nationwide lidar (Interferometric Synthetic Aperture Radar [InSAR] in Alaska) to provide the first-ever national baseline of consistent high-resolution elevation data—both bare earth and 3D point clouds—collected in a timeframe of less than a decade. The USGS coordinated with other Federal agency partners and the State of Alaska to fund the acquisition of the Alaska InSAR data from 2010 to 2019. USGS used its Geospatial Products and Services Contract to acquire 5-meter resolution elevation data using InSAR sensors flown on aircraft. The products available from the Alaska effort include a Digital Terrain Model representing the bare earth, a Digital Surface Model representing the tops of vegetation and structures, and an orthorectified radar intensity image. Final data acquisition occurred in late summer 2019. The data were processed by the vendors through spring 2020 and are now available for users to download free of charge and without use restrictions on The National Map.² In FY 2020, USGS and the National Geospatial-Intelligence Agency (NGA) began collaborating to acquire a statewide satellite imagery mosaic for Alaska to augment the statewide InSAR elevation dataset. Specifications require delivery of a 4-band (RGB natural color and near-infrared) mosaic at 0.5-meter resolution, orthorectified using InSAR to meet specified accuracy requirements. Source imagery for the mosaic comes from archived satellite scenes acquired predominantly from 2017 to present during summer months through a request from the Civil

1 <https://www.usgs.gov/land-resources/nli/landsat/landsat-collection-2>

2 <https://apps.nationalmap.gov/downloader/>

Applications Committee (CAC) to NGA. Data delivery was completed in spring 2021. The imagery is displayed on several state and Federal imagery servers for the public to view and can be used internally by multiple Federal agencies and the State of Alaska. The statewide imagery and InSAR datasets can be used in tandem to support a wide variety of mapping, resource management, and public safety applications. These Alaska mapping efforts were coordinated through the Alaska Mapping Executive Committee (AMEC), an executive body cochaired by the Department of the Interior and the Department of Commerce. AMEC members represent multiple Federal agencies and the state.

Crop Water Productivity of the World's Leading Crops

The USGS is conducting crop water productivity (CWP; “crop per drop”) studies of the world’s major crops (wheat, rice, corn, soybeans, barley, potatoes, pulses, and sugarcane) using multiple-satellite, multiple-resolution remote sensing through machine learning algorithms run on cloud-computing platforms such as Google Earth Engine. The overarching goal is to understand how crops are using water for optimal productivity and how, where, and how much water can be saved through increased CWP. The methodology involves mapping crop types, modeling crop water use (m^3/m^2), modeling crop productivity (kg/m^2), and mapping CWP (kg/m^3). As a beginning, a meta-analysis of the global CWP was conducted and published.³ The meta-analysis established CWP of three of the world’s leading irrigated crops (wheat, corn, and rice) based on studies conducted using remote sensing data and published in peer-reviewed journals. Together, these three crops occupy 30.4 percent (569.3 million hectares) of the total global cropland area of 1.873 billion hectares. This study established that the United States and China are the only two countries that have consistently high CWP for wheat, corn, and rice. The quantum of water that can be saved from each crop in each country was evaluated by increasing CWP by 10, 20, and 30 percent. Based on data in this study, the highest consumers of water for crop production also have the most potential for water savings. These countries are United States, India, and China for wheat; United States, China, and Brazil for corn; and India, China, and Pakistan for rice.

3 <https://www.tandfonline.com/doi/full/10.1080/17538947.2019.1651912>

For example, even just a 10 percent increase in CWP of wheat grown in India can save 6,974 billion liters of water, or the equivalent of 6,974 lakes each of 100 m³ in volume. The USGS CWP webpage provides further details.⁴

Cyanobacteria Assessment Network

Cyanobacterial blooms are a global concern because they pose a threat to human and aquatic ecosystem health and cause economic damage. Cyanobacteria can produce toxins potent enough to adversely affect the health of humans, pets, livestock, and wildlife. The USGS is collaborating with the U.S. Environmental Protection Agency, NASA, and NOAA on the Cyanobacteria Assessment Network (CyAN) project. The overarching goal of this collaborative effort is to detect and quantify potentially toxic cyanobacterial blooms using satellite data records to support the environmental management and public use of lakes and reservoirs throughout the Nation. Data from ocean color instruments on board multiple satellite platforms including Landsat, Medium Resolution Imaging Spectrometer (MERIS), and Sentinel-3 are being used to create a protocol for early identification of cyanobacterial blooms in freshwater systems. The protocol will provide early warning indicators of cyanobacterial bloom development at the local scale while maintaining continuous national coverage.

An Android mobile application, titled “CyAN,” is available for download to the public. The app provides access to cyanobacteria bloom status on large reservoirs across the country, and a web application is being beta tested. The CyAN Field Exploratory Lakes Database (FIELD) Tool is a stand-alone, open-source code application for serving up water quality data for the Nation focused on characterizing the uncertainty of satellite-derived products using field and laboratory data and automated quality assurance. It automatically calculates trophic status and health threshold exceedances due to cyanotoxin presence. National remote sensing archives were scheduled to be publicly delivered in FY 2021. CyAN has met the NASA application readiness level 9, and information from this project is currently being used by several states to identify cyanobacteria blooms and strategically

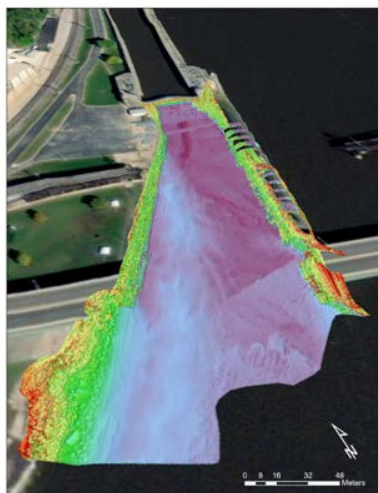
4 <https://www.usgs.gov/centers/western-geographic-science-center/science/global-crop-water-productivity-and-savings>

deploy staff for verification. The results will support decision-making for public health protection balanced against socioeconomic needs.⁵

Development of an Underwater Acoustic Deterrent System for Asian Carp

The USGS Upper Midwest Environmental Sciences Center (UMESC) is leading a study to construct, deploy, and evaluate an underwater Acoustic Deterrent System (uADS) at Lock and Dam 19 (LD19) near Keokuk, Iowa. The uADS will be designed with the goal of deterring Asian carp from moving upstream in the Upper Mississippi River. The uADS will be evaluated for up to three years for its impacts on both native and invasive fish passage and behavior. To design and install such a system, details about the condition of the lock approach and substrate are necessary. U.S. Army Corps of Engineers locks are not surveyed on a regular basis, so additional imaging is helpful for assessing the condition of the structure and identifying locations for uADS deployment and attachment. New remote sensing science and technology with hydroacoustics and lidar was used in support of this Asian carp control project.

Because no single tool can provide a comprehensive picture of LD19, UMESC used various sensors to effectively map the lock and dam approach. Hydroacoustic data, including multibeam bathymetry, MEGA-imaging side scan, and underwater video, were recorded at the same time as terrestrial lidar data to produce a detailed picture of the lock approach at LD19. Data products created from these sensors include digital elevation model, hillshade, backscatter,



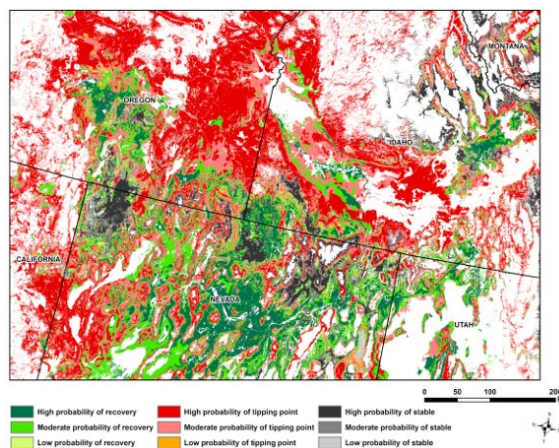
Hydroacoustic data provide a comprehensive picture of Lock and Dam 19 near Keokuk, Iowa, to support the construction, deployment, and evaluation of an underwater Acoustic Deterrent System (uADS) to prevent Asian carp from moving upstream in the Upper Mississippi River.

⁵ <https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan>; <https://www.epa.gov/water-research/cyanobacteria-assessment-network-mobile-application-cyan-app>; <https://code.usgs.gov/water/stats/cyan-database>

bathymetric slope, MEGA-imaging side scan, and underwater videos. These remote sensing technologies will be used to evaluate the condition of the concrete sills and discharge laterals where the uADS will be installed. Additionally, images of the lock gates, ladder wells, and location of an underwater sewer discharge pipe will inform uADS installation plans and provide information necessary for deploying a sound and fish monitoring array on-site. Collecting these data prior to system construction and installation facilitated efficiencies in the uADS construction and deployment process, saving both time and money.

Identifying Tipping Points in Sagebrush Ecosystems

Sagebrush ecosystems provide valuable services to society, including recreational and economic opportunities like hunting and fishing, energy development, and livestock grazing. Sagebrush ecosystems also provide habitat for wildlife, natural systems for carbon sequestration, and resources for human habitation. However, sagebrush ecosystems are imperiled, stressed by climate warming and repeated disturbances that modify the landscape and impact these valuable services. The most common disturbance is wildfire, which is initiated, exacerbated, and perpetuated by the invasion of non-native annual grasses. Knowing where a tipping point (i.e., a long-term or permanent transition) from a species-rich, natural system to an invasive grass-dominated system 1) has occurred, 2) is likely to persist, or 3) is likely to happen in the near future is critical information for land managers, policy makers, and scientists studying and making decisions about sagebrush ecosystems.



A spatially explicit representation of a time series (2001–2015) of the probability of sagebrush condition classes in the western United States. The figure is a product of satellite and abiotic data integrated into a model that was ingested into decision-tree and mapping software. The white mask represents areas not classified as sagebrush ecosystem.

Scientists from the USGS EROS Center and the Bureau of Land Management (BLM) conducted a study that used a time series (2001–2015) of temporally rich enhanced Moderate Resolution Imaging Spectroradiometer (eMODIS) satellite imagery in conjunction with abiotic data integrated into a model that was ingested into machine learning and mapping software.⁶ A spatially explicit, predictive map of three classifications of sagebrush condition resulted. The map shows three probabilities (high, moderate, low) for each of the three classes: tipping point, sagebrush recovery, and stability. Slightly more than 57 percent of the study area was classified as tipping point and 29 percent as sagebrush recovery during the 15-year period. Approximately 14 percent of the study area was classified as stable. The stable class occurred mostly at higher elevations where more precipitation falls and peak summer temperatures are cooler, allowing native vegetation types to better compete against the invading grasses. As climates continue to warm, the environmental advantage for native vegetation at higher elevations may end, and wildfires that result in tipping points may occur here.

LANDFIRE 2016 Remap and “Year Capable” Fuels

LANDFIRE’s mission is to provide agency leaders and managers with a common “all-lands” dataset (including maps) of vegetation and wildland fire/fuels information for strategic fire and resource management planning and analysis. LANDFIRE uses numerous geospatial data sources to develop its products but relies heavily on Landsat imagery and spectral indices for vegetation and disturbance mapping in addition to lidar for quantifying structural characteristics of the vegetation. Always striving to stay up to date, LANDFIRE completed a major milestone of remapping all base layers and product suites for the conterminous United States (over 9 billion 30-meter pixels) with circa 2016 imagery (“Remap”) in July 2020. Remap work is continuing for Alaska, Hawaii, and insular areas. This amazingly rich dataset would not have been possible without remote sensing technology associated with Landsat Thematic Mapper, Enhanced Thematic Mapper Plus, and Operational Land Imager bands. Among the many improvements and innovations as part of the LANDFIRE Remap effort for the wildland fire community is a new approach called

⁶ <https://www.sciencedirect.com/science/article/abs/pii/S1550742419300843?via%3Dihub>

“Year Capable Fuels” involving Time Since Disturbance for surface and canopy fuels. This approach was developed to overcome product latency issues inherent in all mapping efforts, accounting for how much time has elapsed since a disturbance occurred (Time Since Disturbance) to better represent more current (Effective Year) fuel conditions. How is this an improvement? In previous LANDFIRE versions, users had to adjust the fuel products to represent the contemporary condition in areas that had experienced disturbance. In Remap, LANDFIRE does this for the users, reducing the burden on them and improving performance of fire behavior models. Capable Fuels would not be possible without first correctly identifying the extent and severity of disturbed areas. This mapping effort is accomplished through a number of datasets (such as user-contributed polygons where disturbances have occurred) and by using change detection algorithms to identify areas that change spectrally between pre- and post-year remotely sensed imagery; analysts then classify them to LANDFIRE severity categories. Subsequently, disturbed areas are made to represent an Effective Year using the Time Since Disturbance methodology. For Remap, this means that capable fuels represent the Effective Years of 2019 and 2020 since delivery of Remap products was in those calendar years.

LCMAP Collection 1 Product Suite

In 2020, the USGS released new image data products for monitoring land surface change from 1985 to 2017 across the conterminous United States. The Land Change Monitoring, Assessment, and Projection (LCMAP) initiative Collection 1 data release is a major milestone toward LCMAP’s goals of developing the capability to detect and characterize historical land change, producing a suite of validated annual land change/land cover maps and area statistics, and modeling past and future land change outside the current satellite record.

The power of the Landsat archive is leveraged through use of U.S. Landsat Analysis Ready Data (ARD) containing the highest quality radiometric and geometric 30-meter Landsat data processed to a consistent format. A time series of all available cloud-/shadow-free observations serves as input for the Continuous Change Detection and Classification (CCDC) method, which builds per-pixel harmonic time series models of surface reflectance for each Landsat spectral band

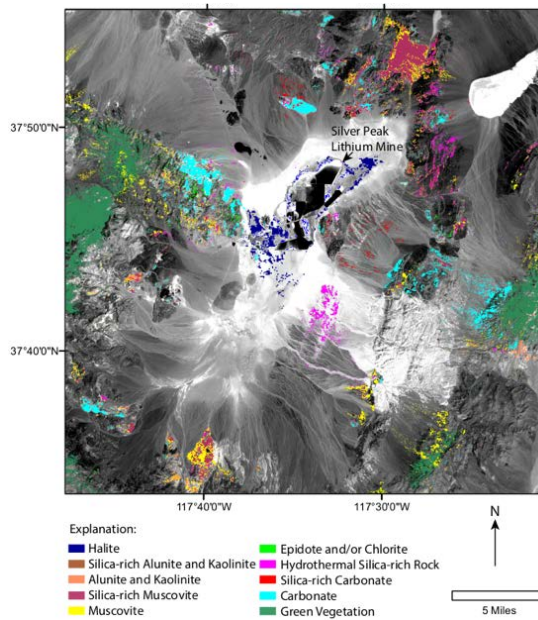
individually. The model predictions are continuously compared to actual observations over time to detect significant differences across multiple bands representing land surface changes. Following identification of changes, boosted decision tree machine learning is applied to model coefficients to classify land cover type and increase statistical confidence. The application of ARD and CCDC provides a systematic and consistent capability revealing land change from the mid-1980s to the present at 30-meter resolution.

LCMAP Collection 1 science products include ten annual land change and land cover map products for the time period 1985–2017 granularized to the 150- by 150-kilometer ARD grid and are available from USGS EarthExplorer. Independently collected LCMAP Reference Data of 24,971 random locations were used to validate land cover accuracy across the full spatial and temporal extent, with a final 82.5 percent agreement. The Reference Data, along with annual and regional accuracies, are available from USGS ScienceBase. Additional assessments of map bias and area statistics are under way, as is the development of methods to update LCMAP outputs; product updates through 2019 were expected in the coming year.

The USGS is defining requirements for additional capabilities such as monitoring change with lower lead times in rapidly changing areas, improved sensitivity for change detection, identification of specific types of change, and development of monitoring capabilities to alert relevant land managers to important changing conditions. The LCMAP Collection 1 data release and other capabilities of LCMAP enable the USGS to meet increasing demands for timely and frequent integrated land cover and land change information.

Mineral Mapping of Lithium-Rich Playas for Lithium Mineral Assessment

Lithium is a critical element for making the high-efficiency batteries used in electric cars, cell phones, computers, and solar grid electric storage. The largest lithium production in the world comes from lithium-rich brines in playas (dry lake beds), such as the Salar de Atacama located in Chile, South America. The United States has approximately 110 playas in the western part of the country that are of sufficient size to contain lithium-rich brines. This study is developing



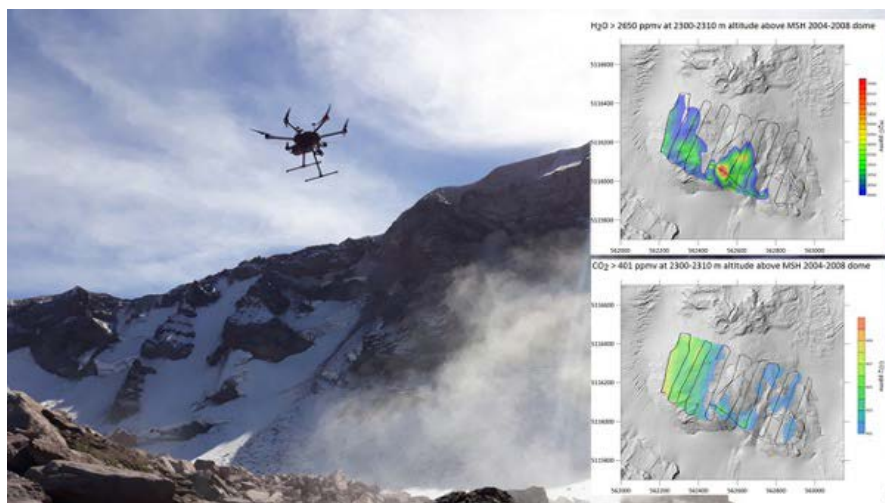
An ASTER mineral map of the Clayton Valley playa, which contains the Silver Peak Lithium Mine. The background image is ASTER band 3.

algorithms to map minerals in playas in the western United States to assess lithium potential. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data have been used to map minerals at the Salar de Atacama and are being used to develop mineral maps of important domestic lithium-rich playas, including Clayton Valley in Nevada. Deposit models suggest that the lithium source at the Salar de Atacama is from silica- and lithium-rich volcanic tuffs that may have been hydrothermally altered.

ASTER-derived mineral maps of the Salar and Clayton Valley show silica-rich hydrothermally altered mineralogy that includes alunite, kaolinite, muscovite, epidote, calcite-dolomite (carbonate), epidote-chlorite, and hydrothermal quartz (silica). In addition, ASTER mineral maps show that the Salar de Atacama and Clayton Valley playas contain halite, which suggests that there is enough precipitation and/or ground water and evaporation in the playa to support a sufficient volume of lithium-rich brine.

Monitoring Volcanic Degassing at Mount St. Helens

The USGS–Cascades Volcano Observatory utilizes a multi-rotor UAS outfitted with a miniature USGS-developed multicomponent gas analyzer system (MultiGAS) sensor to measure quiescent gas emissions above the 2004–2008 lava dome within the crater of Mount St. Helens. These new technologies allowed the team to characterize degassing at Mount St. Helens in unprecedented detail. The UAS survey confirmed that CO₂ emissions from the 2004–2008 lava dome are extremely low and that water vapor constitutes the vast majority (over 99 percent) of present-day gas emissions. Much of this water vapor is not derived from magma,



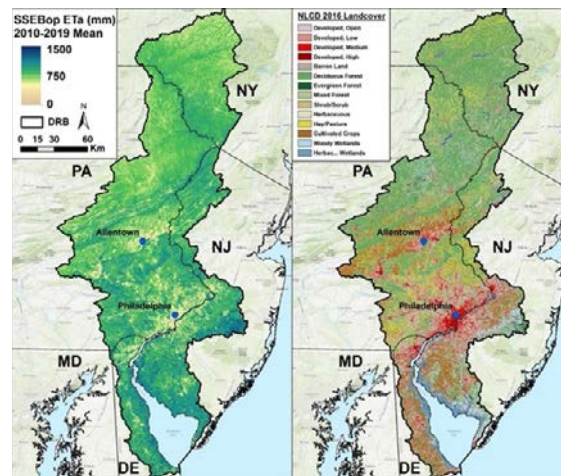
A multi-rotor UAS equipped with a MultiGAS sensor is flown over the 2004–2008 lava dome at Mount St. Helens to detect and measure volcanic gas emissions. Water (H₂O) vapor (top) and carbon dioxide (CO₂) concentrations (bottom) measured from the survey are plotted on the right.

but instead is produced when shallow meteoric and surface waters (such as snow-melt) come in contact with hot dome rocks, generating steam. Results also allow scientists to measure fumarolic heat discharge at Mount St. Helens. The UAS fills an important monitoring role at volcanoes; its small size and maneuverability allow scientists to use portable monitoring technologies like the MultiGAS in hazardous areas. The data are combined with those collected using traditional manned aircraft and at permanent monitoring stations to gain a better understanding of gas emissions at Mount St. Helens. The successful application of these technologies at Mount St. Helens demonstrates the importance of these surveys in the Cascade Range and at other active volcanoes around the globe to provide critical monitoring data to forecast volcanic hazards.

Water Use and Land Cover in the Delaware River Basin

The Delaware River Basin (DRB) was chosen as a test site for integrating USGS water- and land-use research to advance understanding on the interactions and feedbacks among climate, water availability, and land cover. Fundamental interactions can be observed from historical data and simulated using scenarios for changes in land use using projections in precipitation and temperature patterns.

Scientists at the USGS EROS Center are beginning to apply satellite-derived evapotranspiration (ET) information to quantify water demands down to the parcel level. With a greater focus toward a collaborative, interdisciplinary modeling framework, they have begun to move toward field-level water accounting by first examining mapped relationships between the land cover and land surfaces fluxes such as ET. Using the National Land Cover Database, initial work reveals that more than 75 percent of the DRB is covered with forests, croplands, and wetlands. Maps and spatial summaries of these dominant classes using time-integrated Landsat-based Operational Simplified Surface Energy Balance (SSEBop) ET information (2010–2019 average annual ET) show important patterns in magnitude and spatial context within a given cover type. For example, average water consumption through ET processes was over 1,000 millimeters/year in wetlands, 900 millimeters/year for forests, and 800 millimeters/year for cropland. Data insights such as these are key to establishing linkages with land use and land cover models in conjunc-

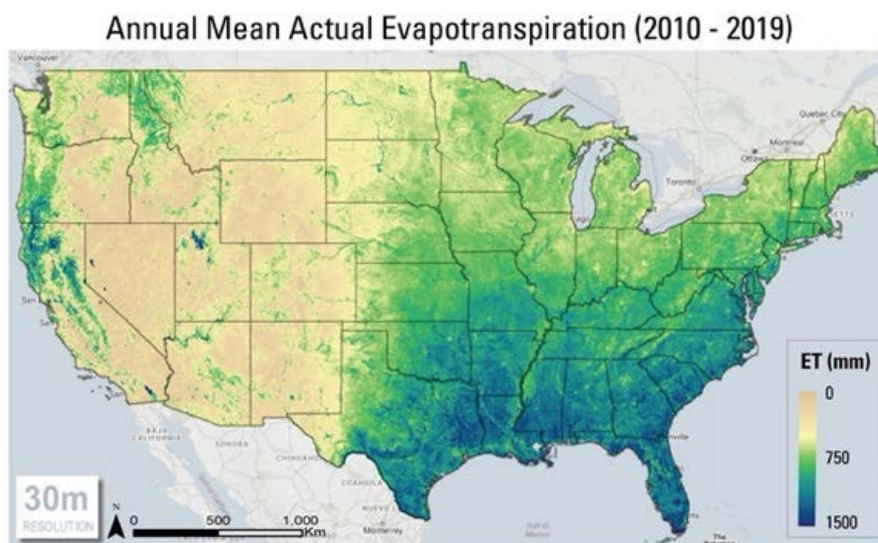


Delaware River Basin annual evapotranspiration (2010–2019 average) and land cover distribution.

tion with models of water use and availability. Staff at the EROS Center are further developing the methodology to respond to the needs of USGS Community for Data Integration and Earth Monitoring, Analyses and Projections initiatives to advance integrated predictive modeling research for the Nation.

Water Use Mapping at the Landsat Scale for the Nation

The estimation and mapping of ET is an active area of applied USGS research in the fields of agriculture and water resources. Specifically, combining remote sensing data along with climate and other weather information in a cloud-based



Annual Total Evapotranspiration using 10-year average (2010–2019) data from the Landsat-based Simplified Surface Energy Balance (SSEBop) Actual ET model.

compute framework has illustrated the value of next-generation ET mapping for nationwide water use information.

Scientists at the USGS EROS Center are leveraging the thermal (surface temperature) components of the Landsat satellite imagery archive to create ET products using the SSEBop model. Recently, more than 150,000 Landsat images were used to generate ten years of annual ET (2010–2019) at unprecedented scale and speed. This accomplishment represents the first-ever set of Landsat ET maps for the conterminous United States at this spatial (30-meter) resolution and temporal (annual) interval. Data will be made freely available with an upcoming product and manuscript release.

Evaluations using Eddy Covariance and Water Balance datasets indicated that the SSEBop model is strong in explaining spatially variable seasonal trends at local and regional levels where water management operates the most. Most importantly, in addition to new data understanding and supporting model enhancements, this work facilitates broader collective opportunities for those in search of increasing timeliness and availability of accurate ET information.

The EROS Center develops and shares these ET products with USGS Water Science Centers around the Nation for use in water availability and use studies and localized applications. The data are also instrumental for meeting the National

Water Census reporting requirements in addition to numerous collaborative efforts among various Federal and state agencies, universities, and others.

Bureau of Indian Affairs

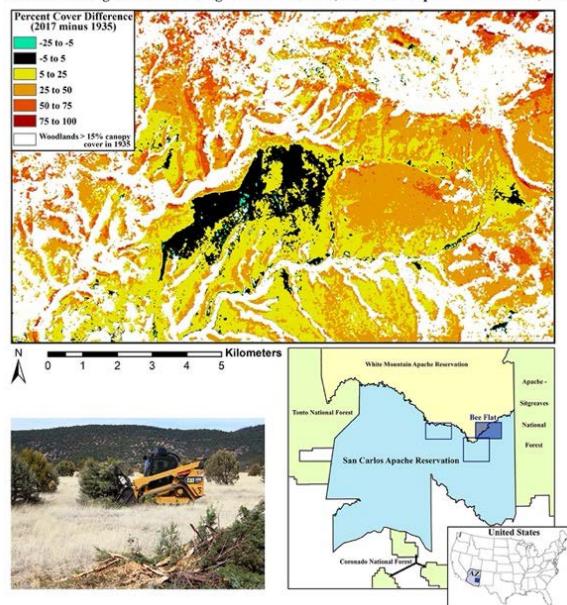
The Bureau of Indian Affairs (BIA) applies remote sensing to activities such as land use planning, responding to non-point source pollution affecting subsistence hunting and fishing, climate change impacts such as sea-level rise for coastal Tribes, location and identification of potential dam hazards, and the generation of digital terrain data for the use of open-channel hydraulics. In collaboration with other agencies, BIA actively explores ways to improve management using remote sensing data and Geographic Information Systems (GIS) technologies.

Quantifying Change in Woodland Canopy Cover

The San Carlos Apache Tribe in Arizona wants to learn more about the historical characteristics of their woodlands, savannas, and grasslands so they have a target for restoration efforts. Restoring juniper woodland to savanna is a focus of the Tribe's intensive management activities, and spatial information that would help to determine where best to attempt restoration is needed. Increases in woodland tree cover, grassland encroachment by juniper, and the trees' negative effects on intercanopy herbaceous vegetation are issues that the Tribe is coping with as livestock and wildlife often depend upon the diminishing grass cover to survive and thrive. To determine changes in woodland canopy cover, researchers from the USGS Western Geographic Science Center developed image analysis techniques to monitor tree cover for three study areas using aerial imagery from 1935 and 2017 and compared results over the 82-year interval. The team used Adobe Photoshop software in a novel way to create multiple, simple, and reproducible supervised classifications that were combined to generate binary canopy maps for each of the study areas. Continuous percent cover was then calculated for each 50- by 50-meter area within the study areas, and a temporal difference image was generated.

In general, there was a substantial increase in the woodland tree canopy cover between 1935 and 2017. For example, in the two woodland-dominated study areas,

Savanna infilling and active management on Bee Flat, San Carlos Apache Reservation, AZ



The top image portrays tree canopy cover change in the former savanna of the Bee Flat study area. The large area of black in the center experienced intensive management to remove juniper trees. The bottom image shows tree removal in progress.

overall percent tree canopy cover estimates increased from 18.3 to 38.5 percent and 28.3 to 43.3 percent. Although the expansive grasslands of one site (Big Prairie) was encroached by juniper trees mostly around its periphery, the smaller grassland units within the former savanna changed more substantially since 1935. Additionally, this research provides evidence of the success of Tribal management efforts at Bee Flat, where managed landscape canopy cover is

roughly analogous to the natural savanna tree cover mapped there in 1935. These results are important as former savanna areas once dominated by native grasses and forbs have been replaced by higher density juniper-pinyon-oak woodlands with degraded soils and limited herbaceous understories. The San Carlos Apache Tribe intends to use map results from this analysis to help locate other woodland areas suitable for restoration. Pinyon-juniper expansion and infilling are increasingly a challenge for land managers across the Intermountain West, and historical remote sensing information may help provide Tribes with data they need.

