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NASA's Small Spacecraft & Distributed Systems: Development and Demonstration of Technologies Enabling Swarms and New Spacecraft Platforms with AI and Edge Computing

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ABSTRACT

NASA's Small Spacecraft & Distributed Systems (SSDS) within the Research and Technology Mission Directorate (RTMD) expands U.S. capability to execute unique missions through targeted investment, rapid development, and flight demonstration of small spacecraft technologies applicable to exploration, science and the commercial space sector. SSDS strategically invests in technology development and on-orbit demonstrations executed across NASA, other government agencies, industry, and academia. The program's University SmallSat Technology Partnerships initiative awards academic researchers with the opportunity to collaborate with NASA to mature innovative technology. Capabilities aligned with RTMD's technology shortfalls and interests - power, processing, propulsion, sensors, communications, autonomous navigation, architectures, and advanced applications like artificial intelligence (AI), machine learning, and edge computing - are prioritized in SSDS investments. These investments enable distributed, autonomous, and cooperative small spacecraft systems that support swarm missions extending beyond low Earth orbit into cislunar and deep space. This paper highlights representative SSDS flight demonstrations that mature these capabilities to enable a future operational infrastructure needed to support sustained exploration of the Moon and beyond.

SSDS's investment strategy emphasizes rapid development and on-orbit demonstration to validate spacecraft technologies required for swarms and distributed mission architectures. The Starling swarm technology demonstration mission exemplifies this approach by advancing distributed spacecraft autonomy, cooperative operations, and space situational awareness. Extended flight testing and ongoing studies of next generation swarm configurations and on-orbit space traffic monitoring and management continue to inform future swarm designs. DiskSat's four-spacecraft demonstration mission represents SSDS's strategic vision to expand the design space for future small spacecraft through its commitment to advance novel platform concepts that can impact how science is performed on orbit. Continuing to invest in future platforms, the notional PY12 concept is a 12-spacecraft swarm hosting neuromorphic processors and is envisioned as an on-orbit testbed for AI, edge computing, and positioning, navigation and timing technologies.

SSDS also invests in single-spacecraft technology demonstrations that underpin the success of future swarm missions and accelerate the availability of validated technologies across the small spacecraft ecosystem. Examples of such demonstrations include Pathfinder Technology Demonstrator-3 (PTD-3), which performed high-rate optical

communications; PTD-R, which demonstrated a camera capable of simultaneous ultraviolet and short-wave infrared optical sensing; and CAPSTONE, the Cislunar Autonomous Positioning System Technology and Operations Navigation Experiment, which validated autonomous navigation in cislunar space.

Collectively, SSDS-funded demonstrations advance capabilities across swarms and illustrate a coordinated investment strategy to mature high-impact technologies required for autonomous, distributed, and cooperative small spacecraft systems for low Earth orbit, cislunar, and deep space applications. Technology demonstrations strengthen SSDS partnerships with industry, academia, and other government agencies, and promote small spacecraft community adoption of capabilities required to close technical gaps for swarm missions.

INTRODUCTION

Small Spacecraft & Distributed Systems (SSDS) is part of NASA's Research and Technology Mission Directorate (RTMD) which advances the development, demonstration, and infusion of transformational technologies.[1] RTMD's investments enhance NASA's efforts to explore the unknown in space, innovate for the benefit of humanity, and inspire the world through discovery. SSDS focuses on advancing technologies and mission architectures that promote affordability and operational utility of small spacecraft for NASA science, exploration, and commercial applications.

RTMD's customers include NASA and the broader U.S. civil space community. As the technology base for civil space, RTMD advances technology to support future NASA, other government, and commercial missions. RTMD investments aim to (1) advance U.S. space technology innovation and competitiveness in a global context, (2) encourage technology driven economic growth with an emphasis on the expanding space economy, and (3) inspire and develop a powerful U.S. aerospace technology community. RTMD bolsters and funds ideas from entrepreneurs, researchers, and innovators across the country, embracing risk and cultivating breakthrough ideas. Space technology research and development occurs at NASA centers, universities, national labs, and small businesses.

