CAPSTONE EXTENDED MISSION: A CISLUNAR TESTBED for AUTONOMOUS SMALLSAT TECHNOLOGIES

Samson Phan (1), Roger C. Hunter (2), Theresa W. Beech (3),
Elizabeth Geist (4), Sun Hur-Diaz (5), Lucie Tran (6), Brad Cheetham (7), Alec T. Forsman (8),
and Julianna L. Fishman (9)

(1) NASA Ames Research Center, Moffett Field, CA, 94035, 650-417-4989,
samson.phan@nasa.gov
(2) NASA Ames Research Center, Moffett Field, CA, 94035, 650-604-5004,
roger.c.hunter@nasa.gov
(3) NASA Goddard Space Flight Center, Greenbelt, MD 20771, 301-286-3987,
theresa.w.beech@nasa.gov
(4) NASA Goddard Space Flight Center, Greenbelt, MD 20771, 301-286-0903,
elizabeth.geist@nasa.gov
(5) NASA Goddard Space Flight Center, Greenbelt, MD 20771, 301-286-4259,
sun.h.hur-diaz@nasa.gov
(6) Advanced Space, LLC, 1400 W 122nd Ave Suite 200, Westminster, CO 80234, 720-545-9191,
lucie.tran@advancedspace.com
(7) Advanced Space, LLC, 1400 W 122nd Ave Suite 200, Westminster, CO 80234, 720-545-9191,
bradley.cheetham@advancedspace.com
(8) Advanced Space, LLC, 1400 W 122nd Ave Suite 200, Westminster, CO 80234, 720-545-9191,
alec.forsman@advancedspace.com
(9) Millennium Engineering & Integration Services, LLC, NASA Ames Research Center,
Moffett Field, CA, 94035, 650-604-0637, julianna.l.fishman@nasa.gov

ABSTRACT

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) is a 12U small spacecraft that successfully demonstrated navigation technologies and characterized the near rectilinear halo orbit as a pathfinder for NASA's Gateway. Following completion of its primary objectives in 2023, CAPSTONE transitioned into an extended mission that repurposes the spacecraft as a cislunar technology testbed.

Managed by NASA's Small Spacecraft & Distributed Systems program within the Space Technology Mission Directorate, the extended mission advances an experimentation-as-a-service model that maximizes the value of flight-proven assets. Through partnership with Advanced Space, LLC, CAPSTONE's commercial operator, the spacecraft enables on-orbit demonstrations of software-defined satellite capabilities, autonomous navigation, guidance and control, and standards-based communications and networking technologies.

Beyond individual demonstrations, the mission provides programmatic insight into how existing spacecraft can be repurposed as reuseable infrastructure supporting technology maturation and operational experimentation. CAPSTONE illustrates how extended missions can accelerate technology development, reduce reliance on oversubscribed ground infrastructure, and support scalable and distributed lunar architectures for sustained cislunar operations in support of NASA's Artemis program.

1 INTRODUCTION

1.1 NASA's Lunar Exploration Goals

Under Space Policy Directive 1, NASA is pursuing a sustained human presence on the Moon through the Artemis program. The goal of Artemis is to establish a long-term exploration architecture supporting scientific discovery, technology development, and preparation for future human missions to Mars. Key to this goal is the United States' lunar program which calls for increasingly complex missions to build the capacity for sustained presence at the Moon's South Pole.

1.2 Strategic Challenges of Sustained Cislunar Operations

NASA's lunar mission architecture studies have revealed unique characteristics that warrant further consideration.

- Operational Scaling Issues
  Sustained activity in cislunar space will require numerous spacecraft operating simultaneously across complex orbital regimes. The increased mission cadence places growing demand on already oversubscribed infrastructure such as NASA's Deep Space Network (DSN) and Near Space Network (NSN). Potential solutions include, integrating additional ground assets into the networks, utilizing commercial services, and reducing communications need through increased spacecraft automation.

- Increased Cislunar Mission Complexity
  Cislunar missions will grow increasingly complex as humanity expands operations beyond low Earth orbit. The region's vast volume, variable gravitational environment, and limited communications coverage introduce new navigation and autonomy challenges. Missions will need to coordinate across multiple system types operating simultaneously around the Moon. Power and propulsion demands will intensify as spacecraft traverse unstable orbital regimes such as near rectilinear halo orbits (NRHO) and distant retrograde orbits (DRO). Architectures may require rendezvous and proximity operations in these orbits to transfer consumables, cargo, and humans across systems. Additionally, building sustainable infrastructure for habitation, resource utilization, and transportation will require advanced systems engineering, resilient supply chains, and sophisticated space traffic management.