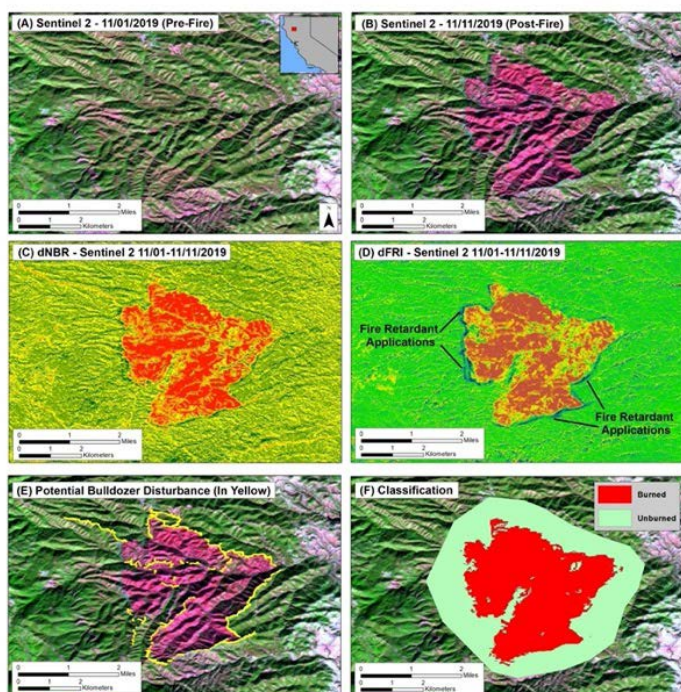
Bureau of Land Management

The Bureau of Land Management (BLM) leverages ground, air, and spaceborne remote sensing technologies to support its mission to sustain the health, diversity, and productivity of public lands for the use and enjoyment of present and future generations. These technologies include aerial and close-range photography;

multispectral, hyperspectral, and thermal infrared camera/imaging systems; as well as radar and lidar. The BLM also utilizes passive and active imaging system information collected by UAS. Remote sensing data and products are being used to address a host of BLM monitoring requirements, including energy development, mine production verification, assessment of land cover condition through time, and wildfire response and mitigation. Finally, the BLM requires field-based measurements to support management decisions covering vast expanses of land. By integrating remote sensing into the BLM's assessment, inventory, and monitoring strategy, field-based data are used to generate information and maps that would otherwise be too expensive to produce. The BLM is leveraging remote sensing to provide an integrated, quantitative monitoring approach to efficiently and effectively document the impacts from authorized and unauthorized disturbance and land treatment activities at local and regional scales.

Emergency Stabilization and Rehabilitation Post-Fire Imagery

The National Operations Center (NOC) provides remotely sensed geospatial data products to support management officials conducting Emergency Stabilization and Rehabilitation (ESR) activities on wildfire-affected BLM lands. The ESR program is implemented to lessen post-fire effects such as erosion and to restore affected habitats. Remote sensing products assist management officials in completing key objectives, including monitoring vegetation treatments and reforestation, and rehabilitating land cover. The NOC currently leverages the European Space Agency's Sentinel-2 constellation to provide ESR support to requesting officials. Sentinel-2's spatial, spectral, and temporal resolution make it well-suited for wildfire applications. ESR support products include pre- and post-event visible to shortwave-infrared imagery, which have been spatially divided to the fire-affected area. Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio (NBR), Delta NDVI (dNDVI), Delta NBR (dNBR), and Delta Fire Retardant location products are also derived and disseminated to meet ESR objectives. Custom datasets may be developed for field offices with event-specific needs, such as maps identifying the spatial extent of bulldozer disturbances. Finally, the NOC provides a classification product identifying burned and unburned cover. Compilations of



Sentinel-2 products derived in response to the Ranch Fire in California. (A) Pre-fire multispectral image. (B) Post-fire multispectral image. (C) dNBR from pre- and post-fire NBRs. (D) dFRI identifying fire-retardant applications. (E) Bulldozer disturbances. (F) Vector classification identifying burned and unburned cover.

all ESR pre- and post-fire multispectral imagery, and classification data, are published as Image and Map Services, respectively, and made available to all interested BLM officials.

Landscape Cover Analysis and Reporting Tools

The BLM NOC, through a NASA ROSES grant, has partnered with USGS and UCLA researchers to create an online mapping application called LandCART: Landscape Cover Analysis and Reporting Tools. LandCART will enhance the BLM's ability to produce estimates of Assessment, Inventory, and Monitoring (AIM) indicators using NASA Earth observation data in places and times where in situ data are not available. This tool will address user-defined management questions, particularly trend analysis questions, and provide documentation required by NEPA (National Environmental Policy Act). Therefore, LandCART will support

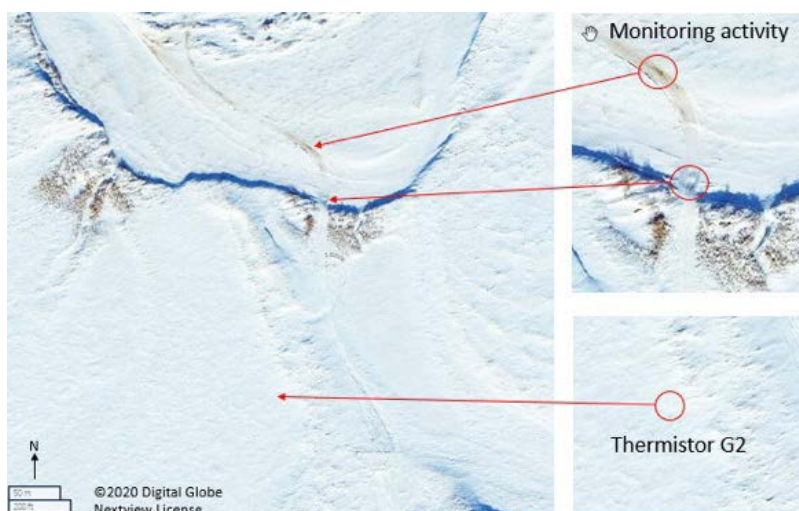
exporting of the input and output data, along with information from the underlying algorithm, to ensure reproducibility and appropriate NEPA documentation. Predictions will be accompanied by error and confidence estimates to enhance their utility in decision making. LandCART is currently in a beta testing stage with all the programming, design, and calculations performed in Google Earth Engine and the application served in Earth Engine AppsExperimental. The project is expected to be published within the Google Cloud Platform once completed. Current case studies using LandCART data include sage grouse brood habitat mapping and change detection, wild horse and burro habitat mapping, and trend analysis of grazing allotments and management decisions for those areas. The project is in its fourth year with the expectation of publishing a fully functional online application for use by all BLM staff as well as the general public in FY 2021.

Monitoring Tundra Travel Across the National Petroleum Reserve-Alaska

Alaska is the only Arctic state in the Nation. The Arctic environment presents some unique challenges to living, working, and operating, including a lack of road infrastructure, high costs of shipping freight, and seasonal daylight limitations during the winter. The Sun drops below the horizon in November and does not rise above the horizon until mid-February.

To help Arctic communities be less isolated during the winter, the BLM Arctic District Office (RDO) authorized Community Winter Access Trails (CWAT) for public use across the National Petroleum Reserve-Alaska beginning January 2019. Made from compacted snow, the CWAT is cheaper and easier to build than ice roads, but snow has a shorter operational season, only supports lower ground pressure vehicles, and is prone to soft spots where tires can get stuck. Still, the North Slope Borough has found a safe way to build and maintain the routes using tracked vehicles. Once the route sets up, it can later be used by passenger vehicles being escorted across the right of way on a weekly basis.

The RDO monitors conditions along one of the CWAT corridors using eight thermistors and acoustic sensors that provide data on soil temperature, frost depth, and snow depths. As the COVID-19 pandemic emerged, the BLM/RDO recognized travel restrictions would prevent these onsite inspections using the installed



Overview of Community Wide Access Trail (CWAT) monitoring activity. Upper right: close-up of observed soft spot near river crossing. Lower right: close-up of Thermistor G2 site location with pole casting a shadow.

sensors. To address this limitation, BLM began acquiring Maxar/DigitalGlobe's high-resolution WorldView imagery in early March 2020 under the NextView Contract. These images allowed RDO to remotely monitor snow conditions along the CWAT, leading to a road closure date in early May, but not before vital COVID-19 supplies and emergency freight were transported in from Prudhoe Bay to Utqiagvik. RDO field staff utilized the winter imagery to identify specific sites for field surveys and monitoring activities as part of the management strategy for the right-of-way grant.

Monitoring Jurassic Dinosaur Tracks with UAS

The Red Gulch Dinosaur Tracksite near Shell, Wyoming, showcases an exposed dry wash with hundreds of Jurassic, carnivorous dinosaur tracks preserved in the rock. The tracks, formed approximately 167 million years ago, were discovered by members of the public in 1997. The BLM has created a 40-acre recreation site around this quarter-acre tracksite and is tasked with preserving the tracks and their value for the public. Stereo image documentation of the site, utilizing a variety of ground-based platforms (booms, monopods, tripods), began in 1998. In 2000, a blimp-mounted camera and low-flying manned aircraft were used to

collect additional imagery. In June 2019, BLM again acquired stereo images over the tracksite, but this time using a 3DR Solo UAS. Mapping flights were designed to capture stereo imagery from 15, 30, 60, and 125 feet above ground level, resulting in orthomosaics of the tracksite with resolutions ranging from 1.5 to 10 millimeters ground sample distance (GSD, the measure of a square pixel edge ground coverage). Paleontological staff intend to use the resulting orthomosaics and digital surface models to better understand the site and measure changes in surface elevation and relative relief of the individual tracks to determine how fast they are eroding. Such data will assist in management decisions for this popular BLM recreation area.

To survey for additional exposed strata potentially containing dinosaur tracks, and to provide baseline imagery for monitoring of the larger Red Gulch Area of Critical Environmental Concern, BLM staff surveyed an additional 200 acres to the east of the tracksite using the 3DR Solo UAS at 1 centimeter GSD, and an additional 1,000 acres at 2 centimeters GSD using the newly acquired Firefly Pro 6S. The Firefly was programmed to fly autonomous mapping missions at 500 feet above ground level. A 42-megapixel camera mounted on the aircraft belly acquired stereo images at locations determined by the flight plan. With a flight time of approximately 30 minutes, each Firefly mission covered approximately 150 acres. The ability to acquire 2-centimeter GSD orthoimagery over 1,000 acres in a single day greatly expands the remote sensing capability of BLM Wyoming, and in this case provides useful monitoring data for the paleontological program.

Bureau of Ocean Energy Management

The Bureau of Ocean Energy Management's (BOEM's) Environmental Studies Program (ESP) develops, funds, and manages rigorous scientific research specifically to inform policy decisions on the development of energy and mineral resources on the U.S. Outer Continental Shelf (OCS). BOEM uses remote sensing to inform its research covering physical oceanography, atmospheric sciences, biology, protected species, social sciences and economics, submerged cultural resources, and environmental fates and effects. Mandated by Section 20 of the Outer Continental Shelf Lands Act, the ESP is an indispensable requirement informing BOEM's decisions on offshore oil and gas, offshore renewable energy, and the marine minerals program for coastal restoration.

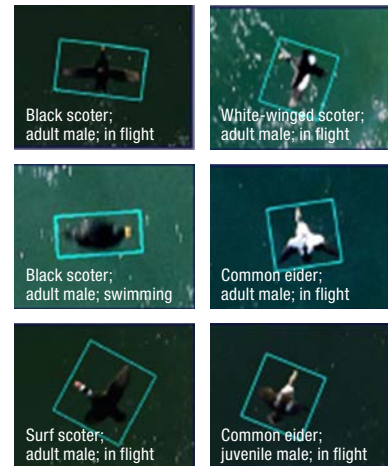
Assessing the Feasibility of Using Satellite Data for Offshore Air Quality Applications

BOEM is required to analyze the air quality impacts from OCS oil and gas activities to the states as mandated by the Outer Continental Shelf Lands Act. To support its air quality regulatory mandate, BOEM is working with the NASA Atmospheric Chemistry and Dynamics Laboratory at Goddard Space Flight Center to conduct a scoping study that will assess the use of satellite data for offshore air quality assessments. Specifically, this study will determine the feasibility of using existing satellite data in offshore environments in the Gulf of Mexico region for estimating and monitoring trends of the ground-level concentrations of pollutants according to the National Ambient Air Quality Standards (NAAQS) (including precursors and visibility pollutants) and to validate the satellite data with offshore monitoring in a field campaign. Preliminary results reveal two air quality “regimes” in the Gulf of Mexico Region: 1) clean marine, where the wind direction is from the south, or ocean based, and 2) polluted continental air, where the wind direction is from the north, or land based. A flaring event from two oil and gas platforms was successfully detected using satellite-based data from the Tropospheric Monitoring Instrument (TROPOMI) nitrogen dioxide (NO₂) sensor and the Visible Infrared Imaging Radiometer Suite within the Hybrid Single-Particle Lagrangian Integrated Trajectory model. At the LUMCON ship port in Cocodrie, Louisiana, TROPOMI overpass data show a mean 13 percent difference from Pandoras before and during the cruise, confirming an excellent correlation between the ship-based Pandora NO₂ data and satellite-based TROPOMI NO₂ data for the offshore environment. These results indicate that TROPOMI is useful to BOEM for measuring the Gulf of Mexico and coastal pollution.

Developing Computer Vision and Deep Learning Methods to Improve Aerial Surveys of Marine Wildlife

BOEM, the U.S. Fish and Wildlife Service (FWS), and USGS are collaborating to foster research on deep learning methods that automate remote sensing data for wildlife population surveys. The Atlantic Marine Assessment Program

for Protected Species, currently in its third phase, is developing automated ways to rapidly filter and subset digital aerial imagery of marine birds, cetaceans, and sea turtles. A major challenge for integrating remote sensing methods for large-scale population surveys is the tremendous volume of data collected during image-based surveys and the lack of suitable tools for automated filtering of imagery, counting detected wildlife targets, and classifying wildlife targets. Computer vision, coupled with deep learning, shows great promise for automating detection and classification of wildlife from digital imagery. These agencies recognize a set of common wildlife population monitoring priorities and shared objectives to enhance employee safety and to improve data quality. This project is also working to deploy remote sensing systems and develop workflows for in-flight orthorectification and machine learning processing to detect and classify wildlife from imagery in near-real time.



Examples of individual sea ducks near Cape Cod, Massachusetts. Individual birds were delineated with a rectangle and identified to the lowest taxonomic level. Additional attributes such as age, gender, and activity were included when resolvable.

Bureau of Reclamation

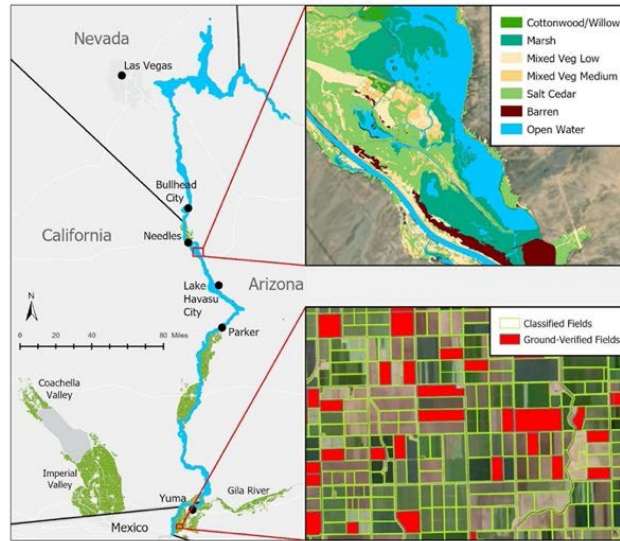
The Bureau of Reclamation (BOR) uses Landsat data to help monitor consumptive water use throughout the western United States. BOR analysts use Landsat imagery to map irrigated crops for estimating water demand and to monitor interstate and inter-basin water compact compliance. The BOR is also involved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

Estimates of Evapotranspiration and Evaporation along the Lower Colorado River

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

Four times per year, BOR performs supervised classifications on every field along the mainstem Colorado River, Imperial and Coachella Valleys, and Gila River. This is accomplished using a combination of multispectral satellite data, aerial images, and ground-based field verifications. Roughly half of the collected verified fields are used to train the satellite imagery and determine the crop growing on each field for each time period. The other half of verified field data are used to assess the accuracy of each classification. Data about the crop type and acreage, along with ET crop coefficients, are then used to estimate the ET from crops within each area. Total ET from agricultural irrigation is close to 3 million acre-feet per year. The most prevalent crops by acreage are alfalfa, lettuce, Sudan grass, small grains, and Bermuda grass. BOR also maintains riparian vegetation and open water datasets to determine ET and evaporation from these sources. Each year, these datasets are updated using the best possible imagery (satellite or aerial) by performing change detection analyses. Results from these efforts are reported annually in the report “Lower Colorado River Annual Summary of Evapotranspiration and Evaporation.” Annual ET from riparian vegetation is usually over 400,000 acre-feet, and annual evaporation from open water sources is over 300,000 acre-feet.

This information assists the BOR in meeting its U.S. Supreme Court mandate to provide detailed and accurate records of diversions, return flows, and consumptive use estimates of water diverted from the mainstem of the Lower Colorado River. This program is an example of implementing remote sensing–based methodologies to meet the BOR’s water management needs.



The BOR uses remote sensing and geographic information systems (GIS) to map agricultural fields, riparian vegetation, and open water to estimate evapotranspiration and evaporation within the Lower Colorado Region (left). A riparian/open water area near the Havasu National Wildlife Refuge, Arizona, is shown in the top right, and an agricultural area near Yuma, Arizona, appears in the lower right.

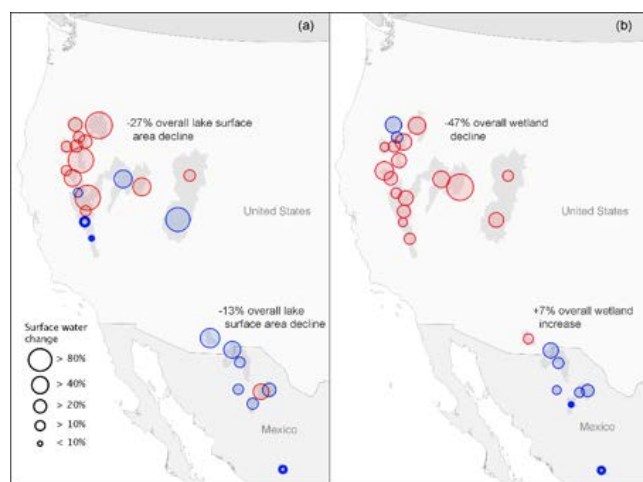
U.S. Fish and Wildlife Service

The U.S. Fish and Wildlife Service (FWS), in concert with its international, Federal, Tribal, state, local, and non-government 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 uses 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 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.

Climate and Human Water Use Diminish Wetland Networks Supporting Continental Waterbird Migration

Migrating waterbirds moving between upper and lower latitudinal breeding and wintering grounds while crossing arid continental interiors rely on a limited network of endorheic lakes and wetlands, which are waterbodies in closed basins with no outflow. Recent drying of global endorheic water stores raises concerns over

deteriorating migratory pathways, yet few studies have considered these effects at the scale of continental flyways. The resiliency of waterbird migration networks across western North America was investigated by reconstructing long-term patterns (1984–2018) of terminal lake and wetland surface water area in 26 endorheic watersheds. Findings were partitioned regionally by snowmelt- and monsoon-driven hydrologies and combined with climate and human water-use data to determine their importance in predicting surface water trends. Nonlinear patterns of lake and wetland drying were apparent along latitudinal flyway gradients. Pervasive surface water declines were prevalent in northern snowmelt watersheds (lakes –27 percent, wetlands –47 percent), while largely stable in monsoonal watersheds to the south (lakes –13 percent, wetlands +8 percent). Monsoonal watersheds represented a smaller proportion of total lake and wetland area, but their distribution and frequency of change within highly arid regions of the continental flyway increased their value to migratory waterbirds. Irrigated agriculture and increasing evaporative demands were the most important drivers of surface water declines. Underlying agricultural and wetland relationships, however, were more complex. Approximately 7 percent of irrigated lands linked to flood irrigation and water storage practices supported 61 percent of all wetland inundation in snowmelt watersheds. In monsoonal watersheds, small earthen dams, meant to capture surface runoff for livestock watering, were a major component of wetland resources (67 percent) that supported networks of isolated wetlands surrounding endorheic lakes. Ecological trends and human impacts identified in this study underscore the



Magnitude of surface water change in the western United States for 26 endorheic watersheds between 1984–1999 and 2000–2018. Change is partitioned by lakes (a) and wetlands (b). Statistically significant ($p < .05$) declines are shown in red and insignificant declines shown in blue. Increases to surface water area are shown in bold blue outline.

importance of assessing flyway-scale change as the model depictions likely reflect new and emerging bottlenecks to continental migration.

Enhancing Wetland Mapping in Alaska Through Automation

The majority of America's wetlands are located in Alaska (65 percent), but to date the FWS National Wetlands Inventory (NWI) Program has produced wetland data covering only 42 percent of the state. Areas without NWI data include over 31 million acres of the FWS National Wildlife Refuge System. Lack of wetland data limits understanding of habitats and impedes conservation of waterfowl, salmon, and big game, which is essential for supporting a stable economy and subsistence populations in Alaska. NWI data are also critical for strategic, cost-effective infrastructure development, especially during project planning, mitigation, and permitting stages. For these reasons, complete wetlands data coverage for the state is a critical priority for NWI, as well as for other Federal and state agencies and Tribes.

Remotely sensed imagery with a relatively fine spatial resolution is required for mapping wetlands, but such imagery has been difficult to obtain for Alaska due in part to low Sun angles at high latitudes. Recent advances in satellite remote sensing provide new data to enhance the efficiency of wetland mapping. Specifically, the 10-meter synthetic aperture radar (SAR) and multispectral data provided by Sentinel-1/2 on a sub-weekly basis are major improvements over historical data. NWI, in partnership with the University of Maryland, recently completed an assessment of Landsat, Sentinel-1/2, and digital elevation data for supporting more time- and cost-efficient NWI data production in Alaska. The project focused on the Selawik and Arctic National Wildlife Refuges and developed innovative algorithms integrated within a streamlined automated workflow supported by a high-performance computing system. Maps of vegetation structure, subpixel water fraction (SWF), and wetlands were produced for 2016–2020. By providing subpixel estimates of fractional water cover within each 10-meter pixel, wetland features smaller than 5 meters could be detected. The water regime, vegetation, and wetland products were found to be well correlated with field data. The automated workflow made it possible to download and process more than 2,000 Landsat and Sentinel images for the selected study regions, which required over 1,200 central processing

unit hours and more than 10 terabytes of disk storage in a single run. These data provide unprecedented spatiotemporal information on wetland hydrology and vegetation dynamics in Alaska and have been well received by stakeholders. NWI is currently testing the utility of these products within an operational workflow.

Lidar and Multispectral Data for Assessing Texas and Oklahoma Songbird Habitat and Density

National Wildlife Refuges in Texas and Oklahoma manage forested habitats to support priority bird populations in the West Gulf Coastal Plain and Ouachitas Bird Conservation Regions. Airborne laser altimetry or lidar can capture details of forest structure that determine bird species diversity, densities, and distributions. Point cloud information from leaf-on multi-return lidar generates a variety of forest metrics such as tree canopy cover, density, and height, as well as other less conventional parameters representing vertical and horizontal habitat structure. PlanetScope multispectral imagery provides a high spatial resolution (3-meter) and frequently acquired (daily) data source that can add plant phenology and composition information when fused with lidar. Forest management relies on continuous forest inventory plots and songbird point counts to monitor habitat conditions and species abundance. Synthesis methods in development will pool data resources for estimating forest inventory parameters, habitat conditions, bird detection bias, availability, and density across each of five refuges.

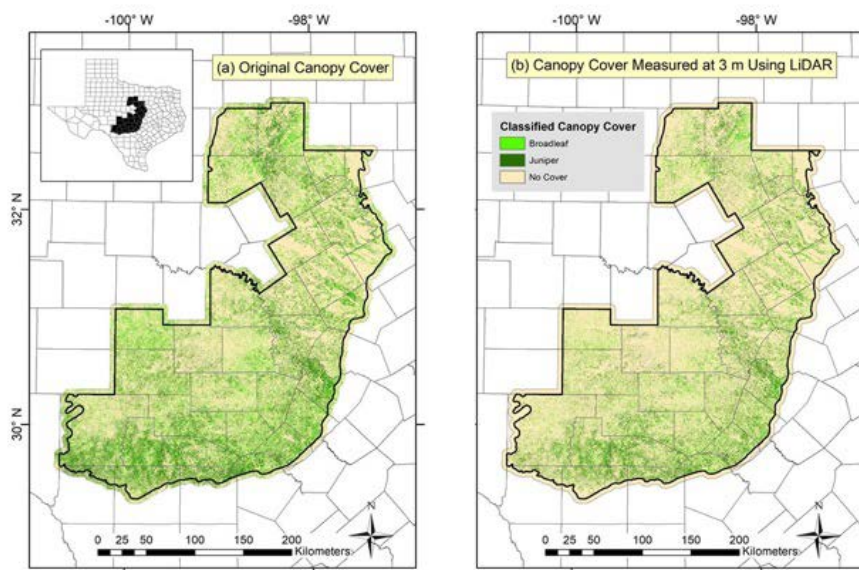
Combined and consistent field surveys and remotely sensed data will provide robust models of species habitat relationships and value-added data layers useful for making land management decisions. Lidar and PlanetScope data and regression tree models showed good performance for estimating basal area and trees per acre. Future work will use these and other metrics to estimate songbird habitat relationships and density. Project outputs will range from standardized data collection protocols to mapped forest inventory parameters, bird density estimates, and information on habitat preferences. Remote sensing applications and songbird models will help inform forest management actions most likely to maintain varied habitat conditions and songbird populations.

Modeling Wildlife Habitat Using 3DEP Lidar

Continuous data on vegetation cover, height, and relative density are increasingly sought as useful metrics for determining animal habitat conditions across large areas. Airborne lidar multi-return information provides a ready source of remotely sensed data that can directly estimate vegetation height and cover at appropriate spatial scales. The USGS 3DEP plans to collect lidar across the entire United States by 2023, creating an unprecedented opportunity for mapping habitat metrics at a fine resolution across entire regions. For this study, the 3DEP lidar point cloud data, which contains all the lidar returns from bare earth and vegetation, were processed to create 2-dimensional canopy height raster maps.

These data are being used to model habitat relationships for the endangered golden-cheeked warbler (*Setophaga chrysoparia*) across its breeding range in the juniper-oak woodlands of central Texas. Researchers obtained 33,897 lidar tiles and their associated digital elevation model (DEM) from 23 separate lidar collections between 2014 and 2018. The lidar data covered 94 percent of the 67,246-square-kilometer warbler breeding range. Canopy height layers were developed at a 1-meter grid cell size using freely available FUSION software. Because most lidar collections did not have classified vegetation returns, the team isolated vegetation canopy for processing by 1) extracting only canopy heights < 40 meters above ground level and 2) extracting points using a mask of classified vegetation cover previously developed at the same resolution from USDA National Agriculture Imagery Program (NAIP) color infrared (CIR) digital aerial photography. The resulting canopy height raster maps better distinguish tree versus shrub or low canopy cover measured at specific heights above ground.

Adjusted juniper and broadleaf tree canopy cover classified from NAIP CIR and attributed with lidar canopy height data are being used to determine the tree height threshold that is most favorable for golden-cheeked warbler habitat. Lidar height data are particularly important across the western range of this woodland-dwelling species, where woody species transition from tree to shrub in response to decreasing precipitation. These habitat metrics will be coupled with more than 1,800-point count surveys of the golden-cheeked warbler conducted in 2018 to determine the distribution of the breeding population and identify desired future conditions



Maps showing (a) original and (b) lidar-corrected tree cover classification at a 1-m grid cell size across the breeding range of the endangered golden-cheeked warbler.

conducive to recovery of this species. A spatially explicit map of golden-cheeked warbler densities across its breeding range will provide land managers an improved understanding of where high-quality habitat currently exists and locations where active management could be used to improve habitat conditions.