To support RTMD's high-priority objectives, SSDS develops and demonstrates technologies capable of enabling increasingly sophisticated and unique U.S. missions using small spacecraft. These investments follow a two-prong approach: (1) utilize small spacecraft to rapidly demonstrate, test, and mature new technologies relevant for all mission classes and (2) improve the capabilities and develop new operational concepts for small spacecraft. Using small spacecraft allows for the execution of technology demonstration missions at much lower cost than previously possible, while substantially reducing overall development timelines. Historically, small spacecraft technology missions primarily focused on demonstrating individual subsystem technologies. Advances in technology, including autonomy, communications, and edge computing have expanded the capabilities of small spacecraft enabling new mission architectures such as swarms, as well as the ability to execute these missions at new destinations and in challenging new environments. Finally, small spacecraft can augment existing assets and future missions with supporting small spacecraft.

SSDS implements its missions through NASA in-house activities and in collaboration with industry und university partners. Beyond direct engagement in projects, the Small Spacecraft Systems Virtual Institute (S3VI), an SSDS affiliate, captures best practices, lessons learned, and produces the annual Small Spacecraft Technology State of the Art report for the community. Overall, S3VI's activities and established community facilitate integration and sharing of NASA's interests and investments in small spacecraft.

SSDS evolved from the Small Spacecraft Technology program that traditionally focused on power, processing, and propulsion sub-systems. Today, SSDS is integrating new artificial intelligence (AI) and edge computing capabilities into small spacecraft, enabling the opportunity to build large swarms as truly distributed systems capable of coordinated operations across Earth, cislunar, and deep space. This paper will outline the vision for distributed small spacecraft systems and present how SSDS past, current, and future missions are maturing the technologies needed to make distributed systems a reality.

VISION: THE AI-ENABLED SMALL SPACECRAFT SWARM AS A TRULY DISTRIBUTED AUTONOMOUS SYSTEM

Why Do We Need AI for Small Spacecraft Swarms

Over the last decade, small spacecraft have become a commodity—increasingly capable, affordable, and accessible. The invention of the CubeSat form factor combined with component miniaturization initiated a transformation of the aerospace industry, affording many nations, commercial entities, and academic programs the opportunity to build and launch spacecraft. While spacecraft hardware and launch options are more affordable, operating spacecraft to their full potential requires skilled mission operations teams and operational infrastructure. Multi spacecraft missions,

such as constellations and swarms, continue to attract significant interest across government, commercial, and academic communities due to their immense potential.

Large constellations of identical spacecraft that perform the same or similar tasks repeatedly use automation to more efficiently complete their tasks. However, automation based on decision trees is not sufficient when spacecraft must react to novel challenges on orbit. AI-based avionics encompass a higher decision-making logic that manages how information is interpreted, prioritized, and acted upon within the spacecraft, thus enabling distributed spacecraft swarms to operate cohesively together without external commands.[2] Next-generation, distributed swarms are becoming achievable through advances in AI, enabling mission architectures that would otherwise be prohibitively expensive to operate.

In addition to cost concerns, AI has the potential to overcome communication latency issues, both resulting from the need for real-time decisions that are either not feasible due to limited human response times or due to speed-of-light induced lag during deep space missions. The following subsections expand upon the role of AI in enabling distributed spacecraft operations and summarize representative examples relevant to our vision.

AI-Supported Swarm Operations

In this vision, AI enables fully "launch-and-forget" capable spacecraft swarms to conduct autonomous operations with minimal ground intervention. This would allow operators to focus primarily on mission objectives and direct products to their customers on the ground. This ambitious goal supports the spacecraft's initial commissioning, operations, and anomaly resolution.

During commissioning, spacecraft would autonomously perform systems checkout (i.e., self-test of all spacecraft subsystems), instrument calibration and testing. They would then share the results with the other members of the swarm to enable an optimized tasking of the nodes. For example, if not all spacecraft in the swarm have the same instrument sensitivity, or the propulsion systems are not all fully functional, or communication systems might not all have identical performance; information shared between the spacecraft during checkout can allow the swarm to self-organize to optimize performance. Optimizing roles based on sharing checkout results could, for instance, and depending on actual propulsion performance, allow certain spacecraft to assume different orbits, or be tasked differently when entering operations.