USFS-NASA Virtual Pitch Fest

The USFS-NASA Virtual Pitch Fest, virtually hosted in early June 2020, was a creative collaboration inspired by the need for virtual connection due to COVID-19 travel restrictions. The pitch fest provided a platform to share ideas and spark new collaborations around using NASA's remote sensing data products and tools to meet pressing land management needs. During the pitch fest, representatives from NASA and the USFS highlighted key opportunity areas for increased NASA-USFS coordination and collaboration to support sustainable natural resource management. Participants shared and voted for ideas to pilot NASA technology to help address priority land management issues. Up to five ideas from the pitch fest will be selected with the goal of coordinating support in the form of expertise, tools, and knowledge to streamline these efforts. The virtual meeting was attended by 319 people from around the globe and had nearly 60 ideas submitted.

National Park Service

The National Park Service (NPS) has a substantial investment in and a long history of using aerial and spaceborne remote sensing and GPS technologies. The NPS Inventory and Monitoring Program conducts baseline inventories for more than 270 parks across the Nation. Remote sensing data are a critical source of information regarding geology, soils, vegetation, and infrastructure. Aerial photography and satellite imagery have been utilized to compile vegetation maps—a monumental task given the agency has responsibility for more than 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 open and freely available Landsat archive to quantify decadal changes in glacier ice cover and document land cover change in national park units. The NPS has been DOI's sponsoring agency to map all large wildland and prescribed fires as part of the DOI Monitoring Trends in Burn Severity project, using the Landsat archive. GPS supports field data collection, navigation, and search and rescue operations conducted by the agency.

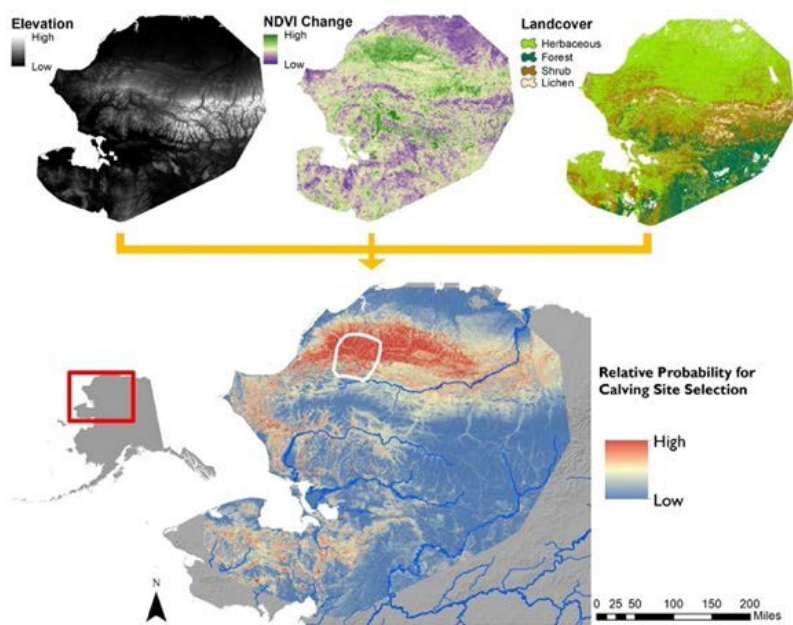
Integrating Satellite and GPS Collar Data to Improve Our Understanding of Caribou Calving

Caribou (*Rangifer tarandus*) are an iconic species of the north and an integral component of the natural ecosystem and socioeconomic wellbeing of local communities. Alaska is home to 32 different caribou herds, which are identified by females returning to specific calving areas each spring to give birth. The Western Arctic Herd, in northwest Alaska, is the largest and ranges across a staggering 150,000-square-mile area. Sound management of a population that relies on such a massive landscape that encompasses numerous land management boundaries requires an understanding of what areas are utilized for calving and why.

Caribou monitoring uses location data from GPS collars deployed on a subset of individuals within the herd. These collars transmit the location of the animal at regular intervals and allow biologists to track nearly real-time movement

throughout the year. Recent analytical developments permit the detection of calving events from this GPS data alone. With data on when and where females birthed calves between 2010 and 2017, scientists can characterize and compare the calving areas and examine how they varied across years. Researchers used remotely sensed data from the new InSAR elevation model, which was collected from airplanes and provides 5-meter-resolution data for Alaska to measure elevation, terrain ruggedness, and solar radiation for the analysis. Coarse land cover classifications were included from a composite of classified satellite and aerial photography and included vegetation indices from the MODIS sensor NDVI. With NDVI, scientists tested whether caribou were selecting for forage quantity (raw NDVI) or for forage quality (change in NDVI values across two weeks, indicating new growth).

The team found that calving areas vary from year to year but are centered in a consistent area that matches estimates going back to the 1960s. Additionally, calving areas were characterized by a unique combination of physical factors and, most importantly, by rapidly greening vegetation at the average time of calving. Results suggest that caribou use memory to guide them back to these general calving areas



The relative probability of caribou calving (lower plot) within the Western Arctic Herd's range, Alaska. The upper three plots illustrate the remote sensing products used in the analysis. The white polygon in the lower figure indicates the calving area used every year from 2010 to 2017.

year after year, at a time when they can access important nutrients after giving birth. Annual variation likely arises as their movements are guided by perception of conditions that year once they arrive. Integrating animal location data with the ever-increasing array of remotely sensed data promises to provide numerous insights into animal ecology that help inform sound management decisions for multiple species.

Monitoring of Permafrost Thaw Erosion Features

The NPS Arctic Inventory and Monitoring Network is using high-resolution satellite images and historical color infrared aerial photographs to monitor the abundance of small landslides resulting from thaw of permafrost. Active-layer detachments (ALD) and retrogressive thaw slumps (RTS) are small landslides that occur from thaw in permafrost regions. They expose bare soil that can be readily mapped on color infrared imagery. NPS mapped the extent of bare soil in thaw-related slope failures in four study areas with continuous permafrost in Alaska's arctic national parks. Aerial photographs from circa 1980, satellite images from 2006 to 2009, and satellite images from 2018 to 2019 were used. In all four study areas, the number of ALD and RTS identified, as well as the area of bare soil they exposed, was lower in the most recent sampling episode than in the previous one, despite recent record warm conditions. One study area had frozen debris lobes (FDLs) in addition to ALD and RTS. In that study area, the bare ground exposed by destabilization and rapid movement of FDLs was greatest in the last sampling episode, probably from deep thaw. These results show that slopes can re-stabilize under warming conditions, if conditions remain cold enough to maintain stable permafrost below the active layer.

Quantifying Glacial Lake Outburst Floods

Physical scientists at Kenai Fjords National Park in Alaska have been using remote sensing methods to monitor an unnamed glacial ice-dammed lake (IDL) and the subsequent glacial lake outburst floods (GLOFs) that regularly occur at Bear Glacier to understand the timing, frequency, and drivers that lead to GLOFs.

These floods are occurring in a popular proglacial lake and may pose a risk to recreational users.

In 2017, a satellite-linked camera was installed and began e-mailing photos daily to be posted on the park's website. Since then, two GLOFs were documented (August 2018 and August 2019). With assistance from the NPS Alaska Regional Office, aerial Structure-from-Motion data were acquired after the IDL drained to capture high-resolution DEMs and orthophotos of the lake basin. Researchers are using monoplotted and GIS software tools to analyze these DEMs and time-lapse photos to calculate rates of filling and discharge at the IDL and to estimate downstream flood magnitude.

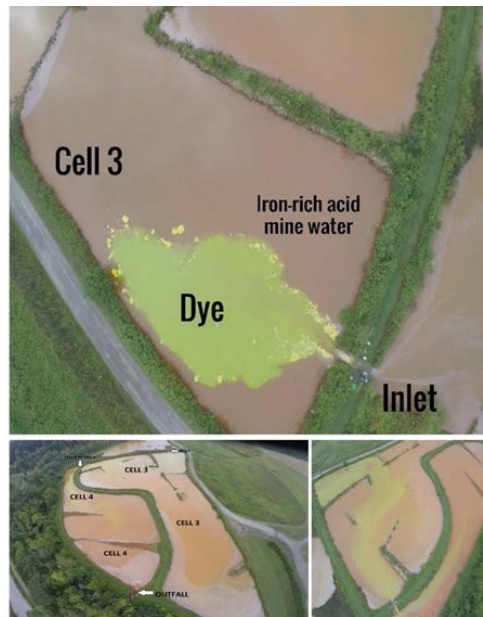
Analysis is ongoing as the team continues to measure weekly lake elevations in the WSL Monoplotted Tool. Lake elevation values in GIS are developed to create polygon contours of the lake and derive IDL volumes with sub-meter accuracy in near-real time. By comparing current lake levels to previous GLOF events, park managers may be able to better assess the timing of future GLOFs and notify the public of a potential GLOF.

Office of Surface Mining Reclamation and Enforcement

The Office of Surface Mining Reclamation and Enforcement (OSMRE) remote sensing program provides OSMRE offices, states, and Tribes with the necessary tools to use remote sensing technologies to support Titles IV (Abandoned Mine Lands) and V (Regulation of Current Mining) of the Surface Mining Control and Reclamation Act of 1977. As part of this support, the OSMRE remote sensing program provides high-resolution satellite imagery, aerial photography, and lidar data to conduct analysis of terrain, vegetation, and hydrologic function on active mine sites to ensure reclamation is consistent with the approved mining permit. These data are also used to support inventory, monitoring, and assessment of abandoned mine land features to ensure there is no threat to the environment or to health and human safety.

Bird's-Eye View of a Dye Tracer Test Using UAS

Monastery Run Wetland 1 near Latrobe, Pennsylvania, is a passive mine water treatment system constructed in 1997–1998 to treat multiple discharges from an abandoned underground mine. The OSMRE Technical Support Division assisted the Pennsylvania Department of Environmental Protection (PA DEP) with diagnosing issues and improving the effectiveness of the water treatment system. The Wetland 1 system was constructed to provide settling ponds and wetlands with sufficient retention time to allow the removal of iron prior to entering Four Mile Run River. In July 2019, OSMRE personnel conducted an optical dye tracer test to determine the approximate retention time of each of the four cells comprising Wetland 1. OSMRE's UAS was not available during a July 2019 dye test when OSMRE and PA DEP personnel added a fluorescent yellow-green dye (Xanthene) at the main mine water source in Cell 1. The initial dye tracer test was successful at determining the retention time in Cells 1 and 2. However, the dye became extremely diluted and difficult to track in Cells 3 and 4 because of the addition



Images show the dye poured at the inlet, moving through the cells to the outfall, captured by UAS video. The width of pond at its thickest is approximately 500 feet, with images oriented clockwise from the top toward the SE, NNE, and W.

of a considerable mine water source in Cell 2. Therefore, a second dye tracer test was conducted in August 2019 with the help of the UAS to record the progression of dye through Cells 3 and 4. In August 2019 the fluorescent dye was added at the outfall of Cell 2 into Cell 3 within the Wetland 1 treatment system. According to the original design information, total retention time should be 29 hours at the peak design flow of 1,710 gallons/minute (gpm). Based on visual dye detection in August 2019, the retention times in Cells 3 and 4 were 61 and 66 minutes,

respectively. When retention times were totaled from the dye tests for each of the four cells, a hydraulic retention time within Wetland 1 was approximately 4.65 hours. Therefore, the results of the testing indicate that major modifications are necessary to the Wetland 1 passive treatment system to improve both retention time and aeration for dissolved iron removal.

Virtual Mine Monitoring with Web Map Applications

During the COVID-19 pandemic, the majority of OSMRE employees easily transitioned into a maximum telework schedule, and with technology in place to stay in contact and have virtual meetings, they have worked successfully on collaborative assignments. On the other hand, employees that have assignments that involve travel and being in the field have faced challenges completing some of their regular assignments. The OSMRE GIS team has been providing geospatial tools and products to support the mine inspectors and other field personnel. One example is the creation of web map applications that allow mine inspectors to remotely view surface coal mines and do collaborative work with the rest of the mine team members.

The web maps are created with ESRI's Web AppBuilder and are hosted on ArcGIS Online. The maps contain several interactive layers:

- Current high-resolution satellite imagery requested through USGS as well as previous collections archived in the Global Enhancement GEOINT Delivery/EnhancedView Web Hosting Service website.⁷
- Mid-resolution Sentinel-2 European Space Agency satellite image service. The image service has been configured to automatically update with the latest image containing less than 20 percent cloud coverage.
- Reference mine data such as the mine permit boundary, pit labels and mine features, post-mining land use, bond status, reclamation status, environmental resources monitoring locations, and other mine-specific layers.

Editable point, line, and polygon layers allow users to create new features on the map with comments that are saved to the map and viewable by the rest of the mine team. The web map applications are simple and offer basic analytical tools (such

⁷ <https://www.maxar.com/products/global-enhanced-GEOINT-delivery>

as measurement, coordinate conversion, bookmark, and swipe tools). Although OSMRE has been using web maps and web map applications for a while now, these have rapidly become even more popular recently by allowing field personnel to continue to monitor mine sites remotely.

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 non-Federal U.S. satellites. Internationally, the FCC coordinates satellite radio-frequency usage with other countries. The FCC's activities in FY 2020 related primarily to commercial communications satellites and Earth observation satellites, as well as experimental satellites.

The FCC took a number of significant actions in administrative and rulemaking proceedings in FY 2020, including the following:

- On April 23, 2020, the FCC updated its rules regarding orbital debris mitigation, which were adopted in 2004. The changes are intended to help ensure the sustainability of space as new satellite constellations proliferate and innovative satellite technologies emerge. The new rules address several issues, including disclosures regarding collision risks and safety measures, casualty risk assessments, post-mission disposal, spacecraft tracking and data sharing, and frequency coordination during orbit-raising, among others. The new rules also clarify that satellite operators should secure satellite commands against unauthorized access and use and update some administrative processes. In connection with these rule changes, the Commission sought further comment on standards for evaluating aggregate constellation risk, satellite maneuverability above a certain altitude in low-Earth orbit, and indemnification requirements. This action will



help to ensure that FCC decisions are consistent with the public interest in ensuring that space remains viable for future satellites and systems and the many services those systems provide to the public.

- On May 13, 2020, the FCC adopted new rules to further facilitate the deployment of Earth Stations in Motion (ESIMs). ESIMs are earth stations located aboard ships, aircraft, and vehicles. The rule changes permit ESIMs to operate in additional frequency bands using geostationary orbit satellites and establish a regulatory framework for ESIMs to operate using nongeostationary orbit satellites. The Commission also sought comment on additional rule changes regarding technical rules for ESIMs operating with nongeostationary orbit satellites using one portion of the Ka-band.
- On May 12, 2020, the FCC adopted new rules to ensure that both U.S.-licensed space stations and non-U.S.-licensed space stations that provide service in the U.S. market pay the same regulatory fees. This action is intended to encourage regulatory equity between domestic- and foreign-licensed space stations.
- On August 26, 2020, the FCC eliminated a rule that required certain fixed satellite service systems using nongeostationary orbits to demonstrate that they were capable of providing coverage to all parts of the United States. In doing so, the FCC found that, as a result of substantial changes in the satellite marketplace, the rule was no longer serving its original purpose. For example, compiled evidence suggested that the rule may have actually discouraged or hindered deployment of satellite systems designed to improve communications coverage in parts of the country like Alaska and the arctic areas, thereby frustrating one of the purposes of the rule. The Commission concluded that the rule should be eliminated in order to better promote service to more parts of the United States and to provide design and operational flexibility for innovative nongeostationary orbit satellite systems.

During FY 2020, the FCC issued rulings facilitating the deployment and operations of several nongeostationary satellite systems designed to provide and support communications services, including high-speed broadband and the “Internet of Things.” These rulings include the following:

- On October 17, 2019, the FCC authorized Swarm Technologies, Inc., to construct, deploy, and operate a satellite system consisting of 150 satellites operating at altitudes ranging from 300 kilometers to 550 kilometers and utilizing the Very High Frequency band. This nongeostationary orbit satellite constellation is intended to provide two-way data communication services throughout the United States and the world.
- On December 19, 2019, the FCC authorized Space Exploration Holdings, LLC, to reconfigure its previously authorized satellite constellation to increase the number of authorized orbital planes and reduce the number of satellites per orbital plane in the 550-kilometer–altitude range.
- On April 22, 2020, the FCC issued a ruling outlining the conditions under which Viasat, Inc., could obtain a license for earth stations in the United States for use with its system, which would operate under the authority of the Netherlands. The system would consist of 20 satellites, operating at an altitude of 8,200 kilometers and utilizing frequencies in the Ka-band and V-band. The system would offer broadband services.
- On May 6, 2020, the FCC issued a ruling outlining the conditions under which Hiber, Inc., could obtain a license for earth stations in the United States for use with its system, which would operate under the authority of the Netherlands. The system would consist of 24 satellites, operating at an altitude of approximately 600 kilometers and utilizing frequencies in the Ultra-High Frequency (UHF) band. The system would provide consumers in the United States and worldwide with connectivity for sensors and Internet of Things devices.
- On May 29, 2020, the FCC issued a ruling outlining the conditions under which Myriota Pty., Ltd., could obtain a license for earth stations in the United States for use with its system, which would operate under the authority of Australia. The system would consist of 26 satellites operating in the UHF band at altitudes between 400 and 600 kilometers. The system would provide communications for Internet of Things devices.
- On July 29, 2020, the FCC authorized Kuiper Systems, LLC (Kuiper), to deploy and operate a new nongeostationary orbit satellite system consisting of up to 3,236 satellites operating in low-Earth orbit at altitudes of

590 kilometers, 610 kilometers, and 630 kilometers. The FCC authorized the Kuiper satellite system to communicate using frequencies in the Ka-band. The system would provide high-speed broadband service to consumers, government, and businesses.

On August 24, 2020, the FCC issued a ruling outlining the conditions under which WorldVu Satellites Limited, debtor-in-possession, doing business as OneWeb, could obtain a license for earth stations in the United States for use with its system that would operate in the V-band, under the authority of the United Kingdom. The FCC ruling addressed 1,280 satellites that would operate at an altitude of approximately 8,500 kilometers, as well as the addition of V-band communications with 720 OneWeb satellites that the Commission previously ruled on, which would operate in the Ku-band and V-band.

In FY 2020, the FCC authorized several other satellite deployments and operations. These authorizations include the following:

- On October 7, 2019, the FCC issued a ruling outlining the conditions under which Spire Global, Inc., could obtain a license for earth stations in the United States for use with the portion of its remote sensing satellite system designated as the MINAS system, consisting of up to 636 low-Earth orbit satellites, operating under the authority of Luxembourg at altitudes from 385 to 650 kilometers.
- On March 25, 2020, the FCC authorized Space Logistics, LLC, to construct, deploy, and operate a spacecraft to be used to extend the mission lifetime of geostationary satellites by docking with the client spacecraft and maintaining the position of the docked spacecraft at its assigned orbital location. The authorization includes operations following deployment from the launch vehicle, during orbit-raising maneuvers, and during rendezvous and docking with the Intelsat-1002 satellite at the longitude 1° west orbit location.
- On May 27, 2020, the FCC authorized BlackSky Global, LLC, to increase the number of satellites in its nongeostationary orbit remote sensing satellite system from 4 satellites to 16 satellites, operating at altitudes ranging from 385 to 600 kilometers.

In addition to these commercial operations, the FCC continued to grant applications for experimental operations by non-Federal small satellites. Many of the experimental grants by the FCC for small satellite operations were to universities and institutions conducting research and developing new spacecraft technologies. The satellites' missions include activities ranging from remote sensing missions, such as collecting data about the ionosphere, to missions testing the performance of certain technologies in space, such as solar sails, optical communications, and propulsion systems. The FCC also granted experimental licenses in FY 2020 for inter-satellite communications between existing nongeostationary satellite constellations and experimental small satellites. Other experimental grants by the FCC included grants for communications associated with launch vehicles and for the testing of new telecommunications satellites and ground terminals, including testing equipment designed to provide satellite connectivity for consumer smartphones when those phones are beyond the range of terrestrial base stations.

In FY 2020, the FCC granted several license modifications and special temporary authorizations for satellite networks. Many involved routine testing or redeployment of satellites with a multi-satellite system. Several of these actions warrant particular mention:

- October 2, 2019, and May 6, 2020: The FCC granted special temporary authority to DG Consents Sub, Inc., relating to the relocation of the WorldView-4 nongeostationary orbit satellite due to technical issues with the satellite's control movement gyros.
- October 24, 2019, November 7, 2019, January 30, 2020, February 10, 2020, and March 19, 2020: The FCC issued a series of grants of special temporary authority to Space Explorations Holdings, LLC, related to positioning and testing of new satellites in its nongeostationary orbit constellation.
- November 14, 2019, and December 5, 2019: The FCC granted EchoStar Satellite Services, LLC (Echostar), special temporary authority to extend the service coverage area of the EchoStar 9 satellite at the longitude 121° west orbit location to cover the Bahamas for emergency operations following Hurricane Dorian. On January 30, 2020, the FCC granted a license modification for Echostar to permanently extend its service coverage to this area.

- January 19, 2020: The FCC granted DIRECTV Enterprises, LLC, special temporary authority to de-orbit the SPACEWAY-1 satellite from the longitude 138.9° west orbit location due to unexpected thermal damage to the satellite's batteries.
- March 16, 2020: The FCC granted a license modification to Planet Labs, Inc., to modify the operational orbital altitude range for the SkySat-3 satellite, to include operations down to an altitude of 400 kilometers and to specify a range of authorized orbital locations for the SkySat-16 to SkySat-21 satellites that would include the inclination range of 40–60 degrees. The modification enhances the image coverage and resolution of Planet Labs' commercial remote sensing satellites.
- June 9, 2020: The FCC modified the conditions for operations of the O3b Limited, Telesat Canada, Audacy Corporation, and Space Exploration Holdings, LLC, nongeostationary satellite systems to include additional frequencies in the V-band.

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

- On April 8, 2020, the FCC added Eutelsat S.A.'s EUTELSAT 139 West A satellite to the permitted list, operating under the authority of France and using the Ku-band at the longitude 139° west orbit location.
- On April 8, 2020, the FCC added Eutelsat S.A.'s EUTELSAT 8 West B satellite to the permitted list, operating under the authority of France and using the Ka-band at the longitude 8° west orbit location.
- On April 8, 2020, the FCC added Eutelsat S.A.'s 12 West B satellite to the permitted list, operating under the authority of France and using the Ku-band at the longitude 12.5° west orbit location.
- On April 29, 2020, the FCC added Intelsat License, LLC's HISPASAT 143W-1 satellite to the permitted list, operating under the authority of Spain and using the S- and Ku-bands at the longitude 143° west orbit location.

- On May 8, 2020, the FCC added SES-17 S.a.r.l.'s SES-17 satellite to the permitted list, operating under the authority of Luxembourg and using the Ka-band at the longitude 67.1° west orbital location.

U.S. DEPARTMENT OF AGRICULTURE

USDA

Agricultural Research Service

The Agricultural Research Service (ARS) is the intramural research branch for USDA. There are a wide variety of interactions ARS has with NASA, including research on space crop production, astronaut nutrition, biotechnology, earth science, environmental monitoring, space flight, and other issues.

For many years, ARS has been integral to the calibration and validation of earth science products, including soil moisture, evapotranspiration, land cover, and drought status. Projects like the Long-Term Agroecosystem Research network have been operating watershed-scale networks that have supported field experimentation and remote sensing calibration and validation sites for satellites like the Soil Moisture Active Passive (SMAP) mission. Future NASA satellites will also use field experiment data from USDA-managed experiments to develop algorithms for retrieval of cropland coverage and soil moisture, including the NASA-ISRO Synthetic Aperture Radar (NISAR) mission set to launch in 2024. ARS scientists served on multiple satellite science teams, including SMAP, NISAR, Ecostress, and Landsat, providing invaluable expertise in agricultural monitoring and interpretation. Currently, the SMAP Validation Experiment 2019–2022 is being conducted by ARS in collaboration with NASA to improve the retrieval of soil moisture data over mixed agriculture/forest landscapes, like those found along the eastern U.S. seaboard.



ARS, in collaboration with NASA Applied Sciences Water Resources Program under the GRAPEX project, has refined and applied a multi-scale remote sensing toolkit for mapping crop water use and crop stress for improved irrigation scheduling and water management in vineyards in the Central Valley of California. This toolkit output will eventually be made available to wineries and orchard growers throughout California and other western states for improving water management and irrigation scheduling through the OpenET platform. This is a public and private partnership involving NASA, USGS, USDA-ARS, Google, Environmental Defense Fund, and several universities to provide crop water use data operationally to the agricultural industry, water districts, and the public.

Water quality monitoring is also being developed, starting with drone-based systems, with the hope of extending this work to satellite-based products to assess harmful algal blooms and contaminated waterways. Carbon monitoring is also a focus of research, with ARS leading an effort to provide continental-scale tillage and carbon storage products that will inform assessments of crop yield and conservation. The basis of this monitoring is a combination of remote sensing observations, models, and ground-based monitoring throughout the United States.

Space crop production is an important and rapidly growing area of synergy between ARS and NASA. NASA is evaluating genetically engineered (GE) crops developed by ARS for fresh food production for lunar and Martian agriculture. ARS's GE fruit trees not only continuously produce fresh and nutritious produce but will help astronauts maintain valuable bone density under microgravity for extended periods. Microbes that ARS developed for controlled environment agriculture will also be used by NASA to accelerate plant growth and increase food production efficiency under artificial environments. ARS and NASA also collaborate on biocontrol research to eliminate pests that threaten crops grown in space during long-term human missions. ARS studied foraging and infection dynamics of beneficial nematodes (small round worms) that control insect pests onboard the International Space Station (ISS). The research was sponsored by the ISS National Lab and NASA. Finally, ARS, NASA, and Disney have joined forces in Orlando at the ARS biotechnology research laboratory at EPCOT to communicate the benefits of plant genome editing and biotechnology for exoplanetary agriculture to up to 6 million visitors per year.

Other partnerships of note are the study and development of microgreens to improve the diets of astronauts in space with fresh food. NASA has been concerned for years about astronauts who returned to earth having lost significant body mass because high CO₂ atmospheres of the space station deadened their taste receptors and their desire to eat. ARS scientists in Beltsville, Maryland, were the first to report that microgreens—a seedling form of fresh vegetables—are 10 to 14 times more nutrient-dense and aromatic than their mature plant forms. The researchers developed a biodegradable, hydrogel-based “artificial soil” that supports a full 14-day growth cycle for microgreens, which equals conventional production yields without the daily watering requirements. NASA scientists are investigating using this technology for producing savory, highly nutritious microgreens during space travel.

To improve these collaborations, a Memorandum of Understanding was established between USDA and NASA in 2020, with an annual meeting being held each spring to update the various agencies on the collaborations that are ongoing and to provide a forum for new partnerships to develop. ARS has served as the organizational leader for this endeavor. ARS serves as the primary point of contact for USDA on Earth observations with respect to NASA collaborations, including serving on the interagency U.S. Group on Earth Observations (USGEO).

Foreign Agricultural Service

The Foreign Agricultural Service’s (FAS) Global Market Analysis (FAS/GMA) serves as a major source of objective and reliable global agricultural production information to the U.S. Department of Agriculture’s (USDA) monthly World Agricultural Supply and Demand Estimates (WASDE) report, the primary source of the USDA’s global commodity outlook. The monthly WASDE report provides public access to information affecting world food security and is crucial to decisions affecting U.S. agriculture, trade policy, and food aid. FAS/GMA uses satellite imagery at regional, national, and subnational scales to operationally monitor and analyze monthly changes in global crop production. FAS archives and displays global

monthly crop production, supply, and distribution (PSD) data from the USDA's WASDE report on the FAS PSD Online web site.¹

During 2020, the International Production Assessment Division (IPAD) operated the remote sensing program at FAS/GMA. IPAD is an operational user of remotely sensed imagery and processed multiple U.S. and international sources of global imagery and satellite-derived weather information. Crop type and crop area were primarily mapped by Landsat 7 and 8 and Sentinel 2A and 2B satellites. Global crop conditions and relative crop yields were monitored and measured by NASA's MODIS (Moderate Resolution Imaging Spectroradiometer) sensor onboard the Aqua and Terra satellites.

The USDA-NASA Global Agricultural Monitoring (GLAM) web system displayed and archived historical NDVI time series imagery from the MODIS-Terra (i.e., 2000–present) and MODIS-Aqua (i.e., 2002–present) satellites. The GLAM-NDVI-MODIS web interface easily allows public users to analyze and compare current NDVI crop conditions with past years' NDVI crop conditions.²

FAS/GMA also maintained several public global agricultural datasets by processing, archiving, and displaying a variety of satellite imagery products on the FAS/GMA Crop Explorer, Global Agricultural and Disaster Assessment System (GADAS), and Global Reservoir and Lake Monitor (G-REALM) web systems. Crop Explorer allows public users to monitor, analyze, and display rainfall, temperature, soil moisture, and vegetation conditions by utilizing satellite imagery from NASA's Terra and Aqua satellites.³ Crop Explorer's global two-layer soil moisture product was enhanced by measurements from NASA's Soil Moisture Active Passive (SMAP), which was processed by researchers based at NASA's Goddard Space Flight Center. GADAS is a new state-of-the-art geographic information system that displays numerous Earth observation data streams from NASA, NOAA, and other agencies, with GIS tools and cropland datasets to support agricultural and disaster assessment analysis. GADAS is available to the public online at <https://geo.fas.usda.gov/GADAS/index.html>. In addition, G-REALM monitored and displayed reservoir

1 <https://apps.fas.usda.gov/psdonline/app/index.html#/app/home>

2 <http://glam1.gsfc.nasa.gov/>

3 <https://ipad.fas.usda.gov/cropexplorer>

and lake water heights by utilizing satellite radar altimeter data from NASA's Ocean Topography Experiment/Poseidon, Jason-1, Jason-2, and Jason-3 satellites.⁴

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; administration and management of 155 national forests and 20 national grasslands collectively known as National Forest System (NFS) lands, totaling 193 million acres (146 million forested); and assistance in the stewardship of approximately 620 million acres of additional forest lands by other Federal, state, Tribal, and community forest agencies and private land owners.

In FY 2020, the USFS collaborated with NASA, NOAA, the USGS, other agencies, and other external agency partners and cooperators to apply operational satellite and airborne imagery and the most advanced remote sensing and geospatial technologies.

Specific accomplishments included the following:

- Planned, organized, and conducted a joint USDA workshop entitled USFS-NASA Pitch Fest in June 2020. The two-day workshop and several follow-up engagements focused on sharing ideas to foster collaboration opportunities between NASA and USDA regarding the use of NASA data products and tools to meet pressing land management needs. Approximately 50 ideas and project concepts were presented and discussed and are at different stages of review and implementation.
- Collected comprehensive Earth Observing System (EOS), MODIS, and Suomi National Polar-orbiting Partnership (Suomi NPP)–Visible Infrared Imaging Radiometer Suite (VIIRS) near-real-time data for the United States and Canada. Provided and disseminated operational near-real-time fire mapping and geospatial data products to fire managers and the public.

⁴ https://ipad.fas.usda.gov/cropexplorer/global_reservoir/

- Continued activities with NASA Goddard Space Flight Center's Direct Readout Laboratory under a USFS-NASA interagency agreement to test and operationally implement near-real-time satellite data-processing technologies, including land, atmospheric, and ocean science processing algorithms for EOS and Suomi NPP sensors, to support evolving resource management and operational information needs. Also continued related USFS-NASA coordination to organize and deliver webinars on new/refined low-latency science data products, decision support systems and other remote sensing science updates to the global near-real-time community.
- Continued collaboration with NASA Goddard Space Flight Center Terrestrial Information Systems Laboratory/Direct Readout Laboratory to complete the development of a NASA-hosted computing platform to host Forest Service operational needs for near-real-time satellite data processing, strategic Active Fire Mapping processing, analysis and product generation, and forest disturbance monitoring and damage mapping.
- Utilized MODIS and Landsat imagery to conduct coarse-level forest damage assessments for large geographic areas of the continental United States in the immediate aftermath of significant forest disturbance events (e.g., hurricanes, tornadoes). This strategic information supported the agency in targeting areas for fuels management activities and/or areas where higher-resolution forest damage assessments are required.
- Continued to maintain and distribute 250-meter forest attribute data surfaces derived from MODIS imagery and other geospatial predictor data using nearest neighbor imputation methods.
- Continued to maintain and distribute 250-meter forest carbon estimates derived from MODIS imagery and other geospatial predictor data using nearest neighbor imputation methods.
- Continued coordination with NASA Ames Research Center to upgrade the Automated Modular Sensor (AMS) electronics and sensor components and further develop the AMS firmware and software for onboard processing system capabilities and user interface to support operational integration flights on USFS aircraft.

- Operationally applied Landsat 7 Enhanced Thematic Mapper (ETM), Landsat 8 OLI, and Sentinel 2 imagery to respond to 119 requests to map the location, extent, and severity of large wildfires amounting to more than 5.2 million acres in FY 2020. These rapid-response products support post-fire emergency stabilization/hazard mitigation activities conducted by Forest Service Burned Area Emergency Response (BAER) teams.
- Operationally applied Landsat 7 ETM, Landsat 8 OLI, and Sentinel 2 imagery to map and estimate post-fire basal area loss and canopy cover loss for 92 large wildfires totaling over 5.1 million acres in FY 2020. These products support forest restoration planning management activities and efficient use of resources to support those activities.
- Continued to operationally apply Landsat 4/5 Thematic Mapper (TM), Landsat 7 ETM, Landsat 8 OLI, and Sentinel 2 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 2020 included the completion of an additional 1,129 fires, increasing the extent of the historical MTBS data record to include 25,614 fires covering more than 184 million acres of burned lands.
- Coordinated with the University of Maryland, NASA, and the USGS under the auspices of a NASA ROSES A35 Wildfires Project to continue to refine the Landsat 8 active fire detection algorithm and related fire remote sensing science initiatives using NASA and European Space Agency (ESA) remote sensing data.
- Continued technical collaboration activities between the USFS and NASA Ames Research Center regarding the exchange, technology transfer, and implementation of relevant NASA, Forest Service, and commercial technologies, capabilities, and emerging data sources. These collaboration activities supported manned and unmanned airborne remote sensing activities in the USFS and interagency community through the Tactical Fire Remote Sensing Advisory Committee.
- Used imagery from Landsat 8—Operational Land Imager (OLI) and the USDA National Agriculture Imagery Program (NAIP) to initiate,

complete, and update mid-level vegetation mapping, riparian mapping, land cover change, and FSVeg spatial update products for national forest lands and adjacent land areas throughout the country. Mapped areas included ten National Forests encompassing approximately 10 million acres.

- Initiated effort to conduct Tree Canopy Cover data updates for 2019/2021 for the contiguous United States, interior Alaska, Hawaii, Puerto Rico, and the Virgin Islands, using imagery from Landsat and NAIP.
- Used Landsat TM/ETM/OLI and NAIP imagery in conjunction with other core geospatial datasets to conduct ecological land-type associations and soil-type mapping on NFS lands in the northeast and western United States, which the USFS, Natural Resources Conservation Service, and other agencies apply to resource management, planning, and decision making.
- Completed and delivered a comprehensive and consistent land-cover/land-use monitoring system, the Landscape Change Monitoring System (LCMS), for the continental United States. LCMS utilizes Landsat TM/ETM/OLI time-series stacks within Google Earth Engine to detect and monitor land-cover/land-use change from the mid-1980s to the present across all administrative ownerships including CONUS and southeast Alaska. In FY 2020, the 1985–2019 CONUS change product was extended to include 2020. This effort is being conducted in collaboration with several Federal and academic partners.
- Continued to develop and refine standards and practices for integrating light detection and ranging (lidar) into forest and resource management (i.e., defining acquisition specifications, data-quality assessment, analysis/modeling procedures for forest parameters).
- Continued to expand USFS participation 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.
- Continued to provide operational web mapping and data services for NAIP imagery. Additionally, provided resource management guidance based on airborne imagery, and selected moderate resolution imagery

from NASA satellite assets for consumption/use by USDA and Bureau of Land Management staff. The approximately 1 PB data archive provided spatially and temporally comprehensive coverage for the United States and is essential for daily USDA and partner operational business information needs.

- Forest Inventory and Analysis (FIA) and Forest Health Protection (FHP) staff continue to utilize CONUS and OCONUS Landsat 8, MODIS, and NAIP imagery products to support inventory and monitoring of the Nation's forests, including mapping and use in post stratification to improve forest attribute estimates.
- Conducted a geotechnical evaluation on joint lidar-hyperspectral datasets and analyses for use in forest applications. The pilot study assessed the practicality of the use of NASA's Goddard's LiDAR, Hyperspectral & Thermal Imager (G-LiHT) data for land-cover classification. Results of the study indicate integration of G-LiHT lidar and hyperspectral data improved land-cover classification accuracy. Additionally, USDA continued ongoing work with NASA scientists to continue to use G-LiHT data to augment forest inventory of interior Alaska, including initiating investigations for improving carbon monitoring.
- USDA continued in FY 2020 to use NASA G-LiHT data with NAIP imagery throughout CONUS to assess and monitor forest conditions.
- NASA and USDA are continuing a 50-year legacy of collaboration regarding public engagement and STEM education around "Moon Trees" by again partnering to send tree seeds to space on Artemis I, scheduled to launch in August 2022. This collaboration continues the legacy of "Moon Trees" grown from seeds that orbited the moon in Apollo 14 in 1971. The collaboration connects Artemis I programming to Earth science, conservation education, data literacy, and citizen science, serving both educators and youth nationwide via such programming as the Forest Service's Natural Inquirer Moon Tree Lesson Plans and Learning Modules⁵ and NASA's Office of STEM Education.⁶

5 <https://www.naturalinquirer.org/Artemis-Moon-Trees-v-397.html>

6 <https://www.nasa.gov/stem/about.html>

- NASA hosted a Forest Service Distinguished Visiting Scientist at JPL, studying landscapes in the Amazon.
- USFS scientists serve on the Global Ecosystem Dynamics Investigation (GEDI) science team and use NASA's GEDI instrument on the International Space Station, which collects lidar waveform data for assessing the existing biomass of forests and how changes in this biomass caused by human activities or variations in climate may impact atmospheric CO₂ concentrations. Additionally, the three-dimensional structure of forests is a key component of habitat quality and biodiversity at local to regional scales.
- USFS helped support NASA's Carbon Monitoring System (CMS) with two USFS scientists serving as team members in Phase 3 CMS in 2020, and three scientists as Biomass Working Group Team Lead and participating members. A Forest Service scientist served as co-investigator for "Preparing the global CMS Flux system for application to carbon flux inventories via regional-scale, observation-based evaluations."
- The Forest Inventory and Analysis program has 11 agreements to share Forest Service data with NASA (JPL, Goddard Flight Center) active in FY 2020. Remote sensing scientists often rely on Forest Inventory and Analysis field data to calibrate or validate observations, or combine with observational data for scientific studies.
- The USFS/USGS/NASA Silvacarbon partnership for building capacity in developing nations in 2020 included hosting the following workshops:
 - NASA CMS Science Team Meeting—La Jolla, California—November 12–14, 2019
 - Regional—Collaboration with SERVIR-Mekong: Training on Forest Stand Height Estimation Using SAR Data—Bangkok, Thailand—January 13–15, 2020
 - 16th GFOI Regional Workshop—How is REDD+ data used for management, policy, and other reporting mechanisms in Latin America—Fort Collins, Colorado—January 21–24, 2020

Risk Management Agency

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

Through crop insurance, RMA provided assistance to farmers and ranchers impacted by natural disasters, including hurricanes and fires. In FY 2020, RMA used remote sensing data, such as Landsat, Sentinel-2, MODIS, and high-resolution aerial and satellite imagery. Many of these imagery products were collected as a result of the USDA's interagency coordination.

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

RMA staff were active participants in the Science Teams, such as the USDA Soil Moisture Working Group that focuses on the use of data from the NASA SMAP mission. As an operational user of remote sensing products, RMA's participation in these work groups provided insight to scientists in developing applications that benefit crop insurance delivery and oversight, as well as farmers and ranchers across America.

In addition, RMA often partnered with scientists and researchers to develop products to meet agency business needs, including Oregon State University-Parameter-elevation Regressions on Independent Slopes Model, University of

Illinois, and Tarleton State University–Center for Agribusiness Excellence on integrating satellite imagery for enhancing program integrity models.

NATIONAL SCIENCE FOUNDATION

NSF

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

Division of Astronomical Sciences

The Division of Astronomical Sciences (AST), within the Directorate for Mathematical and Physical Sciences (MPS), 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, the Arecibo Observatory, the Green Bank Observatory, and the National Solar Observatory. During FY 2020, the former National Optical Astronomy Observatories were merged with the Gemini



Observatory and operation of the Vera C. Rubin Observatory to form NSF's National Optical-Infrared Astronomy Research Laboratory (NOIRLab).

During FY 2020, AST, in partnership with the European Union, Canada, Japan, the Republic of Korea, and Taiwan, continued science operations of the Atacama Large Millimeter/Submillimeter Array (ALMA), an interferometric array located near San Pedro de Atacama, Chile. ALMA continued to receive a high number of observing proposals (approximately 1,600). Capabilities offered to the community included simultaneous observations with arrays of 12- and 7-meter-diameter antennas, observations with antenna separations of up to 16 kilometers, and observations at frequencies of up to 900 gigahertz. ALMA continued to provide unique insights across a broad range of topics, including planets and planet formation, proto-stellar and debris disks, low- and high-mass star formation, stellar evolution, normal galaxies, galactic centers, and galaxy formation and evolution. For most of FY 2020, the COVID-19 pandemic caused significant issues for ALMA: from mid-March 2020 science operations were stopped, and the observatory was closed. While no science observations were made, support of the scientific user community continued, and access to the data archives was possible. Toward the end of FY 2020, the observatory began working to restart science operations, expected to occur by mid-March 2021.

The NSF's Green Bank Observatory (GBO) continued to operate throughout FY 2020, despite COVID-19 pandemic challenges. GBO's primary instrument is the 100-meter Green Bank Telescope (GBT), the world's largest fully steerable single-dish radio telescope, operating at frequencies from 0.2 GHz to 116 GHz. The GBT's large sky coverage, very high sensitivity, wide wavelength coverage, and extensive suite of instruments enable work in almost all areas of astrophysics, from pulsars and very-low-frequency gravitational waves to interstellar chemistry and physics. Recent highlights include discovering large carbon-bearing ringed molecules, shedding light on the growth of molecular complexity in space. GBT is complementary and synergistic with interferometric arrays. It is a highly sensitive and thus critical element in very-long-baseline interferometry, and a bistatic radar receiver for rapid and sensitive imaging of near-Earth objects and asteroids. Research and development of radar transmit capabilities at the GBT began in FY 2020, and development of a high-power radar for planetary and solar system astronomy is being explored.

Construction of the NSF's Daniel K. Inouye Solar Telescope (DKIST) continued through FY 2020, albeit at a slower pace due to delays caused by the COVID-19 pandemic. The pandemic completely halted on-site construction for a period of 2.5 months in the third quarter of FY 2020, with on-site activities resuming in the fourth quarter. Also in the third quarter, the NSF Acting Director, Dr. Kelvin K. Droegemeier, authorized an increase to the award for DKIST construction. 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 Academies of Sciences, Engineering, and Medicine. After completion, DKIST will be the world's flagship ground-based solar telescope designed specifically for the study of solar magnetic fields on scales as small as 30 kilometers. Despite setbacks due to the pandemic, the project is approximately 97 percent complete. In FY 2020, the NSF and the DKIST project issued a press release showing the highest-resolution images of the Sun ever recorded and demonstrating the imaging capabilities of the observatory. These images were the result of the first sunlight campaign designed to test the capabilities of the telescope optics and the first of the DKIST instruments to come online, the Visible Broadband Imager. The project continues to carry out the critical integration, testing, and commissioning phase of construction, with work primarily focused on the remaining three facility-class instruments and the supporting optical and thermal control systems.

The National Solar Observatory (NSO) is the lead organization for the construction of DKIST and will be responsible for telescope operations when completed. NSO was also impacted by COVID-19, with all staff working from home and all non-essential travel cancelled. Despite the pandemic, operations staff were able to issue the first call for DKIST cycle-1 observing proposals. More than 100 proposals were received from U.S. and international investigators. NSO was able to test the time allocation and review process, and these proposals marked the first science to be executed during the observatory commissioning phase (OCP) when the telescope came online in 2021. NSO continues to build up the DKIST Data Center infrastructure at its headquarters in Boulder, Colorado. The Data Center is expected to process up to 12 terabytes of DKIST data per day.

Personnel from AST, along with colleagues from the Directorate for Geosciences' Division of 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. SWORM developed a National Space Weather Strategy and Action Plan (NSW-SAP) and is implementing that plan. SWORM itself has become a working group of the Subcommittee on Space Weather, Security, and Hazards (SWSH). AST continues to participate in two of the SWORM sub-working groups related to space weather observations and research. NSO's Global Oscillations Network Group (GONG) provides detailed synoptic solar data crucial to operational space weather forecasting. Operations of the GONG facility are jointly funded through a five-year Interagency Agreement between the NSF and the National Oceanic and Atmospheric Administration (NOAA). This agreement expires in FY 2021: the NSF and NOAA are preparing its renewal.

Construction of the Vera C. Rubin Observatory (formerly the Large Synoptic Survey Telescope) continued in FY 2020, reaching over 85 percent complete. While realized foreseeable risks remained within the originally assigned cost and schedule contingencies, the coronavirus global pandemic forced a shutdown of construction activity from March 21 through September 27 and delayed the expected completion date by about one year. Just prior to the shutdown, the dome was about a month away from closure of the structure, and construction of the telescope mount assembly was rapidly advancing. Work on data management development continued with a remote workforce throughout the pandemic. A ramp-up of construction activity on the summit began on September 28 under coronavirus protocols. The NSF allocated management reserve as a first step in providing additional funds to cover impacts of the pandemic. In Rubin Observatory's planned ten-year prime mission, imaging the entire accessible sky many hundreds of times, the multicolor survey will populate a science-ready database of unprecedented size, enabling breakthrough research in dark energy and dark matter, in galactic structure, and in solar system astronomy. The relentless, repeated observations will also open up the time domain and revolutionize the study of transient events. The Federal partners, the NSF and the Department of Energy (DOE), expect this survey to generate about 20 terabytes of data every night, night after night, throughout its operational

life. 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. DOE is funding the camera in a project led by the SLAC National Accelerator Laboratory, and the NSF and DOE support installation and commissioning together. The pandemic interrupted construction of the camera at SLAC for about two months, and work resumed in May under coronavirus protocols. In September, SLAC released the first full images taken with the 3,200-megapixel camera. Operations support has been requested from both agencies and will be augmented by negotiated non-Federal and international in-kind contributions. Federally funded pre-operations ramp-up activity continued in FY 2020.

Also in FY 2020, AST's Mid-Scale Innovations Program (MSIP) ran its latest competition, which resulted in recommendations for 11 new awards, of which six continue a previously supported activity and five were for new efforts. The full MSIP portfolio now contains more than two dozen activities. Noteworthy are continued operations support for the Event Horizon Telescope (EHT) project, which is preparing to announce new results, and for the interferometer of the Center for High Angular Resolution Astronomy (CHARA). MSIP supports several Cosmic Microwave Background experiments and contributes to the Keck Planet Finder instrument as well as a number of survey programs, all of which assist and support research from current and future space platforms. MSIP projects related to the Arecibo Observatory, including the NANOGrav pulsar timing experiment and the enhanced L-band feed instrument, were affected by cable failures toward the end of FY 2020 and the collapse of the 305-meter telescope early in FY 2021. This work is being redirected to the GBT where feasible. Replanning continues. The MSIP program supports laser surface monitoring and correction at the GBT, which helps all of its research, including future planetary radar possibilities. The Next Generation EHT (ngEHT) design effort, funded by NSF's Mid-scale Research Infrastructure (MSRI) program, continued in FY 2020.

Repair of the damage to the Arecibo Observatory resulting from Hurricane Maria, which hit the island of Puerto Rico in September 2017, began in FY 2018. Unfortunately, during the course of the ongoing repairs, on August 10, 2020, an auxiliary cable from tower 4 supporting the suspended platform above the

305-meter reflector pulled loose from its socket and fell into the reflector below, damaging about 250 of the approximately 40,000 aluminum panels that make up the dish of the telescope. This cable failure is not thought to have been related to the hurricane damage, and investigation of the possible causes is ongoing. Following structural analyses to determine if it was safe to approach the dish, the failed socket was removed and sent to NASA's Kennedy Space Center for analysis. Engineers designed a stabilization plan, including friction clamps to prevent other cable failures where slippages were observed, and cables were ordered and set to be installed in December. The implementation of these stabilization efforts was due to begin on November 9, 2020, but the telescope collapsed early in FY 2021. Further work is still planned, however.

Division of Physics

MPS's Division of Physics (PHY) continued to operate its Laser Interferometer Gravitational-Wave Observatory (LIGO), which ended its third observational run (O3) by the end of March 2020. During the O3 10-month run, LIGO released 56 trigger alerts, each considered a gravitational-wave event (more than one event per week). Starting in April 2020, LIGO is undergoing a series of upgrades collectively called "A+," increasing its sensitivity by about 70 percent and its detection rate by a factor of five (to start in summer 2022). In 2020, LIGO published some of the O3 exceptional events, including the discovery of black holes in the "mass gaps" and the first intermediate mass black hole.

Complementing LIGO, PHY, in partnership with AST, continued its funding of North American Nanohertz Observatory for Gravitational Waves (NANOGrav). NANOGrav uses large radio telescopes to study the arriving clocklike signals from more than 80 rapidly spinning pulsars to search for deviations in the timing that could indicate the passage of a single gravitational wave through our galaxy or the presence of a stochastic background of many gravitational wave sources throughout the universe. A typical source of gravitational waves for NANOGrav would be a black hole pair with millions of times the mass of the Sun, in contrast to LIGO's tens of times, and the wave itself would have a period of several years. In 2020,

NANOGrav published the first evidence of stochastic background detection in the analysis of its 12.5-year catalog.

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

Division of Atmospheric and Geospace Sciences

During FY 2020, the Space Weather Operations, Research, and Mitigation (SWORM) Working Group under the Space Weather, Security, and Hazards (SWSH) subcommittee within the Committee for Homeland and National Security of NSTC began implementing the goals and objectives identified in the National Space Weather Strategy and Action Plan (NSW-SAP).¹ This new plan has three main objectives, the second of which requires agencies to “develop and disseminate accurate and timely space weather characterization and forecasts.” The NSW-SAP, monitored by the SWORM subcommittee, encourages the NSF to support fundamental research linked to societal needs for space weather information and to work with other agencies, specifically to “improve observations and modeling for characterization and forecasting.”

In FY 2020, the NSF continued fulfilling this goal through its science programs in AGS, AST, and the Directorate for Geosciences program Prediction and Resilience against Extreme Events. Additional support comes through interagency collaborations, such as the joint sponsoring of the Community Coordinated Modeling Center located at NASA’s Goddard Space Flight Center and the NSF-DOE plasma partnership.

The NSF, through AGS and AST participation, remained active in SWORM activities. Representatives from the NSF participated in the efforts to start implementing the new NSW-SAP. In addition, AGS played a leading role in the publication of the Next Step Space Weather Benchmarks report.² The benchmarks identified in this report specify the nature and intensity of extreme space weather

1 Found at <https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf>.

2 <https://www.ida.org/research-and-publications/publications/all/m/ne/next-step-space-weather-benchmarks>

events and provide a point of reference to improve understanding of their effects. This report was the culmination of work by 32 space weather experts who reviewed white papers from the international space weather community and a series of workshops that allowed them to identify gaps and recommendations.

The Geospace Section (GS) within AGS supported a wide variety of research programs in space science in FY 2020. These included the funding of advanced radar systems to study the ionosphere and magnetosphere (Incoherent Scattering Radars and Super Dual Auroral Radar Network), ground-based passive and active optical equipment and meteor radars to study the neutral upper atmosphere, as well as aurora and airglow phenomena, partial support to ground-based solar telescopes and instruments, and a wide-ranging portfolio of basic research in space physics. Major GS-funded activities in FY 2020 included the Geospace Facilities (GF) program; the Space Weather Research program; the Solar-Terrestrial Research program; the Aeronomy and Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) programs; and the Magnetospheric Physics (MAG) and Geospace Environment Modeling (GEM) program. In collaboration with NASA's Heliophysics Division and NSF's Divisions of Physics, Astronomical Sciences, and Mathematical Sciences and the Office of Advanced Cyberinfrastructure, AGS made six grant awards totaling more than \$16 million to advance space weather modeling. These university-led projects bring together multidisciplinary teams, including partners from government and the private sector to integrate the latest statistical analysis and high-performance computing methods in space weather modeling.

The Geospace Section runs the Faculty Development in Space Sciences Program to ensure the health and vitality of solar and space sciences within university teaching faculties; it offers five-year awards for the creation of new tenure-track faculty positions within the intellectual disciplines that compose the space sciences. In FY 2020, the GS funded one new faculty position to complete the class that included six awards funded in the previous fiscal year.

In FY 2020, the GS supported multiple CubeSat missions, including four that were selected in the previous fiscal year. The Impulsive Phase Rapid Energetic Solar Spectrometer experiment is a CubeSat science mission to study hard x-ray emission from solar flares. The Climatology of Anthropogenic and Natural Very Low Frequency (VLF) wave Activity in Space CubeSat will measure VLF wave

energy that originates from lightning and ground-based transmitters and propagates to the outer reaches of Earth's magnetic field. The Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS) mission supports the use of constellations of CubeSats through designing, building, and operating two satellites that together form an ultraviolet telescope for observing the Sun. The Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) project provides an important step in the advancement of designing and building CubeSat constellations. Both VISORS and SWARM-EX measurements are to be used for space weather observation and research.

In FY 2020, the GS continued to support the satellite-based Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE), which is now in its second implementation phase, AMPERE-II. AMPERE utilized the 66 networked satellites of the existing Iridium constellation to create a new facility for collecting geomagnetic field data. The AMPERE facility continued to provide the first-ever global observations of the electric currents that link Earth's magnetosphere and ionosphere and the first-ever continuous global observations for tracking geomagnetic storm-time dynamics. Geomagnetic storms occur when charged particles emitted by solar eruptions interact with Earth's magnetosphere. Large geomagnetic storms can cause major disruptions of power and high-frequency (HF) communications systems on the ground and degrade the accuracy of satellite-based navigation services. During FY 2020, the data collection for AMPERE continued and the data remained freely available to researchers.

Research facilities remained as the key component of GS efforts. The Geospace Facilities program in FY 2020 continued to enable basic research on the structure and dynamics of Earth's upper atmosphere. In particular, the CEDAR and GEM programs supported research efforts utilizing these facilities. Throughout FY 2020, observations made by the Advanced Modular Incoherent-Scatter Radar (AMISR) facility at Poker Flat, Alaska, examined the ionospheric effects of auroral particle precipitation in three dimensions. AMISR is ideally situated to observe the properties of the ionosphere in the polar cap, a region that is characterized by high ionospheric variability that often causes disruption of important navigation and communication systems.

AGS continued its support of the U.S. consortium within the international Super Dual Auroral Radar Network (SuperDARN), which encompasses more than 35 radars distributed from mid- through high polar latitudes in both the northern and southern hemispheres. The radars observe a wide range of effects in the coupled magnetosphere-ionosphere thermosphere system and produce maps of the large-scale circulation of ionospheric plasma. The wider U.S. research community is given access to data from the entire set of SuperDARN radars.

In collaboration with the Division of Astronomical Sciences, the GS co-funded and supervised a cooperative agreement with a consortium led by the University of Central Florida to operate the radar facility at Arecibo. A cable failure that occurred at the end of FY 2020 contributed to the catastrophic failure of the 305-meter dish that supported the radar operations. Plans for how the facility will continue to operate in the future are under careful consideration.

The GS supports additional ground-based infrastructure through magnetometer networks. Magnetometers are crucial for understanding space weather impacts of geomagnetically induced currents, which can cause power grid outages. The FY 2020 support for the Magnetometer Array for Cusp and Cleft Studies allows this network to continue into a third decade of operation. Two new magnetometer investments include the Surface Magnetic Assessment in Real Time Network, which deploys updated magnetometers in an array of 14 new sites in the United States and three in Canada, and the Conjugate Experiment to Investigate Sources of High-Latitude Magnetic Perturbations, which will be deployed in Antarctica. The GS supports SuperMAG, along with ongoing NSF-funded magnetometers, to collect and disseminate these important measurements to researchers and space weather operators across the country.

In FY 2020, 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 and its collaborator, Taiwan's National Space Organization (NSPO), 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. On April 30, 2020, the mission was formally decommissioned as its last remaining satellite was reporting sporadically. Over the course of its life cycle, COSMIC provided more

than 6.9 million GPS radio occultation (RO) neutral atmospheric soundings and more than 4.6 million ionospheric RO soundings. The COSMIC team is now conducting a reprocessing campaign to create whole-mission datasets with consistent and state-of-the-art processing for all the observations generated over the 14-year mission lifetime. The team also processes data for several other RO satellite missions, including South Korea's KOMPSAT-5 and Spain's Paz, which are used operationally. Support for this activity comes from NASA as well as NSF. The follow-on COSMIC 2 tropical mission, with a 30-degree inclination, was launched by the USAF on June 25, 2019, and is now producing over 4,000 RO soundings per day. The data have been in operational use since March 2020 and started to show strong impact to the research community with high interest in using this new dataset to study both the lower atmosphere and ionosphere. The mission is operated through a collaboration between NOAA, the USAF, and NSPO.