During active operations, rather than being commanded from the ground, spacecraft would self-negotiate tasking, reacting to external events and measured data in real-time, i.e., implement "tip and cue". This would enable capabilities that are currently not possible with human operators due to either cost or latency reasons. Spacecraft operating cooperatively could also analyze data on orbit, sending only relevant data and/or results to customers, saving data bandwidth. Such capabilities are particularly important for deep space missions where communication links to Earth are constrained by lower data rates and increased latency resulting from the much greater distances involved. Additional autonomous tasks could also support orbit maintenance, and collision avoidance with other spacecraft or debris. In Earth orbit, these maneuvers would be coordinated within both the swarm and with other external spacecraft, possibly involving an overarching (automated) space traffic management system.

Anomaly resolution is often the most challenging part of spacecraft operations. Without direct access to the on-orbit spacecraft and with limited or no real-time access to data, operators rely on spacecraft 'flat sats' (lab-based hardware representations of the full system) and fault tree analysis to find and fix issues. Implementing fixes can pose similar challenges. The vision for anomaly resolution supported by AI is one that includes both a single spacecraft and the entire swarm. Individual spacecraft would be able to detect errors and correct them where possible. For example, issues with power generation could be fixed by automatically adjusting duty cycles of instruments or radio transmissions. Attitude determination and control system (ADCS) biases could be quantified and corrected. In a similar fashion instrument biases could be included in the data analysis. Switching to backup systems would be the last resort, if such systems were available. At the swarm level, the spacecraft would report issues where possible, or the swarm could monitor connectivity and data quality. If necessary, the swarm would re-assign the tasks of the faulty spacecraft to alternate team members or ultimately reconfigure the swarm, implement a form of self-healing, without any intervention from the ground.

Applications of AI-Supported Small Spacecraft Swarms

The outlined vision supports many different use cases, and many of the identified capabilities would certainly be nice-to-have for most space missions. The following outlines a few example applications of AI-supported small spacecraft swarms for science and exploration missions that would be difficult or impractical to implement using traditional single-spacecraft systems.

Multipoint Science Data Collection

Many science investigations require simultaneous multi-point measurement of phenomena in space, often across large regions. One example is the solar wind, to be investigated by the HelioSwarm mission.[3] During this mission, simultaneous recordings of multiple physical parameters will be taken at defined positions to refine our understanding of the physics of the solar wind. Synthetic aperture technology represents another example application that falls into this same category, but that is even more complex to implement than other multi-point measurements. Synthetic apertures require multiple nodes in a swarm to utilize precise timing synchronization and formation flying to create large baseline apertures, with a corresponding increase in resolution compared to smaller telescopes or antennas. The main benefit in this example is that there is no physical limit imposed to aperture sizes along with the potential for measurements that would be impossible to achieve in space otherwise. AI-supported swarms enable functions offered by these systems while relating the location and timing of each separate measurement to a degree that allows reconstruction of phase information. This leads to the requirement of timing and location synchronization of the multiple nodes to a degree that could not be manually implemented from multiple mission operations centers on the ground.

Off-World Satellite-Based Navigation

A second use case utilizes swarms to support navigation and positioning for science and exploration operations in cislunar and deep space environments. Today, beyond Earth, position determination depends on ranging provided by NASA's Deep Space Network (DSN), which cannot 'scale up' to provide GPS-like services to hundreds or thousands of users. With GPS-like swarm systems at the Moon and Mars currently in the discussion and planning stages, cost and latency issues would impact the operations of such systems. If these extensive systems could operate autonomously, implementation would be in reach.

Space Situational Awareness and Space Traffic Management

Related application cases include space situational awareness and space traffic management in cislunar and deep space. AI-enabled swarms could provide both space-based sensors and analysis to provide awareness in lunar and Martian orbits to enable safe operations and potentially even automate space traffic management and collision avoidance tasks.

Vision Summary

The SSDS vision is to enable new use cases for future lunar and deep space missions through development of capable small spacecraft with "launch-and-forget" autonomy that supports commissioning, spacecraft swarm operations, data collection, and data analysis. This scenario allows the end user to receive only the data products they need. While this is an ambitious vision, SSDS invests in technology and conducts missions that advance the vision, leveraging the flexibility, adaptability, and lower cost of small spacecraft that bring implementation closer to reality.

The next section outlines SSDS work and results to date that illustrate the path towards implementation of such autonomous operational architectures.

SSDS MISSIONS: COMPLETED, CURRENT, AND FUTURE

SSDS implements missions with industry partners, academia, other government agencies, and across NASA centers. Several investment mechanisms are utilized by SSDS to select and fund industry and university projects. These mechanisms include the University SmallSat Technology Partnerships (USTP) initiative, Announcements of Collaboration Opportunities (ACOs), Tipping Point partnerships, and Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) awards, all of which are competitive, open solicitations utilized by SSDS and structured to address technology shortfall and other capability needs.

Occasionally, SSDS also directly funds Missions of Opportunity that address a targeted technology need.

Completed Missions

In the recent past, SSDS focused on subsystem development to increase the capabilities of small spacecraft. Two examples are the Pathfinder Technology Demonstrator (PTD) series of missions and the Advanced Composite Solar Sail System (ACS3) mission.

Pathfinder Technology Demonstrator

The PTD mission series was comprised of four missions to demonstrate and advance technologies in the following areas: (1) propulsion to advance the capability to maneuver small science platforms and send small spacecraft to deep space, (2) high-bandwidth laser communications to increase the amount of data that can be transmitted from the spacecraft to the ground, (3) power systems with increased capacity necessary for missions in deep space, and (4) imaging technology that

may be used in a wide range of applications. The mission series used a commercial Terran Orbital 6-unit (U) spacecraft bus and avionics platform common to all PTD missions. The PTD mission series is an example of industry-inspired small spacecraft innovation that offers affordable, rapid turn-around opportunities to demonstrate technologies needed to increase the capability and utility of small spacecraft.

Table 1: Completed Pathfinder Technology Demonstrator Missions

Mission & Launch	Payload	Outcome	Collaborators
PTD-1: Jan. 24, 2021	Hydros-C propulsion system	Baseline data for Hydros propulsion on PUNCH.	Tethers Unlimited
PDT-3: May 25, 2022	High-bandwidth laser communication, TeraByte InfraRed Delivery (TBIRD)	Achieved 200 gigabit per second throughput on a space-to-ground optical link between a satellite in orbit and Earth.	Massachusetts Institute of Technology, Lincoln Laboratory & NASA Goddard Space Flight Center
PTD-4: Aug. 16, 2024	Deployable solar array with an integrated antenna (LISA-T)	Experiment did not deploy as planned; data gathered.	NASA Marshall Space Flight Center
PTD-R: Aug. 16, 2024	Ultraviolet and short-wave infrared optical sensing (Deep Purple)	Mission completed in December 2025 and all mission objectives were met.	Lawrence Livermore National Laboratory

On August 16, 2024, the third and fourth PTD technology demonstrations, PTD-4 and PTD-R respectively, launched. PTD-R demonstrated simultaneous monolithic ultraviolet (UV) and short wavelength infrared (SWIR) optical sensing from space for the first time in a CubeSat form factor. The combined dual telescope payload, called 'Deep Purple', was built by Lawrence Livermore National Laboratory of Livermore, California and successfully provided imagery of ground objects, resident space objects and celestial objects. Figure 1 is an image of the Moon taken by Deep Purple using ultraviolet imaging. Figure 2 (C) shows an image of the PTD-R spacecraft.

The intention of PTD-4 was to demonstrate a high-power, low-volume deployable solar array with an integrated antenna called the Lightweight Integrated Solar Array and anTenna, or LISA-T, developed by NASA Marshall Space Flight Center. While the team was unable to overcome the challenges to fully extend the payload's central boom, some power generation and communication operations were conducted, and helpful lessons learned on deployment challenges were captured.



Figure 1: The Moon in monolithic ultraviolet (UV) and short wavelength infrared (SWIR) with a mapping of UV/SWIR to visible light bands red, green, and blue. Credit: Lawrence Livermore National Laboratory

Another PTD mission was PTD-3 that completed its mission and set a Guinness World Record for fastest satellite data downlink. This mission demonstrated a CubeSat less than 20 kilograms can deliver throughput up to 200 gigabits, which is on par with high-capacity geostationary communications satellites.[4] Lastly, the water-based propellant Hydros-C propulsion system demonstrated on PTD-1 was the baseline for a larger Hydros propulsion system on NASA's Polarimeter to UNify the Corona and Heliosphere (PUNCH) mission (four ~40 kg spacecraft) that launched March 11, 2025.[5] Table 1 summarizes the payloads, outcomes, and collaborators for each PTD demonstration mission.