Office of Polar Programs

For FY 2020, the primary activities of the Office of Polar Programs in ground-based space science and astronomy included continued full-scale observations at the U.S. Amundsen-Scott South Pole Station with the 10-meter off-axis radio South Pole Telescope (SPT); and the battery of five small-aperture telescopes called the Background Imaging of Cosmic Extragalactic Polarization (BICEP) Array—wide-field cryogenic refractors with a 55-centimeter aperture and fast optics that achieve an order of magnitude increase in throughput. These telescopes currently have a total of 5,000 detectors (“pixels”) in their focal planes. Recent scientific results from the BICEP Collaboration include deep multi-frequency (95, 150, 220, and 270 gigahertz) maps of degree-scale *B*-mode polarization that measure gravitational lensing and foregrounds to unprecedented precision. This project also produced the deepest-ever maps of cosmic microwave background (CMB) polarization at four different frequencies, or colors, of light. The constraints that BICEP telescopes have produced on primordial gravitational waves continue to improve, leading the way in probing models of inflation that operate near grand-unified theory (GUT) energy scales.

The SPT continued observations with the third-generation receiver SPT-3G, which has a total of 16,000 detectors in its focal plane. Both the SPT and BICEP research groups are currently focusing on measurements of the CMB polarization anisotropy towards detecting imprints of primordial gravitational waves generated during the inflation of spacetime after the Big Bang.

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

The ICNO has produced the world's best limit on the flux of cosmogenic neutrinos, which places very strong constraints on the sources of ultra-high-energy cosmic rays. The PeV neutrinos observed by IceCube have a thousand times the energy of the highest-energy neutrinos produced with Earthbound accelerators and a billion times the energy of the neutrinos detected from supernova SN1987A in the Large Magellanic Cloud, the only neutrinos that had been detected on Earth from outside the solar system prior to IceCube's breakthrough. However, the most surprising property of these cosmic neutrinos is their large flux rather than their high energy or their origination outside our galaxy.

The NSF's Division of Polar Programs also supports NASA's Long Duration Balloon (LDB) Program in the Antarctic. McMurdo Station provides the necessary logistics for astrophysics payload assembly and final testing and then helps launch the balloons and support payload recovery after the flights in various regions of the Antarctic continent. A total of 57 LDB science payloads have been successfully launched from McMurdo since the first interagency Memorandum of Understanding was signed in August 1988.

DEPARTMENT OF STATE

DOS

The Department of State (DOS) carries out diplomatic and public diplomacy efforts to strengthen American leadership in space exploration, applications, and commercialization by increasing understanding of, and support for, U.S. national space policies and programs and to encourage the foreign use of U.S. space capabilities, systems, and services. The Office of Space Affairs within the Bureau of Oceans and International Environmental and Scientific Affairs (OES/SA) directly supports civil space cooperation through the negotiation of bilateral and multilateral agreements, engagement with partner countries, and by leading U.S. participation in numerous international space and technological activities and international organizations. The Office of Emerging Security Challenges within the Bureau of Arms Control, Verification and Compliance (AVC/ESC) supports diplomatic and public diplomacy engagements to promote space security cooperation, including the pursuit of space-related transparency and confidence-building measures as well as bilateral and multilateral space security dialogues.

The year 2020 was a uniquely challenging year for face-to-face diplomacy due to the COVID-19 pandemic. Globally, governments and organizations like OES/SA and AVC/ESC reconfigured their means of work and methods of executing space diplomacy. Yet, even with those structural challenges, both offices executed their mission within the following activities.



Bilateral Dialogues

Japan

The usual cadence of in-person bilateral dialogues was interrupted by the travel restrictions and health measures instituted to mitigate the spread of COVID-19. State transitioned many bilateral dialogues from in-person to virtual. One significant exception was the Seventh Meeting of the Japan-U.S. Comprehensive Dialogue on Space. This in-person meeting took place in Tokyo on August 26, 2020, and was cochaired by representatives from the Ministry of Foreign Affairs and National Space Policy Secretariat, Cabinet Office for Japan, and by representatives from the Executive Office of the President's National Space Council and National Security Council for the United States.

At this meeting, both sides provided updates on their respective space policies and strategies. Both sides renewed their strong determination to expand bilateral cooperation in a variety of areas, including space security, international rulemaking, SSA, space exploration, commercial space activities, and global navigation satellite systems, and to seek opportunities for cooperation with third countries and in international fora. Both sides engaged in robust bilateral cooperation in Earth observation, including weather forecasting, Earth science, land and ocean observation, and environmental and space weather monitoring. Japanese and U.S. weather and Earth observation satellite arrays are essential systems on which other nations rely. Both sides discussed other important issues regarding space utilization, such as space resources and the use of space for maritime domain awareness. The United States welcomed Japan's effort to establish a new framework for satellite development and demonstration.

Both sides reaffirmed their commitment to the Artemis Program, the U.S.-led international space exploration program through which the United States and its international and commercial partners will sustainably explore the Moon in preparation for a human mission to Mars. Recognizing the increasing importance of space for national security as well as the dependence of contemporary society on space systems, both sides welcomed significant developments in their respective defense institutions, namely, the establishment of the Space Operation Squadron

of the Japan Air Self-Defense Force and the Space Command and Space Force of the United States. Both sides recognized the role of space applications such as satellite-based Earth observation and navigation in the context of solving global issues, including achieving the Sustainable Development Goals.

Luxembourg

On October 22, 2019, leaders of the Luxembourg Space Agency and NASA signed a joint statement to pursue a Space Framework Agreement to encourage greater bilateral space cooperation with NASA. In addition, Luxembourg, Japan, and the United States are the only countries to have dedicated laws on space resources. The initiative has attracted more than 50 start-ups from the space sector, which came to Luxembourg to take advantage of research grants and other start-up subsidies. Luxembourg is one of the original signatories to the Artemis Accords.

Russia

In January 2020, the United States and Russian Federation decided to establish a U.S.-Russia dialogue on space security under the framework of the bilateral Strategic Security Dialogue. On June 27, 2020, officials from the Departments of State, Defense, and Energy met with Russian counterparts in Vienna, Austria. In this meeting, the two sides exchanged views on current and future space threats, policies, strategies, and doctrine, and discussed a forward-looking agenda to promote safe, professional, and sustainable activities in space. Both delegations expressed interest in continuing these discussions and improving communications, such as how to enhance communications between the two countries about space-related operational issues in order to reduce the risks of misunderstanding, help prevent or manage space-related incidents, and prevent inadvertent escalation.

Multilateral Activities

Artemis Accords

DOS and NASA also concluded negotiations on the Artemis Accords, which include principles for lunar exploration. Australia, Canada, Italy, Luxembourg, Japan, the United Arab Emirates, the United Kingdom, and the United States signed the Accords on October 13, 2020. The Accords are a multilateral declaration negotiated under U.S. leadership that provides nonbinding guidance for implementation of the Outer Space Treaty of 1967 and reinforces obligations under the Registration Convention and Agreement on the Rescue of Astronauts. Countries signing the Artemis Accords also publicly endorse principles related to transparency, public release of scientific data, responsible behavior, and support for the ability to extract and utilize space resources.

COSPAS-SARSAT

In 2019, the founding States Parties to the International COSPAS-SARSAT Programme Agreement began negotiations for an amendment to the 1988 agreement. Canada, France, Russia, and the United States adapted to virtual negotiations in the fall of 2020 and were able to make progress on the amended agreement that governs the search-and-rescue satellite program.

Space Resource Utilization

In April 2020, the administration released Executive Order (EO) 13914 on Encouraging International Support for the Recovery and Use of Space Resources, reaffirming the long-standing U.S. position on the utilization of space resources for civil and commercial purposes and highlighting the administration's prioritization of growing the U.S. space economy. In response to EO 13914, the Office of Space Affairs led drafting on a report detailing actions taken by DOS in consultation with DOC, the Department of Transportation, and NASA to fulfill executive

order responsibilities. The report was submitted to the President via the National Space Council in October 2020.

United Nations Committee on the Peaceful Uses of Outer Space

In FY 2020, OES/SA continued to lead the U.S. delegation to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and supported its subcommittees, even as the annual meeting of the full committee was cancelled due to the COVID-19 pandemic. While COPUOS's Scientific and Technical Subcommittee was able to meet in February 2020, the Committee's Legal Subcommittee was unable to meet. As a result, the United States worked constructively with like-minded countries and the UN Secretariat to advance a UN General Assembly resolution adopted in December 2020 that called for the continuity of work of the COPUOS as pandemic restrictions continue to lessen in the future.

Space Security and Sustainability

During the 74th session of the UN General Assembly in October 2019, the United States worked in the First and Fourth Committees to advance U.S. policy principles and goals regarding space security and sustainability. These engagements highlighted the U.S. commitment to international cooperation to preserve the safety, stability, security, and long-term sustainability of outer space activities. U.S. delegations also reiterated the long-standing U.S. commitment to consideration of proposals and concepts for arms control measures which are equitable, effectively verifiable, and enhance the national security of the United States and its allies.

Due to the COVID-19 pandemic, sessions of the Conference on Disarmament and the UN Disarmament Commission in 2020 were postponed. In response, State continued virtual consultations in virtual formats with like-minded allies on space security to prepare for virtual space security discussions during the 75th session of the UN General Assembly's First Committee in October 2020. This diplomatic outreach resulted in the adoption of a U.S. co-sponsored resolution on "Reducing space threats through norms, rules and principles of responsible behaviors" by the full General Assembly on December 7, 2020.

DEPARTMENT OF ENERGY

DOE

The Department of Energy (DOE) participates in the national effort to enable U.S. interests in space. Various organizations within DOE, including the National Nuclear Security Administration (NNSA), provide support to NASA that has natural synergies with existing programs and capabilities to maximize use of national investments in science and technology. DOE support, funded by NASA through either Strategic Partnership Programs or Laboratory Directed Research and Development, is aligned to four major goals:

- power the exploration of space,
- support the secure and peaceful use of space,
- solve the mysteries of space, and
- enable the development of space.

Each of these areas has aspects that support NASA's mission.

Power the Exploration of Space

DOE, through its Office of Nuclear Energy (NE), supports NASA's planetary science and human exploration programs by maintaining capabilities needed to develop, produce, and deliver Radioisotope Power Systems (RPS) for space mission applications. RPS convert the heat from the radioactive decay of plutonium (Pu)-238 into electricity and reliably operate for decades in the harsh conditions encountered in space or on the surfaces of other planets where solar energy or stored energy devices are ineffective or impossible to use.



Radioisotope Power Systems Powered Missions

In FY 2020, DOE supported two RPS-powered missions, Mars 2020 and Dragonfly, that completed major milestones:

- DOE successfully fueled the flight multi-mission radioisotope thermoelectric generator (MMRTG) F-2 for Mars 2020 in August 2019 and completed acceptance testing in October 2020, six months ahead of schedule, resulting in a power output of 120 We at 28 V (specified power greater than 110 We). The flight unit (F-2) was transported to NASA's KSC in spring 2020. DOE/NNSA provided the ground operations support, which consisted of a hot-fit-check integration with the Perseverance rover at the Payload Hazardous Servicing Facility, storage monitoring for approximately three months, and final integration at Space Launch Complex 41 approximately one week prior to launch. The Mars 2020 rover was launched successfully on July 30, 2020. DOE/NNSA staged technical specialists and sensors in the vicinity of the launch site to respond immediately in the unlikely event of a launch anomaly. DOE's portion of the Mars 2020 mission activities was completed \$14 million under budget (20 percent under initial DOE estimates).
- DOE formally established a support team for the Dragonfly mission to provide an MMRTG-powered dual-quadcopter mission to Saturn's moon Titan. DOE supported multiple mission studies on assessing MMRTG compatibility with Titan's atmosphere, convective cooling versus additional cooling loops for surface operation, and fin length to reduce unnecessary size and weight.
- DOE also supported procurement of additional flight MMRTGs intended for potential future missions to maintain the industrial base and reduce schedule risk by maintaining an equipment inventory.

Constant Rate Production

With NASA funding support, DOE, through NE, continues to invest in RPS production infrastructure through the Constant Rate Production (CRP) program.

In early 2017, DOE and NASA agreed to transition the delivery of RPS from a mission-driven approach to a CRP approach. Under the CRP program, components, materials, facilities, and expertise across the plutonium production supply chain are managed to produce a steady flow of heat sources, instead of producing in response to individual mission needs. The outcome of CRP is an underlying base of shelf-ready, flight-quality components that are readily available once NASA selects a nuclear-enabled mission, thus reducing overall mission schedule risks. The CRP goals are to produce an average of 1.5 kilograms of heat source Pu-238 oxide annually by 2026 and to manufacture an average of 10–15 fuel clads (FCs) a year (goal demonstrated).

The initial focus of CRP was on exercising the supply chain from start to finish, but after its demonstrated success to provide new heat source oxide for the Mars 2020 mission, the focus shifted in FY 2020 to scaling up production; optimizing processes; and maintaining, modernizing, and replacing equipment and infrastructure. In FY 2020, the CRP program key accomplishments included the following:

- Scaling up production capabilities:
 - A second target irradiation campaign in the Advanced Test Reactor (ATR) was introduced at the Idaho National Laboratory (INL). The ATR, coupled with the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL), increased the average annual production capability to 700 grams of new-heat-source plutonium oxide.
 - The Neptunium-237 pellet pressing process at ORNL was automated, tripling the number of pellets produced in FY 2020 for inserting into targets for irradiation in ATR and HFIR.
 - The installation of a plutonium load-out capability at ORNL was completed, enabling the handling, packaging, and shipping of larger quantities of heat source material necessary for scale-up to meet CRP goals.
- Optimizing processes to achieve efficiencies and increase production rates:
 - At the Los Alamos National Laboratory (LANL), a Manufacturing Management System tool was developed and the Material

Management Plan revised to enable and optimize blend plans for heat source material.

- Process refinement was conducted by reducing the steps needed for chemical processing and separations for producing the plutonium heat source material while reducing waste streams.
- The effects of different target designs and target placement/positions in reactors were studied to optimize irradiations in ATR and HFIR.
- Maintaining, modernizing, and replacing equipment and infrastructure to reduce programmatic risk:
 - A second pellet press at ORNL was designed and a new Hot Press at LANL was installed to eliminate single-point failures in the production process.
 - A new Ultrasonic Tester and welder was procured and installed, the Astro furnace was reconfigured, Hot Press 4 was completed, and Furnace Line was installed at LANL.

Technical Expertise and Advancements

DOE, through NE and the DOE national laboratories, provided technical expertise, procurement coordination, and planning and support to NASA in conducting basic and applied energy conversion research and development to advance state-of-the-art performance in heat-to-electrical-energy conversion. Both static and dynamic energy conversion projects are under way at this time; however, dynamic conversion, which can achieve higher efficiency, has not been developed to a flightworthy status yet. The goal of these investments is to provide higher conversion efficiency and improve mission performance over design life.

DOE initiated three development efforts that encompass both static and dynamic conversion systems: the enhanced multi-mission radioisotope thermoelectric generator (eMMRTG), the next-generation radioisotope thermoelectric generator (NGRTG), and a dynamic radioisotope power system (DRPS). In FY 2020, the eMMRTG project focused on technology transfer from the laboratory to industry. The eMMRTG will utilize the MMRTG housing with enhanced thermoelectric materials for improved thermoelectric efficiency and degradation. The NGRTG

project proceeded through Phase 1 of the project to develop concepts of NGRTGs and identify areas of risk. The team settled on Phase 2/3 proceeding with well-characterized thermoelectric material technologies. The DRPS project focused on technology maturation of the conversion system in FY 2020.

Surface Fission System Development

DOE, through NE and the DOE national laboratories, provides technical support for surface fission system development. In FY 2020, DOE completed a detailed study on evaluating the ability of various reactor classes to meet a set of NASA program requirements for a surface fission system. The study concluded that both highly enriched uranium and high-assay low-enriched uranium could likely meet the technical parameters and outlined the technical maturation that would be required for both. Following this study, NASA and DOE worked toward commercializing this fission surface power concept. DOE published a Request for Information in July 2020 followed by an industry day in August 2020 to discuss the overall goals and direction of the program with industry participants. It was attended virtually by more than 20 companies.

Nuclear Thermal Propulsion System Development

DOE, through NE and the DOE national laboratories, provides technical support for the Nuclear Thermal Propulsion (NTP) system development. In FY 2020, DOE completed a series of Sirius-2a irradiations at the INL's Transient Reactor Test Facility (TREAT) and preliminary examination of an advanced nuclear thermal propulsion fuel type—a uranium nitride ceramic-metallic test specimen that was fabricated at Marshall Space Flight Center. These tests consisted of irradiating a single half-inch-tall uranium nitride/molybdenum-tungsten ceramic metallic fuel wafer in a static capsule to prototypical temperatures. The Sirius-2 experiments are used to evaluate thermal stress cracking of the test specimen, dissociation of the uranium nitride fuel, hydriding of the fuel wafer materials, and other signs of potential fuel failure.

DOE and NASA also implemented the Space Nuclear Propulsion fuel and moderator development plan (FMDP) to guide maturation of Space Nuclear Propulsion (SNP) reactor materials and components. The FMDP defined 48 individual tasks associated with design, fabrication, and testing of reactor components and identified organizations to lead and support work performed under the plan, including NASA centers, DOE national laboratories, industry organizations (e.g., Babcock and Wilcox Technologies, Inc., Aerojet-Rocketdyne, Inc.), and universities (e.g., MIT, University of Tennessee, Knoxville). The integrated FMDP team initiated technical analysis and hardware fabrication work to support future nuclear and non-nuclear experiments. These preliminary FMDP work activities were focused on preparing for capstone tests at TREAT to demonstrate operation of multiple SNP fuel and moderator systems under prototypic operating conditions.

Support the Secure and Peaceful Use of Space

In FY 2020, DOE conducted programs that support NASA missions and are synergistic with national security activities. For example, NASA leverages DOE-unique engineering, scientific, and computing capabilities for analyzing asteroids and planetary defense scenarios. This work helps to develop and exercise capabilities that are relevant to the weapons program, including high-performance computing, two- and three-dimensional simulations, weapon effects, systems engineering, and weapon component design.

Planetary Defense

DOE worked with NASA, the Department of Defense, and the Department of Homeland Security to develop and implement the actions outlined in the National Near-Earth Object Preparedness Strategy and Action Plan. This Strategy and Action Plan was developed to help improve our Nation's preparedness to address the hazards of near-Earth object (NEO) impacts. The NEO plan has five strategic goals. The two pertaining to DOE focus on improving NEO modeling, predictions, and information integration and developing technologies for NEO deflection and disruption missions.

In FY 2020, DOE collaborated with NASA to

- characterize the potentially hazardous asteroid target sets, define mission requirements, and identify capability gaps;
- examine the effects of either a kinetic impactor and/or a nuclear detonation, either at the surface or at a standoff distance from a model asteroid, using simulations from peta-scale computers at the National Labs;
- define additional development and system engineering requirements to address technical gaps such as arming, fusing, and firing a deflection device;
- participate in planetary defense tabletop exercises and technical interchange meetings;
- advise on risk-assessment analysis and effectiveness of mitigation approaches;
- conduct impact studies, which will serve as the initial conditions for Federal Emergency Management Agency (FEMA) emergency response planning if mitigation approaches fail; and
- partner with NASA scientists and engineers to publish refereed technical papers.

In addition, DOE continued to support NASA's Double Asteroid Redirection Test, scheduled for a launch in July 2021, by providing essential numerical methods and simulation results.

NASA's Environmental Continuous Air Monitors

DOE maintained the NASA-owned Environmental Continuous Air Monitors for deployment around launch sites in advance of a launch to provide indication of a radioactive release, should one occur. NASA agreed to loan these sensors in support of DOE/NNSA's nuclear incident response mission when they are not being used for mission launch support. These devices were upgraded to provide real-time associated data telemetry systems and will be interoperable with NNSA's existing data telemetry capability.

Global Nuclear Monitoring

DOE builds the Nation's operational sensors to monitor the entire planet from space to detect and report surface, atmospheric, or space nuclear detonations. DOE develops, builds, and delivers these satellite payloads to meet interagency performance and schedule commitments and provides launch and on-orbit operational support for the current generation of the U.S. Nuclear Detonation Detection System (USNDS). This information helps to characterize space weather, which helps NASA to characterize the radiation environments that NASA space exploration vehicles must endure. DOE also provides much of the underlying science and technology capability for space-based detection of foreign nuclear weapon detonations to meet test ban treaty monitoring needs.

The DOE weapons laboratories—Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and Lawrence Livermore National Laboratory (LLNL)—supply the science, technology, and engineering required for USNDS. LANL and SNL lead the production of sensors, 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 distinct sensor suites are built at DOE laboratories to accomplish the nuclear detonation reporting mission: the Global Burst Detector (GBD) and the Space and Atmospheric Burst Reporting System (SABRS). The GBD is hosted on all GPS satellites, and SABRS is carried on satellite hosts in geosynchronous orbit.

In FY 2020, DOE continued full-scale production and delivery of both sensor suites as needed to meet national security requirements. To ensure that the technologies and capabilities developed for the program support the stakeholder needs, DOE actively engaged in intergovernmental working groups to reduce duplication of effort, refine user requirements, and improve the quality of relevant technologies

across funding agencies. In order to maintain a vital capability to design and implement these systems, DOE 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.

Solve the Mysteries of Space

In FY 2020, DOE supported numerous activities that contributed to a broad range of space interests. These activities included fundamental research of mutual interest to NASA and DOE, collaborative research efforts with NASA, and the operation of DOE scientific facilities that are available to NASA and the broader scientific community for space-related research.

Plasma Science

DOE, through its Fusion Energy Science program, supports frontier plasma science research that contributes to DOE-NASA mutual interests in the knowledge of heliospheric and astrophysical systems. In FY 2020, DOE continued to support plasma science research activities at the Large Plasma Device at the Basic Plasma Science Facility at the University of California, Los Angeles (controlled studies of Alfvén waves); the Magnetic Reconnection Experiment at DOE's Princeton Plasma Physics Laboratory (magnetic reconnection and particle energization processes); the Big Red Plasma Ball and Madison Symmetric Torus experiments at the Wisconsin Plasma Physics Laboratory at the University of Wisconsin–Madison (high-fidelity measurements of magnetic reconnection, dynamo, turbulence, and particle-energization processes); and the Max Planck-Princeton Center for Plasma Physics (applications of plasma science to solar and astrophysical problems and their connection to fusion science). New knowledge and data derived from these experiments and research activities not only contributed to DOE's mission to advance fusion energy science, but also contributed to greater understanding of complex space weather phenomena, enabling more accurate models and predictions of this behavior and mitigating the risk to both humans and technology operating in the space environment.

High Energy Physics (HEP) and Astrophysics

In FY 2020, DOE, through its High Energy Physics program, continued to support fundamental physics and high-priority national science objectives. Examples of these efforts included the Alpha Magnetic Spectrometer (AMS) and the Fermi Gamma-ray Space Telescope (FGST). AMS science goals include a search for evidence of dark matter and cosmic domains of antimatter, and the origin and characteristics of charged cosmic rays. Extravehicular activities (spacewalks) in the first quarter of FY 2020 by NASA to replace the AMS cooling system has enabled it to operate beyond 2028. As of 2020, observations of more than 150 billion cosmic-ray events have been collected.

The Large Area Telescope, the primary instrument on FGST, continued successful operations and data analysis, including a study comparing 11 years of data from measurements of excess gamma rays from our galaxy's center to the expected flux using models for the Milky Way diffuse emissions. The data were consistent with models, but alternative explanations (e.g., dark matter annihilation) could not be definitively ruled out.

Finally, NASA, through its Strategic Astrophysics Technology program, initiated funding in FY 2020 for a project at SLAC National Accelerator Laboratory to further develop readout and signal-processing electronics for low-noise cryogenic detectors. The work is building on HEP-funded research at SLAC over several years to demonstrate and deploy an RF/signal processing system with 4,000-times multiplexing for cosmic microwave background observation experiments at the South Pole.

High-Performance Scientific Computing for Cosmology and Astrophysics

DOE, through the Advanced Scientific Computing Research and High Energy Physics programs, continued to support analysis of data from the European Space Agency–NASA Planck Cosmic Microwave Background mission, which took data from 2009 to 2013. In FY 2020, LBNL led the “NPIPE” analysis of the Planck data, which was the first joint analysis of the Planck low- and high-frequency instrument data. This analysis resulted in the cleanest sky maps and most precise constraints

on inflation to date. The software stack developed for this work—called TOAST—is also being used at the National Energy Research Scientific Computing Center (NERSC) for simulations to support the design of and science forecasts for the JAXA-led LiteBIRD mission and the proposed NASA probe of inflation and cosmic origins mission. Overall, there were more than 20 projects at NERSC in FY 2020 supported by NASA.

The Advanced Scientific Computing Research (ASCR) Leadership Computing Facilities made significant contributions to space science projects. In FY 2020, nearly two dozen projects at the Argonne Leadership Computing Facility and the Oak Ridge Leadership Computing Facility cited funding support from NASA. These projects spanned a wide range of topics, highlighted by high-resolution models of astrophysical explosions; simulation of the Type 1a supernova double detonation model; studies of magnetic reconnection and turbulence in astrophysical phenomena; and studies of radiation hydrodynamics, turbulence phenomena, and computational fluid dynamics in a variety of contexts.

As part of DOE's Exascale Computing Project, DOE's Argonne National Laboratory carried out simulation efforts for NASA missions. For example, the Hardware/Hybrid Accelerated Cosmology Code general cosmology simulation software, which simulates cosmology data from an initial set of conditions and particles in the early universe, continued to make use of the Summit supercomputer in FY 2020 to produce simulations used by ground- and space-based surveys, including NASA's upcoming Nancy Grace Roman Space Telescope mission (formerly called the WFIRST mission). Simulations that generate extragalactic catalogs tailored to specific wavebands and filters were also used in the Roman Space Telescope mission. Computer allocations for this work were made through ASCR's Argonne Leadership Computing Challenge program.

Atmospheric Science and Terrestrial Ecology

DOE, through the Biological and Environmental Research program, also engaged in many collaborative research efforts with NASA in the areas of atmospheric science and terrestrial ecology. During FY 2020, DOE's Atmospheric Radiation Measurement Research Facility (ARM) and Terrestrial Ecosystem

Science (TES) activities continued to support measurements of atmospheric trace gases in Oklahoma to improve understanding of the influence of atmospheric and terrestrial processes on atmospheric carbon dioxide (CO₂) concentrations. ARM provided support for ground-based measurements of CO₂ in Oklahoma as part of the Total Column Carbon Observing Network and supported the launch of dedicated radiosonde observations during satellite overpasses at the Southern Great Plains, Oklahoma; Graciosa Island, Azores; and Barrow, Alaska, ARM sites to obtain profiles of temperature and moisture for the validation of algorithms for two sounding instruments on the Suomi National Polar-orbiting Partnership satellite and Joint Polar Satellite System satellites. DOE's Atmospheric System Research activity also supported collaboration with NASA scientists at Goddard Space Flight Center, Goddard Institute for Space Studies, and the Jet Propulsion Laboratory on studies using ARM and NASA observations to investigate aerosol and cloud processes and their role in Earth's energy balance.

The TES activity supported the Next Generation Ecosystem Experiment-Arctic, which continued to collaborate with the NASA Arctic-Boreal Vulnerability Experiment to couple real-time ground-based and airborne-based measurements of soil moisture, temperature, carbon dioxide, and methane flux over Utqiagvik (formerly Barrow) and Nome, Alaska. Finally, TES-supported AmeriFlux Network continued to collaborate with the NASA ECOSTRESS mission by sharing flux tower measurements such as vegetation cover data and soil moisture data that are coupled with water flux/evapotranspiration measurements to serve as validation sites.

Nuclear Astrophysics

DOE, through the Nuclear Physics program, supported fundamental research on nuclear reactions of astrophysical interest, contributing knowledge to DOE and NASA interests in stellar evolution, neutron star mergers, gamma-ray bursts, and the composition of interstellar space. DOE contributed to the analysis of data from the NASA Messenger Mission to see how well the neutron lifetime can be determined from thermal neutrons created by cosmic rays striking the surface of Mercury. Additionally, DOE researchers studied the reaction $^{30}\text{Si}(p,\gamma)^{31}\text{P}$ (a proton

(p) incident on ^{30}Si produces ^{31}P plus a gamma ray(γ) to determine whether NGC 2419 is a true globular cluster or multiple stellar populations.

Experimental Facilities for Space Science and Technology Development

DOE continued to work 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 at DOE's Brookhaven National Laboratory (BNL) continued to study the effects of cosmic radiation exposure on astronauts, using beams of heavy ions extracted from BNL's Booster accelerator, part of the Relativistic Heavy Ion Collider complex. The work advances the understanding of the link between ionizing radiation and cell damage. NASA continued to provide funding in FY 2020 to support the operation of DOE's 88-inch cyclotron at LBNL for electronics space-radiation effects testing, which is necessary for NASA mission assurance.

DOE's scientific user facilities continued to contribute to NASA's missions in space science and technology development in FY 2020. Representative techniques and their applications used in FY 2020 included scattering/diffraction to study the structure of space mission materials (e.g., the thermal barrier coating), x-ray and electron imaging to study the form and shape of space rock samples, and spectroscopy combined with imaging to study the chemical content of space rock samples. As a specific example, scientists at LBNL and NASA used x-rays at the Advanced Light Source to explore, via 3D visualizations, how the microscopic structures of spacecraft heat shield and parachute materials survive extreme temperatures and pressures, including simulated atmospheric entry conditions on Mars.

Isotope R&D and Production

DOE, through the Office of Isotope R&D and Production, supplied critical isotopes for NASA space-related R&D and applications in FY 2020, such as Helium-3 for use in cryogenics; Mercury-199 and Mercury-202 for space-qualified atomic clocks and atomic clock research; and Rubidium-87 for navigation satellite systems.

DOE also monitored the Helium-4 supply chain to ensure adequate supplies for production of rocket fuel.

Enable the Development of Space

In FY 2020, DOE conducted significant industry outreach to identify gaps and opportunities to connect its labs and capabilities with space industry counterparts. DOE also focused on ensuring that the transfer and commercialization of its technologies were specifically highlighted and supported in policy documents, setting the stage for further engagement on space-related activities.

DOE evaluated opportunities for quantum networking in free space, which included space applications and leveraging artificial intelligence. In FY 2020, DOE moderated and hosted a public webinar on quantum networks using satellites and other free space technologies to discuss potentially transformative opportunities for global communications and transportation, including drones, automotive, space, air, and marine sectors. The webinar featured speakers from NASA, private industry, and the DOE national labs.

SMITHSONIAN INSTITUTION

The Smithsonian Institution continued to contribute to national aerospace goals in FY 2020. The Smithsonian Astrophysical Observatory (SAO) is a partner of the Center for Astrophysics | Harvard & Smithsonian (CfA) in Cambridge, Massachusetts, and represents the largest component of the Smithsonian's space contributors. The organization has more than 300 scientists engaged in a broad program of research in astronomy, astrophysics, Earth and space sciences, and science education. The Smithsonian's National Air and Space Museum (NASM) and National Museum of Natural History (NMNH) in Washington, DC, contributed to reaching national aerospace goals through their research and education activities.

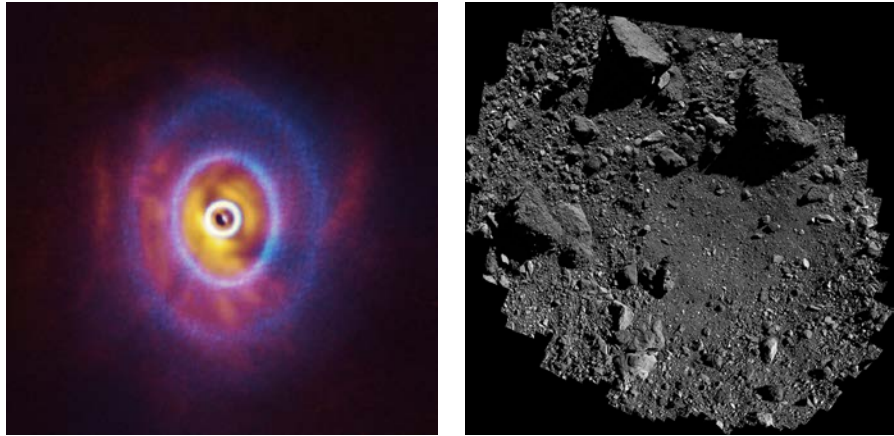
Six widely reported news stories in FY 2020 featured Smithsonian scientists and space historians. SAO astronomers used NASA's Hubble Space Telescope to study the brightest star in the constellation of Orion, the red giant star Betelgeuse.



An artist's conception of an eruption of obscuring material darkening the brightest star in the constellation of Orion, Betelgeuse. (Credit: NASA, ESA, and E. Wheatley (STScI))

During 2019–2020 the star faded dramatically, losing more than two-thirds of its brilliance, a dimming visible even to the naked eye that created speculation that the star might be about to explode as a supernova. The astronomers found that the periods of dimming were most likely caused by the ejection and cooling of dense hot gases that blocked the light. As SAO astronomer and project Principal Investigator Andrea Dupree explained, “No one knows how a star behaves in the weeks before it explodes, and there were some ominous predictions





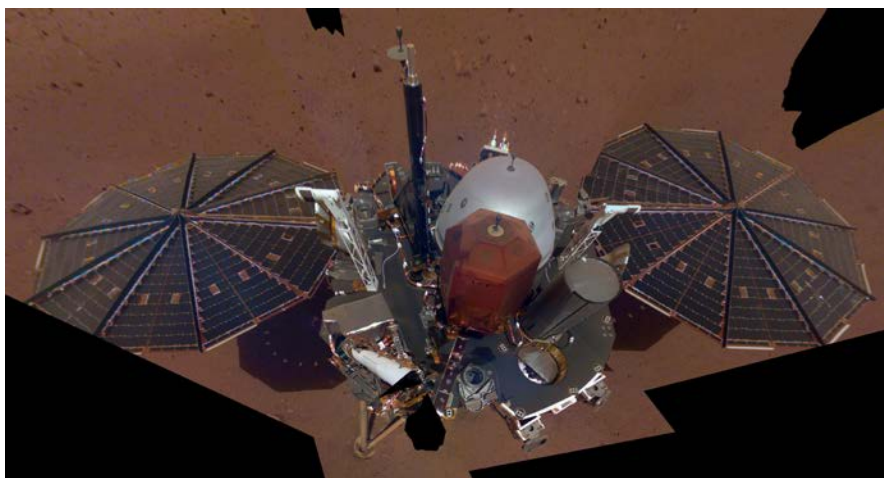
Left: A composite image of a warped planet-forming disc around a young triple star system showing the disc's ringed structure. (Credit: Kraus et al. 2020.) Right: A reconnaissance image of the Nightingale sampling site on the asteroid Bennu from a distance of 250 meters. At full resolution, each pixel is 4 mm. The large, dark boulder in the upper right is 13 meters long. A successful sample retrieval was completed on October 20. (Credit: NASA/OSIRIS-REx)

that Betelgeuse was ready to become a supernova. Chances are, however, that it will not explode during our lifetime, but who knows?"

A team including SAO astronomers imaged the triple-star system GW Orionis and its warped disk to study how strong disruptions may affect planetary development, as reported in a widely viewed article in *Science*. The astronomers observed the young system (only about one million years old) at optical, infrared, and millimeter wavelengths and showed that the disk has been broken into at least three rings. The largest of the rings contains about thirty Earth-masses of material, enough for future planet formation.

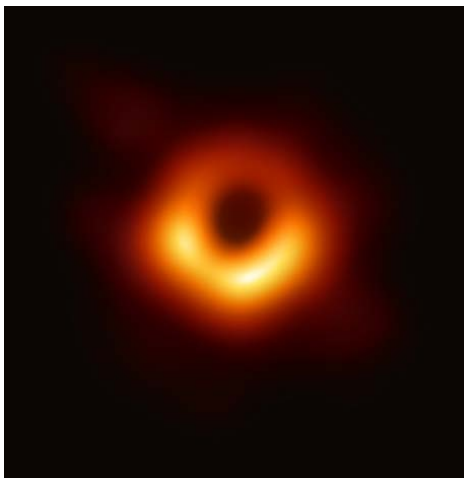
NMNH scientist Tim McCoy was a Co-Investigator on NASA's OSIRIS-REx mission to the asteroid Bennu, which successfully completed a sample acquisition at the Nightingale site on October 20. Plans are for the samples to return to Earth in 2023, with the end goal for the Museum to display some samples to the public.

NASM's Center for Earth and Planetary Science's (CEPS) newsworthy results focused on early findings at the Mars InSight landing site and the processes shaping the landscape there. The work includes study of wind-driven transport of sand and dust on and around the landed spacecraft with implications for understanding Mars' geology and climate, as well as mitigating risks to landed instruments and future human explorers.



An image of the InSight lander on Mars, which has been studying the processes shaping the Martian landscape. (Credit: NASA)

Scientists at SAO used NASA's Chandra X-ray Observatory to reveal that the giant black hole in the galaxy Messier 87 is propelling particles in jets at speeds greater than 99 percent of the speed of light. SAO's Chandra X-ray Center runs the Observatory's science and flight operations for NASA. The media in FY 2020 continued their active coverage of the first images of a black hole, made by the international Event Horizon Telescope consortium led by SAO astronomer Shep Doeleman. The consortium uses a global array of radio telescopes involving dozens of institutions, including SAO's Submillimeter Array facility on Mauna Kea. The telescopes, in a breakthrough discovery, obtained an image of the supermassive black hole in the center of the galaxy Messier 87 measuring 6.5 billion times the mass of our Sun. Said Dr. Doeleman, "We now have access to a cosmic laboratory of extreme gravity where

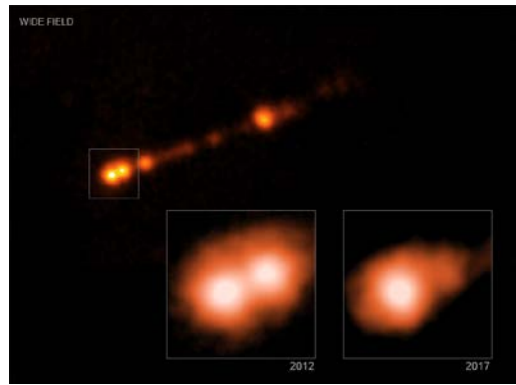


The first radio-wavelength image of a black hole. This supermassive black hole lies at the nucleus of the galaxy Messier 87. The radiation shown here arises from hot gas swirling around the black hole. The black hole is invisible, but its powerful gravitational field distorts the background radiation around it. (Credit: The Event Horizon Telescope consortium)

we can test Einstein’s theory of General Relativity and challenge our fundamental assumptions about space and time.”

The Smithsonian plays an ongoing leadership role in space research. NASA’s Chandra X-ray Observatory is operated for NASA by the Smithsonian Astrophysical Observatory (SAO) observing critical targets proposed by scientists around the world. Chandra continues to operate with high (~70%) efficiency and a spatial resolution unmatched by any other x-ray telescope either currently in operation or planned for the future; Chandra’s results appear in an average of 480 highly cited refereed papers per year. In FY 2020, Chandra continued to play a pivotal role in studying celestial targets including comets, black holes, galaxy clusters, supernova remnants, supernovae, dark matter, and dark energy. Its discoveries included x-ray emissions from relativistic jets emitted by supermassive black holes in the nuclei of galaxies, complex structure in the hot gas in clusters of galaxies, cosmic ray acceleration in supernova remnants, and an off-axis jet in a pair of merging neutron stars that were discovered via their gravitational wave emission.

SAO is a key participant in ESCAPE (the Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution), a NASA Small Explorer concept employing ultraviolet spectroscopy to explore the high-energy radiation environment in the habitable zones around nearby stars, to provide the first comprehensive study of the stellar extreme ultraviolet (EUV) environments that directly affect the habitability of rocky exoplanets. During 2020, the SAO team demonstrated the alignment of the novel Hettrick-Bowyer telescope configuration that would be used by ESCAPE, and also provided and tested mirror coating samples.



A Chandra X-ray Observatory image of the jet of particles emitted from the black hole at the center of the galaxy M87 moving at close to the speed of light. The jet with its knots extends over 18,000 light-years. (Credit: NASA/CXC/SAO/B. Snios et al.)

NASA's Spitzer Space Telescope was turned off in FY 2020 after 17 years of operation, during which period it produced dramatic new views of the universe at infrared wavelengths. Spitzer was 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 the Principal Investigator and was the only instrument operating after Spitzer ran out of cryogenics nearly 12 years ago.

The Solar Dynamics Observatory spacecraft provides better-than-high-definition-quality images of the Sun's surface and outer atmosphere, measuring physical conditions that help scientists model the stellar wind and its influence on the "space weather" around Earth. SAO is a major partner in one of its instruments, the Atmospheric Imaging Assembly (AIA). In FY 2020 its four telescopes photographed the Sun in ten different wavelength bands once every twelve seconds, continuing to produce 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 in FY 2020 continued its active role in IRIS operations, calibration, and science to provide information on particle acceleration in hot coronal loops, and a better understanding of the physical processes powering solar flares. During FY 2020, SAO scientists also continued their involvement in other solar satellites, including Hinode and the Deep Space Climate Observer.

SAO is a team member on the Lockheed MUSE mission providing members to the science team as well as portions of the Context Imager and the Spectrometer feed telescope. MUSE was selected for a competitive Phase A in the 2020 NASA Heliospheric Medium-Class Explorer (MIDEX) round. The Context Imager, when launched, will be the highest resolution EUV solar imager ever placed in orbit, with a 0.14 arc seconds per pixel focal plane scale, 4.2 times better than the SDO-AIA imagers. The final selection to move forward with construction is to take place in 2021. In FY 2020, SAO continued to design and build instruments to observe total solar eclipses from NSF/NCAR's Gulfstream V observatory, High-performance Instrumented Airborne Platform for Environmental Research (HIAPER). Having successfully fielded campaigns in 2017 over the United States and in 2019 over the Mid-Pacific, the team prepared a new platform to fly in the 2020 eclipse over South

America. It was canceled due to COVID-19 but preparations were made for the next solar eclipse over Antarctica in 2021 .

FY 2020 marked continued progress for the Giant Magellan Telescope (GMT), on which SAO is a team leader. The GMT is a facility in development for optical and infrared observations that will combine seven huge mirrors to create one of the world's largest telescopes. It will address key questions in cosmology, astrophysics, and the study of planets outside our solar system. NASA's space-based James Webb Space Telescope and the GMT will provide access to complementary biomarkers from exoplanet atmospheres. Five of the seven eight-meter-diameter mirror segments have been fabricated, and three of them have been polished and prepared for shipment to the site in Chile.

The Tropospheric Emissions: Monitoring Pollution (TEMPO) mission has made excellent progress in FY 2020; it is scheduled for a launch in the next few years. The NASA mission will study the constituents of the atmosphere in more detail and precision than ever before, compiling a new dataset of atmospheric chemistry as measured from space. TEMPO will be the first space-based instrument to monitor major air pollutants across the North American continent every daylight hour at high spatial resolution. SAO is also a team member of a successful 2019 NASA MIDEX selection, SPHEREx, a space-based telescope that will conduct four all-sky infrared spectral surveys of the sky. SAO manages the Science Center for NASA's Transiting Exoplanet Survey Satellite (TESS), which is engaged in a two-year mission to discover transiting exoplanets with an all-sky survey. Optical follow-up observations of exoplanet candidates found with TESS rely on SAO's facilities in Arizona and Chile to confirm exoplanet classifications.

SAO pursues a wide variety of nationwide STEM education and outreach initiatives, many of which are aimed at broadening public participation in and maximizing the societal benefits of the astrophysics research efforts of the institution. The MicroObservatory is a robotic network of telescopes operated by the CfA for research and public outreach purposes. Until forced to shut down temporarily due to COVID-19, SAO continued its popular monthly Observatory Night lectures and observing sessions. Begun by observatory director Harlow Shapley in 1930, these public nights offer the local community an opportunity to learn about the latest advances in astronomy and to view the Moon, stars, and planets through a variety

of telescopes. Observatory Night talks also reach worldwide audiences via YouTube. “The Dynamic Sun,” an exhibit conceived, designed, and built by SAO researchers, features a giant seven- by six-foot video wall intended to create a visceral impact and show visitors how an ever-changing Sun affects Earth. The “Dynamic Sun” at NASM in Washington, DC, continues to be seen by millions of visitors each year. Chandra operates the Data Sonification program that converts data into sound, providing the public with a new perspective that enables the vision-impaired to appreciate astronomical data.

The Smithsonian’s National Air and Space Museum, despite the obstacles encountered in FY 2020, continued its leadership role in educating and inspiring the public, conducting historical and scientific research, and preserving the national collection of aerospace objects and documents. Although it was closed to the public for much of the year, NASM adapted to the challenges of the times by expanding online and digital reach with exciting new programs. The Museum continued development of new exhibitions, re-imagining and updating all major galleries, to inform and inspire our audiences and bring the diverse stories of air and space history and science to new generations of visitors.

Learning at the National Air and Space Museum sparks curiosity and empowers learners to imagine the possibilities of the future. NASM combines one-of-a-kind collections and research to foster lifelong learning. Throughout FY 2020, the Education team placed particular emphasis on how to bring meaningful and relevant learning opportunities into people’s homes through virtual interactions and activities. Examples include family programs, virtual field trips, story times, and podcasts.

Soar Together @ Air and Space is a monthly family-focused program. By engaging in these activities and experiences, families can imagine their *own* futures by sharing in the stories of innovators and explorers from diverse backgrounds who challenged conventions and changed the world. Each month focuses on a different theme. For the foreseeable future, *Soar Together* will be available online for families to participate in no matter where they live. Activities include scavenger hunts, videos, and hands-on demonstrations that learners of all ages can do at home.

Virtual Field Trips provide unique opportunities for students to engage with the Museum’s content online. Each reservable experience is aligned with national

standards and provides a suite of materials surrounding the content area. The program engages students through hands-on experiences adapted for completion at home, content deep-dives ready for instructional use, artifact immersions, and virtual games and activities. In *Flights of Fancy Story Time*, educators Ann Caspari and Diane Kidd tell stories, do sketches, and demonstrate crafts that families can enjoy together at home. *AirSpace* podcasts tell the stories behind the Museum's amazing artifacts, including tales of exploration, human achievement, failure, perseverance, and innovation.

In curatorial and research areas, in FY 2020 the iconic Apollo 11 command module Columbia returned to display at NASM's Steven F. Udvar-Hazy Center after a five-city tour marking the 50th anniversary of its historic mission. In May 2020, the Telly Awards recognized Department of Space History content developed through the Smithsonian Channel. "Apollo's Moon Shot," a six-part series that Space History curator Teasel Muir-Harmony proposed and guided, received two Gold Awards, one for Television General—Documentary: Series and one for Immersive & Mixed Reality Craft-Use of AR. Likewise, "Black in Space: Breaking the Color Barrier," which debuted in February 2020 with Space History curator Cathleen Lewis as a subject matter expert, received a Gold Award for Television General—History.

Space History publications in FY 2020 included two significant first books: Jennifer Levasseur, *Through Astronaut Eyes: Photographing Early Human Spaceflight*, and Matthew Shindell, *The Life and Science of Harold C. Urey*. In addition, James David published an important article, "Starting to Crack a Hard Target: U.S. Intelligence Efforts against the Soviet Missile Program through 1957," which was posted on the National Security Archive website in February 2020. The American Astronautical Society announced the winner of the annual Eugene M. Emme Astronautical Literature Award, which recognizes outstanding books that advance public understanding of astronautics. The 2019 winners were Brian C. Odom and Stephen R. Waring, for editing *NASA and the Long Civil Rights Movement* (University Press of Florida, 2019). Space History curators Cathleen Lewis and Margaret Weitekamp have chapters in the volume.

Space History curator Martin Collins received a \$25,000 award from the Smithsonian Provost's Office to support public programming within the Institution

and with NASA regarding “Earth Optimism,” an ongoing effort to approach the pressing problems of climate crisis and environmental disaster through a focus on solutions and success. During the Earth Optimism Summit, more than 55,000 devices in over 170 countries tuned in to watch 102 hours of live stream. The hashtag, #EarthOptimism, reached over 19 million people.

In the area of aeronautics, several significant acquisitions were made to the national collection, including the Wing drone, the craft that performed the first commercial drone delivery to a U.S. home. Paintings, photographs, and rare aviation posters were added to the Museum’s art collection. Among the highlights is an original Alan Bean (1932–2018) painting depicting the cancellation of stamps on the surface of the moon by Apollo 15 astronaut Dave Scott and a cancelled stamp cover carried to the moon from the same mission. Bean served as lunar module pilot on Apollo 12, landing on the moon in November 1969, and returned to space for 59 days in 1973 as commander of the second Skylab mission. After his resignation from NASA in 1981, Bean dedicated his life to painting his memories and the stories of Apollo missions.

Another important acquisition is a collection of over 100 photographs by Anne Noggle (1922–2005) depicting the portraits of women pilots who flew for the United States and the Soviet Union during World War II. As a collection, these photographs document some of the earliest women pilots to have served for their prospective military units and convey a group of women who pursued aviation when flying was against the societal norms for women. Anne Noggle is a recognized fine art photographer known for her feminist artwork on women, aging, and self-portraiture. Noggle also served as a Woman Airforce Service Pilot from 1943 to 1944, a stunt pilot and crop duster after the war, and a captain in the U.S. Air Force from 1953 to 1959.

Scientists in the Museum’s Center for Earth and Planetary Studies (CEPS) participate on the science teams of numerous spacecraft missions and play significant roles in mission operations and planning. John Grant was appointed to the Joint NASA/ESA Mars Sample Caching Strategy Steering Committee and in that capacity, he works on the strategy for acquiring and caching samples to be collected by the Perseverance rover for possible eventual return to Earth. He also participates in evaluation of candidate Martian landing sites for future human

missions associated with both NASA and SpaceX. NASM scientists are also on the science teams for the Europa Clipper, Jupiter Icy Moons Explorer (JUICE), Mars Science Laboratory (MSL), Mars Reconnaissance Orbiter (MRO), Mars 2020 rover (Perseverance), InSight, Mars Express, Lunar Reconnaissance Orbiter (LRO), and the proposed Lunar Geophysical Network. NASM scientists are on the teams for three of the four NASA Discovery missions that were selected for concept studies: the Trident flyby mission to Neptune's moon Triton and the Venus missions VERITAS and DAVINCI+. In addition, NASM's director is on the team for the NASA New Frontiers Dragonfly mission to Saturn's moon Titan.

This year's NASM science research highlights include insights into the development of small rocky planets. In research for the *Nature* journal *Communications Earth & Environment*, Thomas Watters showed that MESSENGER-era estimates of the amount Mercury has contracted due to cooling of its interior are greatly exaggerated, suggesting that the planet has retained more primordial heat than previously thought. For Mars, several CEPS papers focused on early findings at the InSight landing site and the processes shaping the landscape there. In addition, CEPS research covered geologic mapping of Mars, Mars fluvial geomorphology and landscape evolution, development of science processing for radar sounder data on future missions, and radar sounding studies indicating that thick deposits along the equator of Mars may have ice buried beneath hundreds of meters of volcanic ash.

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 a regular year, approximately one million people visit the Moon, Meteorites and Solar System Gallery of the Geology, Gems and Meteorites Hall, where they can see one of the finest displays of meteorites anywhere in the world, ranging from presolar diamonds separated from the Allende meteorite, to the carbonate-bearing Allan Hills 84001 meteorite, which spurred the debate about past microbial life on Mars, to impactites including a square-meter section of the Cretaceous-Tertiary boundary. In FY 2020 the Museum was closed to the public for about 6.5 months due to the coronavirus pandemic. As a result, digital outreach was greatly increased, including the award-winning "Science How" broadcasts, NMNH social media takeovers, and numerous web postings.

The collections of the Division of Meteorites continue to grow. Notably, the Smithsonian's partnership with the NSF and NASA in the U.S. Antarctic Meteorite Program surpassed 27,000 individual meteorites collected in Antarctica, including samples from Mars, the Moon, and numerous poorly known asteroids. Provided free of charge to qualified scientists, these samples have addressed fundamental questions about the origin and evolution of our solar system. Unfortunately, the 2020–2021 field season was cancelled due to the pandemic, but meteorites from previous years continue to be classified.

Scientists in the Department of Mineral Sciences remain engaged in the study of meteorites and asteroids to unravel their origin in the early solar nebula, their evolution on asteroids, the differentiation of asteroids in the early history of the solar system, and the geologic evolution of Mars. Glenn MacPherson continues his work on understanding processes in the solar nebula and linking observations made in the laboratory with those made from astronomical observations. His research is focused on a possible periodicity in formation of the solar system's first components related to episodic T Tauri activity observed in forming stars. Catherine Corrigan continues her studies of fragments of meteorites formed during melting caused by collisions. Age-dating these samples is key to understanding the extent and duration of the intense impact history of the early solar system. She is a Co-Investigator in the Apollo Next Generation Sample Analysis Program, studying drill cores collected by Apollo 17 but not opened for 50 years. These cores promise to reveal the stratigraphy of the near-surface, including regolith movement, impact gardening, and interactions with the solar wind.

NMNH scientists remain actively engaged in spacecraft missions, with Tim McCoy serving as Co-Investigator on the OSIRIS-REx and Psyche missions. During FY 2020, OSIRIS-REx completed orbital operations around asteroid Bennu and was preparing for the sample acquisition at the Nightingale site, which was successfully completed on October 20, 2020. Postdoctoral Fellow Erica Jawin documented mass movement on the surface of Bennu, demonstrating that mass movement is currently the dominant geologic process on this rubble pile asteroid. Movement of material from the mid-latitudes to the poles has occurred during the most recent spin-up cycle since Bennu has been in near-Earth space. McCoy and Jawin are also leading the effort to produce global and site-specific geologic

maps that will both document the geologic features and provide context for the samples to be returned to Earth in 2023. Discussions with NASA Headquarters are also underway for NMNH to be one of the first sites to display a sample from Bennu to the public as part of the ongoing education and outreach efforts. The Psyche mission, which is now in the spacecraft and instrument fabrication phase before a planned 2022 launch, will visit the asteroid of the same name, which is a 200-kilometer-diameter asteroid thought to be composed of metallic iron, similar to Earth's metallic core. McCoy is leading the efforts to constrain the oxidation-reduction conditions of the asteroid, which is a major control on its mineralogy and constrains its formation in time and space.

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		Calendar Year	Earth Orbit ^a		Earth Escape ^b	
	Success	Failure	Success	Failure		Success	Failure	Success	Failure
1957	0	1	0	0	1990	40	0	1	0
1958	5	8	0	4	1991	32 ^c	0	0	0
1959	9	9	1	2	1992	26 ^c	0	1	0
1960	16	12	1	2	1993	28 ^c	1	1	0
1961	35	12	0	2	1994	31 ^c	1	1	0
1962	55	12	4	1	1995	24 ^{c,d}	2	1	0
1963	62	11	0	0	1996	30	1	3	0
1964	69	8	4	0	1997	22 ^e	0	1	0
1965	93	7	4	1	1998	23	0	2	0
1966	94	12	7	1 ^b	1999	35	4	2	0
1967	78	4	10	0	2000	31 ^f	0	0	0
1968	61	15	3	0	2001	23	0	3	0
1969	58	1	8	1	2002	18	0	0	1 ^b
1970	36	1	3	0	2003	28 ^{c,f}	0	2	0
1971	45	2	8	1	2004	8 ^c	0	1	0
1972	33	2	8	0	2005	10	0	2	0
1973	23	2	3	0	2006	20 ^d	0	2	0
1974	27	2	1	0	2007	16	2	2	0
1975	30	4	4	0	2008	22 ^f	0	0	0
1976	33	0	1	0	2009	24 ^f	1	0	0
1977	27	2	2	0	2010	15	0	0	0
1978	34	2	7	0	2011	16	1	3	0
1979	18	0	0	0	2012	13	0	0	0
1980	16	4	0	0	2013	18	0	1	0
1981	20	1	0	0	2014	22	1	0	0
1982	21	0	0	0	2015	12	1	1	0
1983	31	0	0	0	2016	27	3	2	0
1984	35	3	0	0	2017	20	1	0	0
1985	37	1	0	0	2018	33	0	3	0
1986	11	4	0	0	2019 ^g	21	0	0	0
1987	9	1	0	0	2020	32	3	2	0
1988	16	1	0	0	TOTAL	1,881	166	118	16
1989	24	0	2	0					

- a. The criterion of success or failure used is attainment of Earth orbit or Earth escape rather than judgment of mission success. "Escape" flights include all that were intended to go to at least an altitude equal to lunar distance from Earth.
- b. This Earth-escape failure did attain Earth orbit and, therefore, is included in the Earth-orbit success totals.
- c. This excludes commercial satellites. It counts separately spacecraft launched by the same launch vehicle.
- d. This counts various sets of microsatellites as a single payload.
- e. This includes the Small Spacecraft Technology Initiative (SSTI) Lewis spacecraft that began spinning out of control shortly after it achieved Earth orbit.
- f. This includes American spacecraft not launched in the United States.
- g. Totals updated. Electron launches counted under United States in FY 2019 report now counted under New Zealand. The one previous noted failure is also counted as a success given the criterion noted above in footnote a.