Advanced Composite Solar Sail System

The ACS3 mission was a technology demonstration of a 12U spacecraft that launched April 23, 2024, and deployed a solar sail approximately 84 m^2. ACS3 used novel lightweight booms made of composite materials. The four booms spanning the diagonals of a square, unspooled to reach seven meters in length, pulling with



Figure 2: (A) Green Propulsion Dual Mode model (B) Advanced Composite Solar Sail System's unfurled solar sail Credits: NASA. (C) Pathfinder Technology Demonstrator-R spacecraft Credit: Terran Orbital Corporation.

it a solar sail that when fully deployed unfurled to a square-shaped sail measuring approximately nine meters per side. The composite booms are made from a flexible polymer material reinforced with carbon fiber, known for its robustness and resistance to bending and warping due to changes in temperature. Figure 2 (B) shows ACS3's sail unfurled in the laboratory.

CURRENT OPERATIONAL MISSIONS

At this stage, SSDS has established a strong focus on autonomy, while continuing to advance subsystem capabilities that are not yet fully developed. A number of SSDS technology demonstration missions currently on orbit exemplify technologies of interest.

Dual Propulsion Experiment

An example of a small spacecraft mission demonstrating a novel propulsion system is the Dual Propulsion Experiment (DUPLEX) mission. Champaign-Urbana Aerospace, LLC of Champaign, Illinois, NearSpace Launch of Upland, Indiana, and the University of Illinois at Urbana-Champaign built and tested a 6U CubeSat equipped with two different propulsion systems. These systems were developed with NASA SBIR funding and offer high-performance, low-cost, and safe pre-launch processing. The two propulsion systems are the Fiber-fed Pulsed Plasma Thruster (FPPT) and Monofilament Vaporization Propulsion (MVP).[6,7] The FPPT system uses an electric pulse to vaporize Teflon, using the resulting ions to deliver strong, efficient thrust while using very little fuel. The MVP system draws from extrusion 3D printer technology, heating and vaporizing Delrin, another common polymer material, to create continuous lower levels of thrust. Both systems are inherently safe because they do not use any pressurized tanks or toxic chemicals.

The 6U CubeSat, shown in Figure 3 (A) and (B), was launched on September 14, 2025, and was deployed from the International Space Station on December 2, 2025 as shown in Figure 3 (C). Initial on-orbit checkout was successful. During the mission, these two propulsion systems will be demonstrated.

DiskSat

Another pathfinder SSDS mission is focused on the development and characterization of a new circular satellite platform called DiskSat that launched December 18, 2025. Developed by The Aerospace Corporation of El Segundo, California, and funded by SSDS, DiskSat is an alternative approach to the standard CubeSat platform. This first demonstration deployed four plate-shaped spacecraft that are one meter in diameter and two-and-a-half centimeters thick from a unique dispenser. Figure 4 shows images of the dispenser and DiskSat spacecraft. DiskSat's large surface area can provide high power, support a large aperture needed for future missions, offers a standardized launch interface, and is low-cost, a characteristic of CubeSats.[8,9] The launch dispenser worked as designed, communications with ground network were successful and the team is currently in active mission operations.

Starling

The Starling mission is an active mission that strongly connects to our long-term autonomy vision. Launched on July 17, 2023, into a sun-synchronous orbit, the Starling mission continues to advance the readiness of technologies for cooperative groups of spacecraft, also known as distributed missions, clusters, or swarms. In the first 9 months on orbit, Starling's primary mission successfully tested swarm maneuver planning and execution, communications networking, relative

navigation, and autonomous coordination between four 6U CubeSats. Starling completed the objectives for the networking experiment by automatically establishing a network in space and demonstrating both point-to-point communication and data routing. Additionally, Starling was able to eliminate global navigation satellite system (GNSS) dependencies and exploit the Starling swarm to

opportunity for the Starling swarm to detect atmospheric phenomenon and demonstrate the ability to autonomously react to data collected in the space environment.

The first mission extension, Starling 1.5, tested technologies for automated space traffic coordination

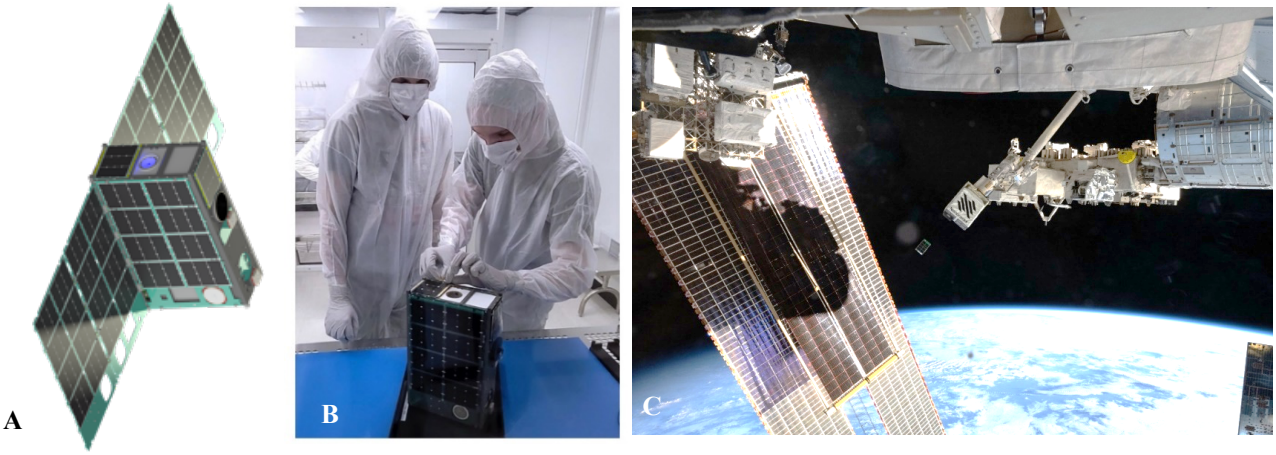


Figure 3: (A) Computer-aided design graphic of the Dual Propulsion Experiment (DUPLEX) (B) Final cleanroom inspection of DUPLEX spacecraft Credits: CU Aerospace, LLC. (C) Deployment of DUPLEX from the International Space Station on December 2025 Credit: NASA

enhance the robustness and autonomy of optical navigation.[10]

The technology that provided the distributed, autonomous, scalable navigation called Starling Formation-flying Optical eXperiment (StarFOX), was matured through SSDS's 2018 USTP initiative between Stanford University in California and NASA's Ames Research Center in California's Silicon Valley. The polar orbit provides complete global coverage over multiple orbits giving Starling's Distributed Spacecraft Autonomy (DSA) payload, led by NASA Ames, the best

using the Starlink constellation. In collaboration with SpaceX, an automated system was designed to warn operators about possible conjunctions, i.e., when two objects exceed the tolerance for a close approach along their orbital paths. Satellite operators were able to submit trajectories and receive conjunction data quickly, then accept responsibility to maneuver away from a potential risk. In this test, Starling accepted maneuvering responsibility, then autonomously planned and executed the maneuver to resolve a conjunction simulation test with a Starlink satellite. The second extension to Starling, called Starling 1.5+, demonstrated Resident

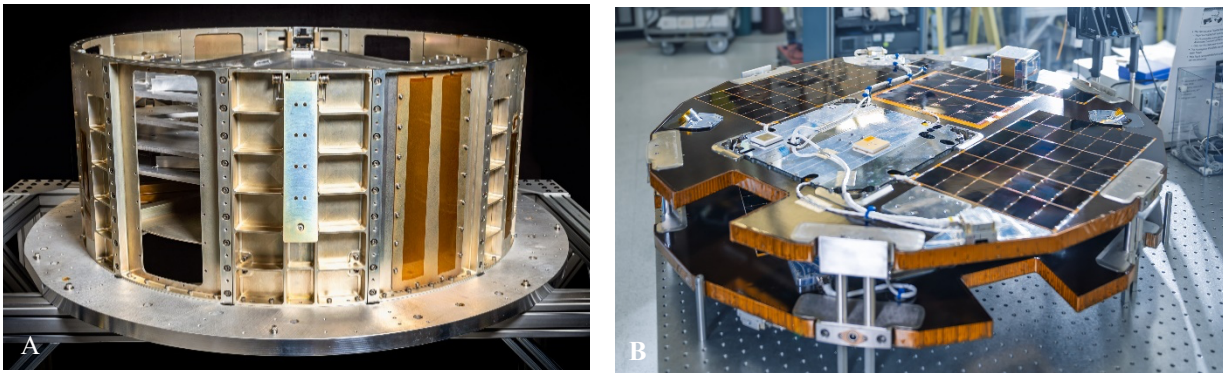


Figure 4: (A) DiskSat dispenser (B) Two DiskSat spacecraft before integration Credits: The Aerospace Corporation