Appendix A-2

WORLD RECORD OF SPACE LAUNCHES SUCCESSFUL IN ATTAINING EARTH ORBIT OR BEYOND

(Enumerates launches rather than spacecraft; some launches orbited multiple spacecraft.)^a

Calendar Year	United States ^b	USSR/ CIS	France ^c	Italy ^c	Japan	People's Republic of China	Australia	United Kingdom ^c	European Space Agency	India	Israel	Iran	North Korea	South Korea	New Zealand
1957		2													
1958	5	1													
1959	10	3													
1960	16	3													
1961	29	6													
1962	52	20													
1963	38	17													
1964	57	30													
1965	63	48	1												
1966	73	44	1												
1967	57	66	2	1			1								
1968	45	74													
1969	40	70													
1970	28	81	2	1	1	1									
1971	30	83	1	2	2	1		1							
1972	30	74		1	1										
1973	23	86													
1974	22	81		2	1										
1975	27	89	3	1	2	3									
1976	26	99			1	2									
1977	24	98			2										
1978	32	88			3	1									
1979	16	87			2				1						
1980	13	89			2					1					
1981	18	98			3	1			2	1					
1982	18	101			1	1									
1983	22	98			3	1			2	1					
1984	22	97			3	3			4						
1985	17	98			2	1			3						
1986	6	91			2	2			2						
1987	8	95			3	2			2						
1988	12	90			2	4			7						
1989	17	74			2				7		1				
1990	27	75			3	5			5		1				
1991	20	62			2	1			9	1					
1992	31	55			2	3			7	2					
1993	24	45			1	1			7						
1994	26	49			2	5			6	2					
1995	27	33			1	2			12		1				

WORLD RECORD OF SPACE LAUNCHES SUCCESSFUL IN ATTAINING EARTH ORBIT OR BEYOND

(Enumerates launches rather than spacecraft; some launches orbited multiple spacecraft.)^a

Calendar Year	United States ^b	USSR/ CIS	France ^c	Italy ^c	Japan	People's Republic of China	Australia	United Kingdom ^c	European Space Agency	India	Israel	Iran	North Korea	South Korea	New Zealand
1996	32	25			1	3			10	1					
1997	37	28			2	6			12	1					
1998	34	24			2	6			11						
1999	32	26				4			10	1					
2000	30	34				5			12						
2001	23	23			1	1			8	2					
2002	18	23			3	4			11	1	1				
2003	26	21			2	6			4	2					
2004	19	22				8			3	1					
2005	16	26			2	5			5	1					
2006	15	16			5	3			5						
2007	25	33			3	13			8	3	1				
2008 ^d	19	26			1	11			7	3					
2009	25	29			3	4			9	4		1			
2010	15	30			2	15			6	1	1				
2011	17	33			3	18			7	3		1			
2012	13	27			2	19			10	2		1	1		
2013 ^e	19	29			3	14			7	3				1	
2014 ^e	22	31			4	16			10	4	1				
2015 ^f	18	24			4	19			11	5		1			
2016 ^f	22	16			4	21			11	7	1		1		
2017 ^f	29	18			6	17			11	4					
2018 ^f	31	16			6	38			11	7					3
2019 ^g	21	22			2	32			8	6					6
2020	34	15			4	35			6	2	1	1			6
TOTAL	1,643	3,117	10	8	114	363	1	1	289	72	9	5	2	1	15

- a. This includes commercial expendable launches and launches of the Space Shuttle as well as launches to useless orbit.
b. Launches from U.S.-Russia joint platform are included in U.S. totals.
c. Since 1979, all launches for ESA member countries have been joint and are listed under ESA.
d. Since 2008, the ESA statistics include the Soyuz launches from Guiana Space Centre.
e. The data published in the FY 2014 report reflect incorrect totals and have been adjusted.
f. Totals adjusted and updated from FY to CY.
g. Totals updated. Electron launches counted under United States in FY 2019 report now counted under New Zealand.

Appendix B

SUCCESSFUL LAUNCHES TO ORBIT ON U.S. VEHICLES

October 1, 2019–September 30, 2020

Launch Date Spacecraft Name COSPAR ^a Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°) ^b	Remarks
October 11, 2019 Ionospheric Connection Explorer (ICON) 2019-068A Pegasus XL	Ionospheric research	601 579 96.5 27.0	Drop launch from Northrop Grumman's Stargazer L-1011.
November 2, 2019 Cygnus CRS-12 (NG 12) 2019-071A Antares 230+	International Space Station	ISS	
November 11, 2019 Starlink v1.0 L1 2019-074A–BM Falcon 9 v1.2	Communications	551 549 95.6 53.0	First operational group of 60 Starlink internet satellites.
December 5, 2019 Dragon CRS-19 (SpX 19, Dragon C106-F3) 2019-083A Falcon 9v1.2	International Space Station	ISS	
December 17, 2019 JCSat 18/Kacific 1 2019-091A Kacific 1 Falcon 9 v1.2	Communications	35,800 35,779 1,436.2 0.08	
December 20, 2019 Starliner OFT 2019-094A Atlas 5-N22 (AV-080)	Uncrewed Orbital Flight Test	261 246 89.6 51.6	Returned successfully, but did not complete the planned rendezvous and docking with the ISS.
January 7, 2020 Starlink v1.0 L2 2020-001A–BM Falcon 9 v1.2	Communications	551 549 90.4 53.0	Second operational group of 60 Starlink internet satellites.
January 29, 2020 Starlink v1.0 L3 2020-006A–BM Falcon 9 v1.2	Communications	551 549 90.5 53.0	Third operational group of 60 Starlink internet satellites.
February 10, 2020 Solar Orbiter (SolO) 2020-010A Atlas 5-411 (AV-087)	Heliospheric science	Heliocentric	
February 15, 2020 Cygnus CRS-13 (NG 13, SS Robert H. Lawrence) 2020-011A Antares 230+	International Space Station	ISS	Demo of crew vehicle.
February 17, 2020 Starlink v1.0 L4 2020-012A–BM Falcon 9 v1.2	Communications	551 549 89.9–91.2 53.0	Fourth operational group of 60 Starlink internet satellites.
March 7, 2020 Dragon CRS-20 (SpX 20, Dragon C112-F3) 2020-016A Falcon 9 v1.2	International Space Station	ISS	Mission closed out the first SpaceX Cargo Resupply Services (CRS-1) contract and use of the company's original cargo Dragon spacecraft type.

a. U.N. Committee on Space Research.

b. Orbital statistics for satellites deployed following delivery aboard ISS re-supply missions are not included. Orbital data are approximate. In some instances, satellites have since de-orbited, including some of the individual spacecraft within satellite constellations.

Appendix B (cont.) SUCCESSFUL LAUNCHES TO ORBIT ON U.S. VEHICLES

October 1, 2019–September 30, 2020

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°) ^b	Remarks
March 18, 2020 Starlink v1.0 L5 2020-019A–BM Falcon 9 v1.2	Communications	551 549 92.1 53.0	Fifth operational group of 60 Starlink internet satellites.
March 26, 2020 AEHF 6 and TDO 2 2020-022B, A Atlas 5-551 (AV-086)	Communications/ Technology Development	35,988 35,586 1,436.1 6.1	The sixth Advanced Extremely High Frequency communications satellite for the U.S. Space Force and the second Technology Demonstration Orbiter. Orbital data listed is for AEHF 6.
April 22, 2020 Starlink v1.0 L6 2020-025A–BM Falcon 9 v1.2	Communications	551 549 95.6 53.1	Sixth operational group of 60 Starlink internet satellites.
May 17, 2020 X-37B (OTV-6) 2020-029A and FalconSat 8 2020-029B Atlas 5-501 (AV-081)	Technology Development/ Military	389 389 92.3 45	The sixth flight of an X-37B Orbital Test Vehicle included deployment of the U.S. Air Force Academy's FalconSat 8.
May 30, 2020 Crew Dragon DM-2 2020-033A Falcon 9 v1.2	International Space Station	ISS	This commercial Crew Dragon test flight to the International Space Station was the first crewed launch from the U.S. since the Space Shuttle retired in 2011.
June 4, 2020 Starlink v1.0 L7 2020-035A–BM Falcon 9 v1.2	Communications	551 (380–551) 549 (378–549) 95.6 53.0	Seventh operational group of 60 Starlink internet satellites.
June 13, 2020 Starlink v1.0 L8 2020-038A–BK SkySat 16, 17, 18 2020-038BL–BN Falcon 9 v1.2	Communications Earth Observation	551 549 95.6 53.0	Eighth operational group of 58 Starlink internet satellites. The launch included three SkySat Earth observation satellites. Orbital data apply to Starlink.
June 30, 2020 Navstar GPS III-3 (Navstar 79, USA 304) 2020-041A Falcon 9 v1.2	GPS	20,199 20,165 718 55.06	
July 15, 2020 NROL-129 2020-046A–D Minotaur 4	Military/Earth Observation	579 569 96.15 54	Four payloads carried into orbit.
July 20, 2020 ANASIS 2 (KMilSatCom 1, Koreasat 116) 2020-048A Falcon 9 v1.2	Communications/Military	35,792 35,781 1,436.1 0.01	First South Korean military communications satellite.
July 30, 2020 Mars 2020 (Perseverance) 2020-052A Atlas 5-541 (AV-088)	Mars Lander	N/A	In addition to the Perseverance rover, the Ingenuity helicopter was delivered to the Martian surface and became the first helicopter to fly on another world.
August 7, 2020 Starlink v1.0 L9 2020-055A–BJ BlackSky Global 7 and 8 2020-055BP–BQ Falcon 9 v1.2	Communications Earth Observation	551 548 95.6 53.0	Ninth operational group of 57 Starlink internet satellites. The launch included two BlackSky satellites. Orbital data apply to Starlink.

Appendix B (cont.)
SUCCESSFUL LAUNCHES TO ORBIT ON U.S. VEHICLES

October 1, 2019–September 30, 2020

Launch Date Spacecraft Name COSPAR ^a Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°) ^b	Remarks
August 18, 2020 Starlink v1.0 L10 2020-057A–BK SkySat-19, -20, -21 2020-057BQ–BS Falcon 9 v1.2	Communications Earth Observation	551 548 95.6 53	Tenth operational group of 58 Starlink internet satellites. The launch included three SkySat Earth observation satellites. Orbital data apply to Starlink.
August 30, 2020 SAOCOM 1B GNOMES 1 EG 1 (Tyvak 0172) 2020-059A–C Falcon 9 v1.2	Earth Observation/Radar Earth Science Communications	608–612 598–606 96.8 97.8	All three satellites are part of larger constellations.
September 3, 2020 Starlink v1.0 L11 2020-062A–BM Falcon 9 v1.2	Communications	551 548 95.6 53	Eleventh operational group of 60 Starlink internet satellites.

Appendix C

HUMAN SPACEFLIGHTS

October 1, 2019–September 30, 2020

Spacecraft	Launch Date	Crew	Flight Time (d:h:min)	Highlights
Soyuz MS-16 “Irkut” Expedition 62, 63	April 9, 2020	Anatoli Ivanishin Ivan Vagner Chris Cassidy	195:18:49	First crewed launch with a Soyuz 2.1a rocket.
Crew Dragon C206 “Endeavour” SpaceX Demo-2 Expedition 63	May 30, 2020	Douglas Hurley Robert Behnken	63:23:25	This commercial Crew Dragon test flight, Demonstration Mission-2 (DM-2), to the International Space Station was the first crewed orbital mission launched from the U.S. since the Space Shuttle retirement in 2011.

Appendix D-1A SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of real-year dollars)

FY	NASA Total	NASA Space	DOD ^a	Other ^b	DOE ^c	DOC	DOI	USDA	NSF ^d	DOT	Total Space
1959	331	261	490	34	34						785
1960	524	462	561	43	43						1,066
1961	964	926	814	68	68						1,808
1962	1,825	1,797	1,298	199	148	51					3,294
1963	3,673	3,626	1,550	257	214	43					5,433
1964	5,100	5,016	1,599	213	210	3					6,828
1965	5,250	5,138	1,574	241	229	12					6,953
1966	5,175	5,065	1,689	214	187	27					6,968
1967	4,966	4,830	1,664	213	184	29					6,707
1968	4,587	4,430	1,922	174	145	28	0.2	1			6,526
1969	3,991	3,822	2,013	170	118	20	0.2	1	31		6,005
1970	3,746	3,547	1,678	141	103	8	1	1	28		5,366
1971	3,311	3,101	1,512	162	95	27	2	1	37		4,775
1972	3,307	3,071	1,407	133	55	31	6	2	39		4,611
1973	3,406	3,093	1,623	147	54	40	10	2	41		4,863
1974	3,037	2,759	1,766	158	42	60	9	3	44		4,683
1975	3,229	2,915	1,892	158	30	64	8	2	54		4,965
1976	3,550	3,225	1,983	168	23	72	10	4	59		5,376
TQ*	932	849	460	43	5	22	3	1	12		1,352
1977	3,818	3,440	2,412	194	22	91	10	6	65		6,046
1978	4,060	3,623	2,738	226	34	103	10	8	71		6,587
1979	4,596	4,030	3,036	248	59	98	10	8	73		7,314
1980	5,240	4,680	3,848	231	40	93	12	14	72		8,759
1981	5,518	4,992	4,828	234	41	87	12	16	78		10,054
1982	6,044	5,528	6,679	313	61	145	12	15	80		12,520
1983	6,875	6,328	9,019	327	39	178	5	20	85		15,674
1984	7,458	6,858	10,195	395	34	236	3	19	103		17,448
1985	7,573	6,925	12,768	584	34	423	2	15	110		20,277
1986	7,807	7,165	14,126	477	35	309	2	23	108		21,768
1987	10,923	9,809	16,287	466	48	278	8	19	112	1	26,562
1988	9,062	8,322	17,679	741	241	352	14	18	115	1	26,742
1989	10,969	10,097	17,906	560	97	301	17	21	121	3	28,563
1990	12,324	11,460	15,616	506	79	243	31	25	124	4	27,582
1991	14,016	13,046	14,181	772	251	251	29	26	211	4	27,999

a. DOD reported that improvements to the estimating methodology resulted in a change in estimated budget authority and outlays starting in FY 2013.

b. The Other column is the total of the non-NASA and non-DOD budget authority figures that appear in the succeeding columns. The total is sometimes different from the sum of the individual figures because of rounding. The Total Space column does not include the NASA Total column because the latter includes budget authority for aeronautics as well as space. For the years 1989–97, this Other column also includes small figures for the Environmental Protection Agency (EPA), as well as \$2.1 billion for the replacement of Space Shuttle Challenger in 1987.

c. DOE has recalculated its space expenditures since 1998.

d. The NSF has recalculated its space expenditures since 1980, making them significantly higher than reported in previous years.

* Transition Quarter

Appendix D-1A (cont.)
SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of real-year dollars)

FY	NASA Total	NASA Space	DOD ^a	Other ^b	DOE ^c	DOC	DOI	USDA	NSF ^d	DOT	Total Space
1992	14,317	13,199	15,023	798	223	327	34	29	181	4	29,020
1993	14,310	13,064	14,106	731	165	324	33	25	180	4	27,901
1994	14,570	13,022	13,166	632	74	312	31	31	179	5	26,820
1995	13,854	12,543	10,644	759	60	352	31	32	278	6	23,946
1996	13,884	12,569	11,514	828	46	472	36	37	231	6	24,911
1997	13,709	12,457	11,727	789	35	448	42	39	219	6	24,973
1998	13,648	12,321	12,359	839	103	435	43	39	213	6	25,519
1999	13,653	12,459	13,203	982	105	575	59	37	200	6	26,644
2000	13,601	12,521	12,941	1,056	164	575	60	44	207	6	26,518
2001	14,230	13,304	14,326	1,062	145	577	60	36	232	12	28,692
2002	14,868	13,871	15,740	1,180	166	644	64	28	266	12	30,791
2003	15,364	14,360	19,388	1,305	191	649	74	42	337	12	35,053
2004	15,379	14,322	19,115	1,464	209	745	71	61	366	12	34,901
2005	16,198	15,234	19,690	1,551	229	807	70	73	360	12	36,475
2006	16,623	15,765	22,114	1,647	245	860	82	84	364	12	39,526
2007	16,285	15,568	22,418	1,680	200	912	87	65	404	12	39,666
2008	17,117	16,502	24,795	1,698	195	862	90	59	479	13	42,995
2009	17,775	17,275	26,528	1,868	200	1,078	64	27	485	14	45,671
2010	18,725	18,228	26,463	2,057	203	1,261	67	27	484	15	46,748
2011	18,432	17,898	27,234	2,186	229	1,444	66	20	412	15	47,318
2012	17,773	17,203	26,677	2,580	199	1,876	76	7	406	16	46,460
2013	17,395	16,865	10,818	2,578	185	1,865	84	20	409	15	30,261
2014	17,647	17,081	10,400	2,839	174	2,087	82	19	461	16	30,320
2015	18,010	17,359	10,325	3,010	182	2,223	83	19	485	18	30,694
2016	19,285	18,645	6,967	3,159	178	2,346	87	19	508	22	28,771
2017	19,653	18,993	10,316	2,995	172	2,214	85	20	480	24	32,305
2018	20,736	19,976	7,861	2,953	175	2,099	79	16	556	29	30,790
2019	21,500	20,775	9,970	2,604	217	1,667	84	19	581	36	33,349
2020	22,629	21,845	11,900	2,401	195	1,507	84	20	543	52	36,146

Appendix D-1B SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY
(in millions of inflation-adjusted FY 2020 dollars)

FY	Inflation Factors	NASA Total	NASA Space	DOD ^a	Other ^b	DOE ^c	DOC	DOI	USDA	NSF ^d	DOT	Total Space
1959	6.958	2,303	1,816	3,410	237	237						5,462
1960	6.866	3,598	3,172	3,852	295	295						7,319
1961	6.772	6,528	6,271	5,513	461	461						12,244
1962	6.705	12,236	12,048	8,702	1,334	992	342					22,085
1963	6.627	24,339	24,028	10,271	1,703	1,418	285					36,002
1964	6.543	33,368	32,819	10,462	1,394	1,374	20					44,674
1965	6.432	33,768	33,047	10,124	1,550	1,473	77					44,721
1966	6.297	32,586	31,894	10,635	1,348	1,178	170					43,876
1967	6.111	30,347	29,516	10,169	1,302	1,124	177					40,987
1968	5.905	27,087	26,160	11,350	1,029	856	165	1	6			38,538
1969	5.647	22,539	21,585	11,368	962	666	113	1	6	176		33,915
1970	5.360	20,080	19,014	8,995	756	552	43	5	5	150		28,764
1971	5.101	16,890	15,819	7,713	826	485	138	10	5	188		24,358
1972	4.870	16,105	14,956	6,852	650	268	151	29	10	192		22,458
1973	4.668	15,901	14,439	7,577	688	252	187	47	9	193		22,704
1974	4.358	13,234	12,023	7,696	689	183	261	39	13	192		20,407
1975	3.950	12,754	11,513	7,473	623	118	253	32	8	212		19,609
1976	3.692	13,108	11,908	7,322	621	85	266	37	15	219		19,851
TQ*	3.585	3,342	3,044	1,649	154	18	79	11	4	43		4,848
1977	3.443	13,147	11,846	8,306	666	76	313	34	21	222		20,818
1978	3.226	13,098	11,688	8,833	729	110	332	32	26	229		21,250
1979	2.985	13,719	12,030	9,063	740	176	293	30	24	218		21,833
1980	2.745	14,386	12,849	10,565	634	110	255	33	38	198		24,048
1981	2.500	13,796	12,481	12,071	586	103	218	30	40	196		25,138
1982	2.338	14,131	12,925	15,616	731	143	339	28	35	186		29,272
1983	2.240	15,401	14,175	20,204	733	87	399	11	45	191		35,112
1984	2.163	16,130	14,832	22,049	854	74	510	6	41	222		37,734
1985	2.093	15,849	14,492	26,721	1,222	71	885	4	31	230		42,435
1986	2.047	15,977	14,663	28,909	976	72	632	4	47	220		44,548
1987	2.002	21,867	19,637	32,605	933	96	557	16	38	224	2	53,175
1988	1.939	17,573	16,138	34,284	1,437	467	683	27	35	223	2	51,859
1989	1.864	20,443	18,818	33,372	1,044	181	561	32	39	226	6	53,233
1990	1.798	22,156	20,603	28,075	909	142	437	56	45	222	7	49,587
1991	1.736	24,330	22,647	24,617	1,340	436	436	50	45	367	7	48,604

a. DOD reported that improvements to the estimating methodology resulted in a change in estimated budget authority and outlays starting in FY 2013.

b. The Other column is the total of the non-NASA and non-DOD budget authority figures that appear in the succeeding columns. The total is sometimes different from the sum of the individual figures because of rounding. The Total Space column does not include the NASA Total column because the latter includes budget authority for aeronautics as well as space. For the years 1989–97, this Other column also includes small figures for the Environmental Protection Agency (EPA), as well as \$2.1 billion for the replacement of Space Shuttle Challenger in 1987.

c. DOE has recalculated its space expenditures since 1998.

d. The NSF has recalculated its space expenditures since 1980, making them significantly higher than reported in previous years.

* Transition Quarter

Appendix D-1B (cont.)
SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of inflation-adjusted FY 2020 dollars)

FY	Inflation Factors	NASA Total	NASA Space	DOD ^a	Other ^b	DOE ^c	DOC	DOI	USDA	NSF ^d	DOT	Total Space
1992	1.694	24,247	22,354	25,443	1,351	378	554	58	49	306	7	49,147
1993	1.655	23,679	21,617	23,341	1,209	273	536	55	41	298	7	46,168
1994	1.619	23,595	21,088	21,321	1,024	120	505	50	50	291	8	43,434
1995	1.586	21,970	19,891	16,880	1,203	95	558	49	51	441	10	37,974
1996	1.557	21,611	19,565	17,922	1,288	72	735	56	58	359	9	38,775
1997	1.529	20,967	19,052	17,935	1,207	54	685	64	60	336	9	38,194
1998	1.511	20,616	18,611	18,669	1,268	156	657	65	59	322	9	38,548
1999	1.492	20,370	18,588	19,698	1,465	157	858	88	55	298	9	39,751
2000	1.462	19,878	18,300	18,913	1,543	240	840	88	64	302	9	38,756
2001	1.427	20,305	18,984	20,442	1,515	207	823	86	51	331	17	40,941
2002	1.405	20,886	19,485	22,111	1,658	233	905	90	39	374	17	43,253
2003	1.378	21,178	19,794	26,724	1,799	263	895	102	58	465	17	48,317
2004	1.345	20,692	19,270	25,719	1,970	281	1,002	96	82	492	16	46,959
2005	1.306	21,152	19,893	25,712	2,025	299	1,054	91	95	470	16	47,631
2006	1.265	21,023	19,938	27,967	2,083	310	1,088	104	106	460	15	49,988
2007	1.231	20,046	19,163	27,595	2,068	246	1,123	107	80	497	15	48,826
2008	1.206	20,639	19,898	29,897	2,047	235	1,039	109	71	578	16	51,842
2009	1.194	21,217	20,620	31,665	2,229	239	1,287	76	32	579	17	54,515
2010	1.183	22,158	21,570	31,315	2,434	240	1,492	79	31	573	18	55,319
2011	1.160	21,381	20,761	31,591	2,535	266	1,675	77	23	478	17	54,887
2012	1.139	20,245	19,596	30,388	2,939	227	2,137	87	8	462	18	52,922
2013	1.119	19,459	18,866	12,101	2,884	207	2,086	94	22	458	17	33,851
2014	1.097	19,366	18,745	11,413	3,116	191	2,290	90	21	506	18	33,273
2015	1.085	19,540	18,834	11,202	3,266	197	2,412	90	21	526	20	33,302
2016	1.076	20,752	20,063	7,497	3,400	192	2,524	94	20	546	23	30,959
2017	1.057	20,777	20,079	10,906	3,166	182	2,341	90	21	507	26	34,151
2018	1.033	21,423	20,637	8,121	3,051	181	2,169	81	16	574	30	31,810
2019	1.013	21,787	21,052	10,103	2,638	220	1,689	85	19	589	37	33,794
2020	1.000	22,629	21,845	11,900	2,401	195	1,507	84	20	543	52	36,146

Appendix D-2 FEDERAL SPACE ACTIVITIES BUDGET

(in millions of dollars by fiscal year)

Federal Agencies	Budget Authority				Budget Outlays			
	2018 actual	2019 actual	2020 actual	2021 est.	2018 actual	2019 actual	2020 actual	2021 est.
NASA ¹	19,976.10	20,775.0	21,845.1	22,442.6	19,109.00	20,886.0	20,698.0	22,789.3
DOD ²	7,861	9,970	11,900	15,500	9,296	9,970	11,900	15,500
DOE	175.39	217	194.76	188.45	165.4	193	198.42	192.58
DOC ³	2,139.79	1,697.47	1,507.08	1,526.62	1,721.45	1,538.80	1,605.45	1,804.31
DOI ⁴	78.5	84.3	84.3	84.3	78.5	84.3	84.3	84.3
USDA	15.96	18.47	20.36	17.01	16.08	20.08	14.60	17.01
DOT	28.96	36.45	51.54	44.40	28.96	36.45	51.54	44.40
NSF	555.59	581.08	543.47	550.94	462.15	444.62	550.01	544.01

1. FY 2020 Budget Authority is based on enacted appropriation language in P.L. 116-260. The 2021 NASA Budget Authority and Outlays amounts are not estimated but represent actual amounts.
2. DOD submitted estimates as billions of dollars, so the figures are rounded to the nearest hundred million. FY 2020 amounts reflect actual enactment; however, FY 2021 is an estimate for future expenditures.
3. DOC Budget Authority reflects the total obligation amounts by fiscal year, i.e., all procurement, acquisition, and construction (PAC) and operations, research, and facilities (ORF) fund codes; Outlays reflect all unpaid and paid totals.
4. For the Aeronautics and Space Report of the President, the USGS reports on actual and estimated funding levels (budget authority and outlays) for Satellite Operations (space category) and the 3D Elevation Program (3DEP) (aeronautics category).

Appendix D-3 FEDERAL AERONAUTICS ACTIVITIES BUDGET

(in millions of dollars by fiscal year)

Federal Agencies	Budget Authority				Budget Outlays			
	2018 actual	2019 actual	2020 actual	2021 est.	2018 actual	2019 actual	2020 actual	2021 est.
NASA ¹	760	725.0	783.9	828.7	650	709.9	825.9	762.7
USDA	42.21	61.67	64.96	70.28	47.34	63.16	74.73	70.28
DOD ²	51,466	58,236	57,700	57,700	55,208	58,236	56,900	56,900
DOE	0	0	0.91	1.04	0	0	0.91	1.04
DOI ³	37.7	37.7	35.7	35.7	37.7	37.7	35.7	35.7
DOT	3,420.91	3,173.09	3,219.65	3,192.70	2,696.659	2,956.3	2,943.01	2,907.33

1. FY 2020 Budget Authority based on enacted appropriation language in P.L. 116-260. The 2021 NASA Budget Authority and Outlays amounts are not estimated but represent actual amounts.
2. DOD submitted estimates as billions of dollars, so the figures are rounded to the nearest hundred million. FY 2020 amounts reflect actual enactment; however, FY 2021 is an estimate for future expenditures.
3. For the Aeronautics and Space Report of the President, the USGS reports on actual and estimated funding levels (budget authority and outlays) for Satellite Operations (space category) and the 3D Elevation Program (3DEP) (aeronautics category).

Appendix E

MEMORANDUM ON SPACE POLICY DIRECTIVE-5

Cybersecurity Principles for Space Systems

Issued on September 4, 2020

MEMORANDUM FOR THE VICE PRESIDENT

THE SECRETARY OF STATE
 THE SECRETARY OF DEFENSE
 THE ATTORNEY GENERAL
 THE SECRETARY OF COMMERCE
 THE SECRETARY OF TRANSPORTATION
 THE SECRETARY OF HOMELAND SECURITY
 THE DIRECTOR OF THE OFFICE OF MANAGEMENT AND BUDGET
 THE ASSISTANT TO THE PRESIDENT FOR NATIONAL SECURITY AFFAIRS
 THE DIRECTOR OF NATIONAL INTELLIGENCE
 THE DIRECTOR OF THE CENTRAL INTELLIGENCE AGENCY
 THE DIRECTOR OF THE NATIONAL SECURITY AGENCY
 THE DIRECTOR OF THE NATIONAL RECONNAISSANCE OFFICE
 THE ADMINISTRATOR OF THE NATIONAL AERONAUTICS AND SPACE
 ADMINISTRATION
 THE DIRECTOR OF THE OFFICE OF SCIENCE AND TECHNOLOGY POLICY
 THE CHAIRMAN OF THE JOINT CHIEFS OF STAFF
 THE CHAIRMAN OF THE FEDERAL COMMUNICATIONS COMMISSION

SUBJECT: Cybersecurity Principles for Space Systems

Section 1. Background. The United States considers unfettered freedom to operate in space vital to advancing the security, economic prosperity, and scientific knowledge of the Nation. Space systems enable key functions such as global communications; positioning, navigation, and timing; scientific observation; exploration; weather monitoring; and multiple vital national security applications. Therefore, it is essential to protect space systems from cyber incidents in order to prevent disruptions to their ability to provide reliable and efficient contributions to the operations of the Nation's critical infrastructure.

Space systems are reliant on information systems and networks from design conceptualization through launch and flight operations. Further, the transmission of command and control and mission information between space vehicles and ground networks relies on the use of radio-frequency-dependent wireless communication channels. These systems, networks, and channels can be vulnerable to malicious activities that can deny, degrade, or disrupt space operations, or even destroy satellites.