Space Object detection and tracking using optical sensors. This technology using commercial off-the-shelf (COTS) star-trackers could enable greater situational awareness and early warning to spacecraft operators to prevent spacecraft collisions.

Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment

CAPSTONE is the first SSDS mission to venture into deep space. Selected as an ACO project in 2019 under the Advanced Communications, Navigation and Avionics topic, Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) serves as a pathfinder to help future space missions navigate more efficiently around the Moon and to Mars. The 12U, 25-kilogram spacecraft shown in Figure 5 (C) launched on June 28, 2022, and entered a unique elliptical lunar orbit in November 2022, called a near rectilinear halo orbit, (NRHO) in cislunar space, which was determined by the primary payload, the Cislunar Autonomous Positioning System (CAPS).[11] An illustration of the CAPS concept of operations is shown in Figure 5 (A). Since then, CAPSTONE has been characterizing the orbit in support of NASA's Artemis architecture. By May 2023, CAPSTONE successfully validated navigation technology that is applicable for future lunar missions and captured its first lunar images near the Moon's North Pole during a close approach to the Moon on May 3, 2023, see Figure 5 (B).

The partnership between Advanced Space LLC of Westminster, Colorado, CAPSTONE's developer, and NASA Goddard Space Flight Center is advancing a navigation system designed for operations between Earth and the Moon. This system has the potential to supplement NASA's DSN and support future exploration missions. Now operating for more than 1300 days in lunar orbit, CAPSTONE is the longest-running SSDS flight project and continues to reduce risks for Artemis. Follow-on activities include refinement and testing of the CAPS software and the conduct of mission analyses that support NASA's Artemis program.

FUTURE MISSIONS

Several SSDS missions are in advanced planning or implementation stages. The technology demonstration missions below are slated for launch between 2026 and 2029.

Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment 02

CAPSTONE 02 is a follow-on mission to CAPSTONE that will use two spacecraft to leverage the findings from its predecessor mission to further characterize the NRHO orbit in cislunar space and demonstrate advanced technologies as an Artemis risk reduction mission. The CAPSTONE 02 spacecraft will collect thermal and radiation data to further characterize the stability of the NRHO and demonstrate relative navigation technologies—including one-way space-to-ground ranging, space-to-space crosslink, and optical visual navigation— to decrease reliance on traditional space-to-ground radiometric data. Other objectives include rendezvous and proximity operations (RPO) with both CAPSTONE 02 spacecraft. During the demonstration, one spacecraft will act as the "chaser" vehicle performing RPO maneuvers while the "target" spacecraft maintains its position in the cislunar NRHO orbit. The spacecraft will also characterize the performance of the ground network to support future cislunar missions. CAPSTONE 02 is anticipated to launch in the second half of 2027.

Green Propulsion Dual Mode

The Green Propulsion Dual Mode (GPDM) project is a 6U CubeSat demonstrating the propulsion capability of a dual mode (chemical and electrospray) propulsion system using a low-toxicity or "green" monopropellant. Dual mode propulsion is highly desired for the capability



Figure 5: (A) Concept of operations for the Cislunar Autonomous Position System (B) An image of the Moon captured May 3, 2023, by CAPSTONE while near its closest approach to the Moon's North Pole (C) CAPSTONE spacecraft. Credits: Advanced Space, LLC, all rights reserved.

to perform high impulse (chemical) and high efficiency (electrospray) space translation maneuvers. The Advanced Spacecraft Energetic Non-Toxic (ASCENT) propellant is a proven monopropellant in chemical thrusters, and its ionic properties make it a viable candidate for electrospray propulsion.[12] With this propellant, GPDM combines both chemical and electrospray modes into one system to demonstrate low-thrust trajectory maneuvers and precision attitude control in space. Numerous collaborators are associated with this project, spanning across academia, industry, and NASA. GPDM is slated for launch in fall 2026. Figure 2 (A) shows the GPDM model at the SmallSat Conference in Logan, Utah in 2024.