Examples of malicious cyber activities harmful to space operations include spoofing sensor data; corrupting sensor systems; jamming or sending unauthorized commands for guidance and control; injecting malicious code; and conducting denial-of-service attacks. Consequences of such activities could include loss of mission data; decreased lifespan or capability of space systems or constellations; or the loss of positive control of space vehicles, potentially resulting in collisions that can impair systems or generate harmful orbital debris.

The National Security Strategy of December 2017 states that “[t]he United States must maintain our leadership and freedom of action in space.” As the space domain is contested, it is necessary for developers, manufacturers, owners, and operators of space systems to design, build, operate, and manage them so that they are resilient to cyber incidents and radio-frequency spectrum interference.

Space Policy Directive-3 (SPD-3) of June 18, 2018 (National Space Traffic Management Policy), states that “[s]atellite and constellation owners should participate in a pre-launch certification process” that should consider a number of factors, including encryption of satellite command and control links and data protection measures for ground site operations.

The National Cyber Strategy of September 2018 states that my Administration will enhance efforts to protect our space assets and supporting infrastructure from evolving cyber threats, and will work with industry and international partners to strengthen the cyber resilience of existing and future space systems.

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

(a) “Space System” means a combination of systems, to include ground systems, sensor networks, and one or more space vehicles, that provides a space-based service. A space system typically has three segments: a ground control network, a space vehicle, and a user or mission network. These systems include Government national security space systems, Government civil space systems, and private space systems.

(b) “Space Vehicle” means the portion of a space system that operates in space. Examples include satellites, space stations, launch vehicles, launch vehicle upper stage components, and spacecraft.

(c) “Positive Control” means the assurance that a space vehicle will only execute commands transmitted by an authorized source and that those commands are executed in the proper order and at the intended time.

(d) “Critical space vehicle functions (critical functions)” means the functions of the vehicle that the operator must maintain to ensure intended operations, positive control, and retention of custody. The failure or compromise of critical space vehicle functions could result in the space vehicle not responding to authorized commands, loss of critical capability, or responding to unauthorized commands.

Sec. 3. Policy. Cybersecurity principles and practices that apply to terrestrial systems also apply to space systems. Certain principles and practices, however, are particularly important to space systems. For example, it is critical that cybersecurity measures, including the ability to perform updates and respond to incidents remotely, are integrated into the design of the space vehicle before launch, as most space vehicles in orbit cannot currently be physically accessed. For this reason, integrating cybersecurity into all phases of development and ensuring full life-cycle cybersecurity are critical for space systems. Effective cybersecurity practices arise out of cultures of prevention, active defense, risk management, and sharing best practices.

The United States must manage risks to the growth and prosperity of our commercial space economy. To do so and to strengthen national resilience, it is the policy of the United States that executive departments and agencies (agencies) will foster practices within Government space operations and across the commercial space industry that protect space assets and their supporting infrastructure from cyber threats and ensure continuity of operations.

The cybersecurity principles for space systems set forth in section 4 of this memorandum are established to guide and serve as the foundation for the United States Government approach to the cyber protection of space systems. Agencies are directed to work with the commercial space industry and other non-government space operators, consistent with these principles and with applicable law, to further define best practices, establish cybersecurity-informed norms, and promote improved cybersecurity behaviors throughout the Nation’s industrial base for space systems.

Sec. 4. Principles. (a) Space systems and their supporting infrastructure, including software, should be developed and operated using risk-based, cybersecurity-informed engineering. Space systems should be developed to continuously monitor, anticipate, and adapt to mitigate evolving malicious cyber activities that could manipulate, deny, degrade, disrupt, destroy, surveil, or eavesdrop on space system operations.

Space system configurations should be resourced and actively managed to achieve and maintain an effective and resilient cyber survivability posture throughout the space system lifecycle.

(b) Space system owners and operators should develop and implement cybersecurity plans for their space systems that incorporate capabilities to ensure operators or automated control center systems can retain or recover positive control of space vehicles. These plans should also ensure the ability to verify the integrity, confidentiality, and availability of critical functions and the missions, services, and data they enable and provide. At a minimum, space system owners and operators should consider, based on risk assessment and tolerance, incorporating in their plans:

(i) Protection against unauthorized access to critical space vehicle functions. This should include safeguarding command, control, and telemetry links using effective and validated authentication or encryption measures designed to remain secure against existing and anticipated threats during the entire mission lifetime;

(ii) Physical protection measures designed to reduce the vulnerabilities of a space vehicle's command, control, and telemetry receiver systems;

(iii) Protection against communications jamming and spoofing, such as signal strength monitoring programs, secured transmitters and receivers, authentication, or effective, validated, and tested encryption measures designed to provide security against existing and anticipated threats during the entire mission lifetime;

(iv) Protection of ground systems, operational technology, and information processing systems through the adoption of deliberate cybersecurity best practices. This adoption should include practices aligned with the National Institute of Standards and Technology's Cybersecurity Framework to reduce the risk of malware infection and malicious access to systems, including from insider threats. Such practices include logical or physical segregation; regular patching; physical security; restrictions on the utilization of portable media; the use of antivirus software; and promoting staff awareness and training inclusive of insider threat mitigation precautions;

(v) Adoption of appropriate cybersecurity hygiene practices, physical security for automated information systems, and intrusion detection methodologies for system elements such as information systems, antennas, terminals, receivers, routers, associated local and wide area networks, and power supplies; and

(vi) Management of supply chain risks that affect cybersecurity of space systems through tracking manufactured products; requiring sourcing from trusted suppliers; identifying counterfeit, fraudulent, and malicious equipment; and assessing other available risk mitigation measures.

(c) Implementation of these principles, through rules, regulations, and guidance, should enhance space system cybersecurity, including through the consideration and adoption, where appropriate, of cybersecurity best practices and norms of behavior.

(d) Space system owners and operators should collaborate to promote the development of best practices, to the extent permitted by applicable law. They should also share threat, warning, and incident information within the space industry, using venues such as Information Sharing and Analysis Centers to the greatest extent possible, consistent with applicable law.

(e) Security measures should be designed to be effective while permitting space system owners and operators to manage appropriate risk tolerances and minimize undue burden, consistent with specific mission requirements, United States national security and national critical functions, space vehicle size, mission duration, maneuverability, and any applicable orbital regimes.

Sec. 5. General Provisions. (a) Nothing in this memorandum shall be construed to impair or otherwise affect:

- (i) the authority granted by law to an executive department or agency, or the head thereof; or
- (ii) the functions of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

(b) This memorandum shall be implemented consistent with applicable law and subject to the availability of appropriations.

(c) This memorandum is not intended to, and does not, create any right or benefit, substantive or procedural, enforceable at law or in equity by any party against the United States, its departments, agencies, or entities, its officers, employees, or agents, or any other person.

(d) The Secretary of Commerce is authorized and directed to publish this memorandum in the *Federal Register*.

Donald J. Trump
The White House,
September 4, 2020

ACRONYMS

3D three dimensional
3DEP 3D Elevation Program

A

A-CDD Abbreviated-Capability Development Document
A-PUFFER Autonomous Pop-Up Flat-Folding Explorer Robot
AAM Advanced Air Mobility
ACCESS Advanced Communications Capabilities for Exploration and Science Systems
ACM attitude control motor
ACN Aircraft Notebook
ACTIVATE Aerosol Cloud Meteorology Interactions over the western Atlantic Experiment
A-DCS Advanced Data Collection System
ADS-B Automatic Dependent Surveillance-Broadcast
AEDT Aviation Environmental Design Tool
AEHF Advanced Extremely High Frequency
AES Advanced Exploration Systems
AFFF Aqueous Film Forming Foam
AFSPC Air Force Space Command
AGS Atmospheric and Geospace Sciences
AHE Advanced Hawkeye
AIA Atmospheric Imaging Assembly
AIM Assessment, Inventory, and Monitoring
AIP Airport Improvement Program
air-LUSI Airborne Lunar Spectral Irradiance
AIS Automated Information System
AIT American Institute in Taiwan
ALD active-layer detachments
ALE Air Launched Effects
ALMA Atacama Large Millimeter/Submillimeter Array
AM advanced manufacturing
AMEC Alaska Mapping Executive Committee
AMISR Advanced Modular Incoherent-Scatter Radar
AMOS Autonomous Medical Officer Support
AMPERE Active Magnetosphere and Planetary Electrodynamics Response Experiment
AMRO A Michael Riley Operation
AMS Alpha Magnetic Spectrometer
AMS Automated Modular Sensor
AMS Alpha Magnetic Spectrometer
APB Acquisition Program Baseline
APKWS Advanced Precision Kill Weapon System
ARD Analysis Ready Data
ARM Atmospheric Radiation Measurement Research Facility
ARMD Aeronautics Research Mission Directorate
AROC Army Requirements Oversight Council
ARS Agricultural Research Service
ARTCC Air Route Traffic Control Center
AS Atmosphere Section
ASCENT Advanced Spacecraft Energetic Non-Toxic

ASCENT	Aviation Sustainability Center
ASCR	Advanced Scientific Computing Research
ASE	Aviation Survivability Equipment
AST	Division of Astronomical Sciences
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASU	Aircraft Sector Understanding
ATD-2	Airspace Technology Demonstration 2
ATF	Armstrong Test Facility
ATR	Advanced Test Reactor
AVC/ESC	Bureau of Arms Control, Verification and Compliance, Office of Emerging Security Challenges
AVS	Aviation Safety

B

BAA	Broad Agency Announcements
BAER	Burned Area Emergency Response
BIA	Bureau of Indian Affairs
BICEP	Background Imaging of Cosmic Extragalactic Polarization
BIG	Breakthrough, Innovative and Game-changing
BIS	Bureau of Industry and Security
BLEO	beyond low-Earth orbit
BLM	Bureau of Land Management
BMGG	Bulk Metallic Glass Gears
BNL	Brookhaven National Laboratory
BoD	Board of Directors
BOEM	Bureau of Ocean Energy Management
BOR	Bureau of Reclamation
BPS	Biological and Physical Sciences
BPSD	Biological and Physical Sciences Division

C

C2	command and control
C&N	communication and navigation
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAC	Civil Applications Committee
CAL	Cold Atom Lab
CAMI	Civil Aerospace Medical Institute
CAPS	Control and Planning Segment
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
CARES	Coronavirus Aid, Relief, and Economic Security
CCAFS	Cape Canaveral Air Force Station
CCDC	Continuous Change Detection and Classification
CCOR	Compact Coronagraph
CCP	Commercial Crew Program
CCS	Counter Communications System
CCSC	Collaborations for Commercial Space Capabilities
CCSDS	Consultative Committee for Space Data Systems
CCSDS	Consultative Committee for Space Data Standards
CDR	Critical Design Reviews
CDRA	Carbon Dioxide Removal Assembly
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CEPS	Center for Earth and Planetary Science
CfA	Center for Astrophysics Harvard & Smithsonian

CFT	Crew Flight Test
CFT	Cross-Functional Team
CHARA	Center for High Angular Resolution Astronomy
CIR	color infrared
CLDP	Commercial Low-Earth Orbit (LEO) Development Program
CLEEN	Continuous Lower Energy Emissions and Noise
CLPS	Commercial Lunar Payload Services
CMB	cosmic microwave background
CMS	Carbon Monitoring System
CMWS	Common Missile Warning System
CNES	Centre national d'études spatiales
CO ₂	carbon dioxide
COMPACT	Complex Plasma Facility
COMSATCOM	Commercial SATCOM
CONOPS	Concept of Operations
CONUS	Contiguous United States
COPUS	Committee on the Peaceful Uses of Outer Space
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COSMIC-2	Constellation Observing System for Meteorology, Ionosphere and Climate 2
COVID-19	Coronavirus Disease 2019
COWVR	Compact Ocean Wind Vector Radiometer
CRP	Constant Rate Production
CRS	Commercial Resupply Services
CT	Computerized Tomography
CTS	Crew Transportation System
CVN	aircraft carrier with nuclear propulsion
CVW	Carrier Air Wing
CWAT	Community Winter Access Trails
CWP	crop water productivity
CyAN	Cyanobacteria Assessment Network

D

DARC	Deep Space Advanced Radar Concept
DCS	Data Collection and location System
DEM	digital elevation model
DevSecOps	development, security, and operations
DHS	Department of Homeland Security
DKIST	Daniel K. Inouye Solar Telescope
DLR	German Aerospace Center
DMSP	Defense Meteorological Satellite Program
dNBR	Delta Normalized Burn Ratio
dNDVI	Delta Normalized Difference Vegetation Index
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
dPDR	Delta Preliminary Design Review
DR	Directed Requirement
DRB	Delaware River Basin
DRPS	dynamic radioisotope power system
DSAC	Deep Space Atomic Clock

DSN Deep Space Network
DVT Design Verification Test

E

ECI Early Career Initiative
EGS Exploration Ground Systems
EHT Event Horizon Telescope
ELV Expendable Launch Vehicle
eMMRTG enhanced multi-mission radioisotope thermoelectric generator
eMODIS enhanced Moderate Resolution Imaging Spectroradiometer
EO Executive Order
EO/IR Electro-Optical/Infra-Red
EOS Earth Observing System
EPS Enhanced Polar System
EPS-R Enhanced Polar System-Recapitalization
EROS Earth Resources Observation and Science
ESA European Space Agency
ESCAPE Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution
ESD Exploration Systems Development
ESIM Earth Stations in Motion
ESP Environmental Studies Program
ESR Emergency Stabilization and Rehabilitation
ESS Evolved Strategic SATCOM
ESSIO Exploration Science Strategy and Integration Office
ET evapotranspiration
ETM Enhanced Thematic Mapper
EU European Union
EUV extreme ultraviolet
EUMETSAT European Organisation for the Exploitation of Meteorological Satellites
EVA Extra-Vehicular Activity
EVAA Expandable Variable Autonomy Architecture
EWS-G Electro-optical/infrared Weather System-Geostationary

F

FAA Federal Aviation Administration
FAB-T Family of Advanced Beyond-Line-of-Sight Terminals
FACA Federal Advisory Committee Act
FARA Future Attack Reconnaissance Aircraft
FAS Foreign Agricultural Service
FCC Federal Communications Commission
FCIC Federal Crop Insurance Corporation
FDL frozen debris lobes
FEMA Federal Emergency Management Agency
FFT/BFT Friendly Force Tracking/Blue Force Tracking
FGST Fermi Gamma-ray Space Telescope
FHP Forest Health Protection
FIA Forest Inventory and Analysis
FIELD Field Exploratory Lakes Database
FLRAA Future Long Range Assault Aircraft
FMDP fuel and moderator development plan
FORGE Future Operationally Resilient Ground Evolution
FORSCOM U.S. Army Forces Command

FRP	Full Rate Production
FT-MMC	Force Tracking Mission Management Center
FTP-27 E2	Flight Test Patriot-27 Event 2
FTUAS	Future Tactical Unmanned Aerial Systems
FUE	First Unit Equipped
FVL	Future Vertical Lift
FWS	U.S. Fish and Wildlife Service
FY	fiscal year

G

G-LiHT	Goddard's LiDAR, Hyperspectral & Thermal Imager
G-REALM	Global Reservoir and Lake Monitor
GADAS	Global Agricultural and Disaster Assessment System
GBD	Global Burst Detector
GBO	Green Bank Observatory
GBT	Green Bank Telescope
GE	genetically engineered
GEDI	Global Ecosystem Dynamics Investigation
GEDS	Gravitational Effects on Distortion in Sintering
GEM	Geospace Environment Modeling
GEO	Geosynchronous Earth Orbit
GeoXO	Geostationary Extended Observations
GER	Global Exploration Roadmap
GeV	gigaelectronvolts
GF	Geospace Facilities
GIS	Geographic Information Systems
GLAM	Global Agricultural Monitoring
GLOF	glacial lake outburst flood
GMA	Global Market Analysis
GMT	Giant Magellan Telescope
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellites
GONG	Global Oscillations Network Group
GPIM	Green Propellant Infusion Mission
GPS	Global Positioning System
GPS III F	GPS III Follow-on
GS	Geospace Section
GSD	ground sample distance
GSFC	Goddard Space Flight Center
GSSAP	Geosynchronous Space Situational Awareness Program
GUT	grand-unified theory

H

HALO	habitation and logistics outpost
HEOMD	Human Exploration and Operations Mission Directorate
HEP	High Energy Physics
HERA	Hybrid Electronic Radiation Assessor
HERO	Human Exploration Research Opportunities
HF	high frequency
HFIR	High Flux Isotope Reactor
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
HLS	Human Landing System
HRP	Human Research Program

HRRR	High Resolution Rapid Refresh
HSC	Human Spaceflight Capabilities
HTV	H-II Transfer Vehicle
HZE	high-charge, and -energy

I

ICAO	International Civil Aviation Organization
ICNO	IceCube Neutrino Observatory
IDL	ice-dammed lake
INL	Idaho National Laboratory
InSAR	Interferometric Synthetic Aperture Radar
InSight	Investigations, Geodesy and Heat Transport
IOAG	Interagency Operations Advisory Group
IOP	Interoperability Plenary
IPAD	International Production Assessment Division
IPP	Integration Pilot Program
IR	infrared
IRAC	infrared array camera
IRIS	Interface Region Imaging Spectrograph
ISECG	International Space Exploration Coordination Group
ISP	In-Space Propulsion
ISR	Intelligence, Surveillance, and Reconnaissance
ISS	International Space Station
ITA	International Trade Administration
ITAC 1	Industry Trade Advisory Committee on Aerospace Equipment
ITE	Improved Turbine Engine

J

JAGM	Joint Air-to-Ground Missile
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JPPS	Joint Polar Satellite System
JUICE	Jupiter Icy Moons Explorer

K

KSC	Kennedy Space Center
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L

LandCART	Landscape Cover Analysis and Reporting Tools
LANL	Los Alamos National Laboratory
LAS	Launch Abort System
LCMAP	Land Change Monitoring, Assessment, and Projection
LCMS	Landscape Change Monitoring System
LCRD	Laser Communication Relay Demonstration
LD19	Lock and Dam 19
LDB	Long Duration Balloon
LDEP	Lunar Discovery and Exploration Program
LEIA	Lunar Exploration Instrument for space biology Applications
LEO	low-Earth orbit
lidar	light detection and ranging
LIGO	Laser Interferometer Gravitational-Wave Observatory

LiON	lithium ion
LLNL	Lawrence Livermore National Laboratory
LRASM	Long-Range Anti-Ship Missile
LRO	Lunar Reconnaissance Orbiter
LRPM	Long Range Precision Munition
LSIC	Lunar Surface Innovation Consortium
LSII	Lunar Surface Innovation Initiative
LTV	Lunar Terrain Vehicle
LuSTR	lunar surface technology research

M

M-STAR	MUREP Space Technology Artemis Research
MAF	Michoud Assembly Facility
MAG	Magnetospheric Physics
MANPADS	Man-Portable Air Defense Systems
MAVEN	Mars Atmosphere and Volatile EvolutioN
MDA	Missile Defense Agency
MDO	Multi-Domain Operations
MEDLI	Mars Entry, Descent and Landing Instrumentation
MEO	medium-Earth orbit
MEP	Manufacturing Extension Partnership
MERA	Multi-model Ensemble Risk Assessment
MFOV	medium field of view
MISSE	Materials International Space Station Experiment
MMAC	Mike Monroney Aeronautical Center
MMRTG	multi-mission radioisotope thermoelectric generator
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSA	Modular Open System Architecture
MOXIE	Mars Oxygen In-Situ Resource Utilization Experiment
MPS	Directorate for Mathematical and Physical Sciences
MRO	Mars Reconnaissance Orbiter
MSFC	Marshall Space Flight Center
MSIP	Mid-Scale Innovations Program
MSL	Mars Science Laboratory
MTA	Middle Tier of Acquisition
MTBS	Monitoring Trends in Burn Severity
MultiGAS	multicomponent gas analyzer system
MUREP	Minority University Research and Education Project

N

NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System
NAIP	National Agriculture Imagery Program
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASM	National Air and Space Museum
NBR	Normalized Burn Ratio
NCEP	National Centers for Environmental Prediction
NDSA	National Defense Space Architecture
NDVI	Normalized Difference Vegetation Index
NE	Office of Nuclear Energy
NEN	Near Earth Network

NEO	near-Earth object
NEOWISE	Near-Earth Object Wide-field Infrared Survey Explorer
NEPA	National Environmental Policy Act
NERSC	National Energy Research Scientific Computing Center
Next-Gen OPIR	Next Generation Overhead Persistent Infrared
NextSTEP	Next Space Technology Exploration Partnerships
NFS	National Forest System
NGA	National Geospatial-Intelligence Agency
ngEHT	Next Generation EHT
NGLAW	Next Generation Land Attack Weapon
NGRTG	next-generation radioisotope thermoelectric generator
NGSC	Next Generation Strike Capability
NIAC	NASA Innovative Advanced Concepts
NICER	Neutron star Interior Composition ExploreR
NISAR	NASA-ISRO Synthetic Aperture Radar
NIST	National Institute of Standards and Technology
NLOS	Non-Line of Sight
NMNH	National Museum of Natural History
NNSA	National Nuclear Security Administration
NO ₂	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NOC	National Operations Center
NOIRLab	National Optical-Infrared Astronomy Research Laboratory
NOTAM	Notice to Air Mission
NPS	National Park Service
NRL	National Research Laboratory
NSF	National Science Foundation
NSN	Near Space Network
NSO	National Solar Observatory
NSPO	National Space Organization
NSS	National Security Space
NSSL	National Security Space Launch
NSTC	National Science and Technology Council
NSW-SAP	National Space Weather Strategy and Action Plan
NTAP	Notice to Air Mission Publication
NTL	NASA Tournament Lab
NTP	Nuclear Thermal Propulsion
NWI	National Wetlands Inventory

O

OADR	Open Architecture Data Repository
OCP	observatory commissioning phase
OCS	Outer Continental Shelf
ODNI	Office of the Director of National Intelligence
OECD	Organization for Economic Cooperation and Development
OES/SA	Bureau of Oceans and International Environmental and Scientific Affairs, Office of Space Affairs
OFT	Orbital Flight Test
OISL	optical-intersatellite link
OLI	Operational Land Imager
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping Profiler Suite
ORNL	Oak Ridge National Laboratory
OSAM	On-Orbit Servicing, Assembly and Manufacturing
OSC	Office of Space Commerce

OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
OSMRE	Office of Surface Mining Reclamation and Enforcement
OSTEM	Office of STEM Engagement
OSTM	Ocean Surface Topography Mission
OT	operational test
OTM	Office of Transportation and Machinery

P

PA DEP	Pennsylvania Department of Environmental Protection
PACE	Payload Accelerator for CubeSat Endeavors
PBRE	Packed Bed Reactor Experiment
PC	Project Convergence
PCM	Post Certification Mission
PDR	Preliminary Design Reviews
PEO	Program Executive Office
PeV	petaelectronvolts
PHM	prognostics and health management
PHY	Division of Physics
PIT	Project Interface Testing
PNT	Positioning, Navigation, and Timing
POR	Program of Record
PPE	power and propulsion element
PPE	personal protective equipment
PRIME-1	Polar Resources Ice Mining Experiment-1
PSD	production, supply, and distribution
PTD	Pathfinder Technology Demonstrator
PTES	Protected Tactical Enterprise Service
PTS	Protected Tactical SATCOM
Pu	plutonium

Q

QueSST	Quiet SuperSonic Technology
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R

RAMPT	Rapid Analysis and Manufacturing Propulsion Technology
RASSOR	Regolith Advanced Surface Systems Operations Robot
RDO	Arctic District Office
RELL	Robotic External Leak Locators
RF	radio frequency
RFI	request for information
RFP	Request for Proposal
RIM	Runway Incursion Mitigation
RMA	Risk Management Agency
RO	radio occultation
RPT	Rocket Propulsion Test
RPS	Radioisotope Power Systems
RR	Rodent Research
RSLP	Rocket Systems Launch Program
RSTA	Reconnaissance, Surveillance, and Target Acquisition
RTS	Reagan Test Site
RTS	retrogressive thaw slumps

SABRS	Space and Atmospheric Burst Reporting System
SAF	sustainable aviation fuels
SAM	Spacecraft Atmosphere Monitor
SANS	Spaceflight Associated Neuro-ocular Syndrome
SAO	Smithsonian Astrophysical Observatory
SAR	Search and Rescue
SAR	synthetic aperture radar
SBEM	Space Based Environmental Monitoring
SBIR	Small Business Innovative Research
SBIRS	Space Based Infrared System
SCaN	Space Communications and Navigation
SDA	Space Domain Awareness
SDA	Space Development Agency
SDB II	Small Diameter Bomb II
SDTA	System Demonstration Test Article
SEM	Space Environmental Monitor
SERFE	Spacesuit Evaporation Rejection Flight Experiment
SFCSCO	Space Force Commercial SATCOM Office
SFS	Space and Flight Support
SGSS	Space Network Ground Segment Sustainment
SHIIVER	Structural Heat Intercept Insulation Vibration Evaluation Rig
SLS	Space Launch System
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SN	Space Network
SNL	Sandia National Laboratories
SNP	Space Nuclear Propulsion
SOHO	Solar and Heliospheric Observatory
SpaceX	Space Exploration Technologies
SPD	Space Policy Directives
SPLICE	Safe & Precise Landing - Integrated Capabilities Evolution
SpRCO	Space Rapid Capabilities Office
SPT	South Pole Telescope
SPTA	Solid Propulsion Test Article
SRB	Standing Review Board
SSA	space situational awareness
SSAEM	Space Situational Awareness Environmental Monitoring
SSC	Stennis Space Center
SSG	Senior Steering Group
SSDP	Space Security and Defense Program
SSEBop	Simplified Surface Energy Balance
SSN	Space Surveillance Network
SST	Small Spacecraft Technology
SSV	Space Service Volume
STA	Structural Test Article
STEM	Science, Technology, Engineering, and Mathematics
STEReO	Scalable Traffic Management for Emergency Response Operations
STMD	Space Technology Mission Directorate
STO-H8	Space Test Program-H8
STPSat-6	Space Test Program Satellite 6
STRG	Space Technology Research Grants
STTR	Small Business Technology Transfer
Suomi NPP	Suomi National Polar-orbiting Partnership

SuperDARN	Super Dual Auroral Radar Network
SWARM-EX	Space Weather Atmospheric Reconfigurable Multiscale Experiment
SWF	subpixel water fraction
SWFO	Space Weather Follow On
SWORM	Space Weather Operations, Research, and Mitigation
SWPC	Space Weather Prediction Center
SWSH	Space Weather, Security, and Hazards

T

TACTOM	Tactical Tomahawk
TALOS	Thruster for the Advancement of Low-temperature Operation in Space
TAS	Thermal Amine Scrubber
TBO	Trajectory Based Operations
TCH	Thermal Conducting Heating
TES	Terrestrial Ecosystem Science
TECRO	Taipei Economic and Cultural Representative Office
TEMPO	Tropospheric Emissions: Monitoring Pollution
TESS	Transiting Exoplanet Survey Satellite
THAAD	Terminal High Altitude Area Defense
TITE	TBO Integrated Test Environment
TM	Terminal Mode
TM	Thematic Mapper
TREAT	Transient Reactor Test Facility
TRIDENT	The Regolith and Ice Drill for Exploring New Terrain
TRISH	Translational Research Institute for Space Health
TRN	Terrain Relative Navigation
TROPOMI	TROPOspheric Monitoring Instrument
TS	test stand
TWI	Training with Industry

U

uADS	underwater Acoustic Deterrent System
UAE	United Arab Emirates
UAG	Users' Advisory Group
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UASSC	UAS Standards Collaborative
UHF	Ultra-High Frequency
ULA	United Launch Alliance
UMESC	Upper Midwest Environmental Sciences Center
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGEO	U.S. Group on Earth Observations
USGS	U.S. Geological Survey
USMC	U.S. Marine Corps
USN	U.S. Navy
USNDS	U.S. Nuclear Detonation Detection System
USPTO	U.S. Patent and Trademark Office
USRC	University Student Research Challenge
USSF	United States Space Force
UWMS	Universal Waste Management System

V

VAB	Vehicle Assembly Building
VHI	Vegetation Health Index
VIIRS	Visible Infrared Imaging Radiometer Suite
VIPER	Volatiles Investigating Polar Exploration Rover
WISE	vehicle interfaces to spacesuit equipment
VISORS	Virtual Super-resolution Optics with Reconfigurable Swarms
VITAL	Ventilator Intervention Technology Accessible Locally
VLF	Very Low Frequency

W

WASDE	World Agricultural Supply and Demand Estimates
WFOV	wide field of view
WGS	Wideband Global Satellite Communications
WIN	Written Impact Narratives
WRC	World Radiocommunication Conference
WSF	Weather System Follow-on
WSF-M	WSF–Microwave
WSTF	White Sands Test Facility
WTO	World Trade Organization

X

xEMU	Exploration Extravehicular Mobility Unit
xEVA	Exploration Extravehicular Activity
XVS	eXternal Vision System