Small Spacecraft Propulsion and Inspection Capability

In 2024, SSDS awarded SBIR Phase III funding to Starfish Space of Seattle, Washington to develop Small Spacecraft Propulsion and Inspection Capability (SSPICY), a demonstration mission with electric propulsion and other advanced capabilities, including autonomous navigation systems, to perform rendezvous, proximity operations, and inspection activities. SSPICY will characterize up to four resident space objects of US-origin in low Earth orbit (LEO).[13] These activities are foundational for critical capabilities to achieve long-term space presence, and SSPICY is designed to mature technologies needed for U.S. commercial capabilities for satellite servicing and logistics. Starfish Space has accomplished successful Mission Concept and Mission Design Reviews and is currently integrating the spacecraft. SSPICY is currently slated for launch at the end of 2026.

PY12

Developed by EarthTraq of San Carlos, California, he PY12 system offers a novel approach to satellite-based positioning. using a time-difference-of-arrival based localization technique, independent of Global Positioning System (GPS). Three clusters of four satellites, each cluster launched separately, will receive RF signals and use triangulation to determine the position of the emitter. The spacecraft can track ultra-low size, weight, power, and cost (SWaP-C) devices on the ground, provide a positioning, navigation, and timing (PNT) service like GPS by providing position information direct-to-device, or precisely determine the orbit and velocity of other space objects.

The PY12 spacecraft are built from COTS hardware, enabling a quick and affordable deployment to LEO. A cluster of four or more satellites enables an ad-hoc private PNT network, and the system scales to the deployment of hundreds of satellites, making it nearly resilient and robust against outages. Long-term, SSDS is interested in both terrestrial and deep space applications. The PY12 swarm mission concept includes 12 clustered EarthTraq spacecraft that also host neuromorphic processors, envisioned as an on-orbit testbed for AI, edge computing, enhanced DSA, and PNT technologies. An SBIR phase I has been awarded to EarthTraq to develop the capability to host AI and edge computing capabilities onboard the PY12 spacecraft. An SBIR Phase III SBIR is in development to fund a first launch in collaboration with the U.S. Department of War's Defense Innovation Unit.

Lunar Assay via Small Satellite Orbiter

Managed by the U.S. Department of War's Defense Advanced Research Projects Agency, the Lunar Assay via Small Satellite Orbiter (LASSO) project aims to develop and demonstrate technologies that support space situational awareness. Using autonomous satellite navigation developed for stressing orbital conditions and increasing satellite maneuverability through continuous dynamic repositioning based on changing conditions, results in a robust and agile spacecraft that can navigate through crowed environments. Additionally, the LASSO project is creating a proven reserve model for resources relevant to in-situ resource utilization on the Moon. The scope of the LASSO project includes the design, test, build, and delivery of a spacecraft capable of determining all areas on the Moon that contain greater than 5% water concentration with a resolution of no larger than four-square kilometres.[14] With a current launch timeframe in early 2029, NASA's contribution to LASSO includes subject matter expertise, launch, and operations support. A focus of this mission is to enable autonomous navigation close to the lunar surface. This poses novel challenges due to the inhomogeneous mass distribution on the lunar surface that impacts trajectories.

CONCLUSIONS

The SSDS and its predecessor organizations have supported the development and flight demonstration of increasingly capable small spacecraft technologies since 2012. Today, the program is transitioning from demonstrating single spacecraft subsystems toward focusing on enabling distributed spacecraft swarms that can operate autonomously. The long-term vision for these mission architectures is for small spacecraft swarms to operate with 'launch-and-forget' autonomy during commissioning, spacecraft swarm operations, data collection, and data analysis phases, offering the ability for the end user to receive only the data products they need. The Starling and CAPSTONE missions operating today are particular stepping stones towards that vision, with CAPSTONE 02 and SSPICY continuing on the path by maturing technologies that

support the envisioned architecture. Future plans include additional lunar and later, deep space missions where distributed autonomous infrastructure capabilities will be demonstrated.

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