1.3 Role of the Small Spacecraft & Distributed Systems Program

NASA's Small Spacecraft & Distributed Systems (SSDS) program, formerly the Small Spacecraft Technology program, within the Space Technology Mission Directorate (STMD) develops and demonstrates technologies that expand the capabilities of small spacecraft. Grounded in a philosophy of agility and risk-tolerant innovation, the program focuses on maturing disruptive subsystems—such as propulsion, communications, autonomy, and navigation—through frequent, targeted in-space demonstrations. This approach enables new mission architectures while shortening development timelines and reducing cost barriers for both government and industry partners. SSDS showcases how investments in small spacecraft expand the achievable envelope for small spacecraft and lay the groundwork for future cislunar and deep space missions.

As part of NASA's agency-wide effort to enable and sustain a human presence on the Moon, SSDS supports the Artemis architecture by developing and demonstrating key technologies using low-cost SmallSat missions. Through its portfolio of projects, CAPSTONE being one, SSDS has validated key concepts within the Artemis architecture and lunar exploration to include:

- Validation of NRHO dynamics models

- Small payload transportation infrastructure for lunar regime delivery
- Advising future lunar exploration and operational requirements
- Informing future navigation and communication constellation technology development

1.4 The Extended Mission as a Programmatic Tool

The CAPSTONE extended mission demonstrates how spacecraft originally designed for a single technology demonstration can evolve into multi-user experimental platforms. The mission extension serves as both a programmatic tool as well as a technical demonstration with continued relevance to Gateway and Artemis. Extending a mission allows NASA to extract greater value from an existing on-orbit asset while advancing operational maturity in emerging domains such as cislunar space. A mission extension transforms a one-off pathfinder, into a persistent experimental testbed, enabling new technologies, operational concepts, and multi-user collaborations to be exercised long after primary objectives are achieved. This shift demonstrates how NASA can adapt its approach to mission scaling—moving from discrete, single-purpose demonstrations toward reusable platforms that support evolving agency needs.

In the cislunar environment, where infrastructure is sparse and operational knowledge is limited, an extended mission provides ongoing opportunities to refine navigation, communications, and autonomy in a real flight setting. It also enables the spacecraft to serve multiple stakeholders, transitioning from a mission with a single sponsor to a shared technology platform supporting experiments, new operational modes, and cross-program objectives. The act of extending a mission itself is a form of technical demonstration: it proves the spacecraft's durability, validates long-term operational models, and supplies engineers with data on system behaviour beyond design lifetimes. CAPSTONE has successfully bridged the gap from a pathfinder to an experimental testbed infrastructure, capable of serving a number of experimenters across a diverse array of technologies.

1.5 Paper Organization

The remainder of this paper describes the CAPSTONE mission and its transition to an extended mission testbed (Section 2), the partnership and experimentation-as-a-service model supporting the extended mission (Section 3), the three technology demonstrations conducted on CAPSTONE during the extension (Sections 4-6), crosscutting programmatic lessons and recommendations (Section 7), and conclusions and future work (Section 8).

2 CAPSTONE as a PROGRAMMATIC ASSET

2.1 Mission Background

The spacecraft was developed under a Phase III Small Business Innovation Research (SBIR) contract beginning in 2019, with Advanced Space, LLC of Westminster, Colorado serving as the principal, integrating CAPSTONE subsystems into a 12U Tyvak Nanosatellite Systems (now Terran Orbital of Irvine, California) bus [1]. Originally scheduled for development in less than two years, the mission experienced delays due to COVID and rideshare availability, ultimately launching on board a Rocket Lab Electron vehicle on June 28, 2022. CAPSTONE achieved successful NRHO insertion on November 13, 2022. Operation centers at Tyvak and Advanced Space performed telemetry and command as well as navigation and flight dynamics management, respectively. CAPSTONE completed its primary mission objectives in May 2023. The mission achieved several important milestones:

- First successful spacecraft insertion into an NRHO
- Characterization of NRHO dynamics and station keeping requirements

- Verified ballistic lunar transfer performance for low-energy cislunar trajectories
- Executed the Cislunar Autonomous Positioning System (CAPS) technology demonstration
- Characterized cislunar communications behavior for a small spacecraft
- Validated small satellite propulsion, attitude determination and control system, and system reliability in deep space
- Provided operational lessons for autonomy, fault management, and recovery

2.2 Transition to an Extended Mission Model

Following completion of the primary mission objectives, spacecraft health and propellant reserves supported continued operations. More than 40% of propellant remained available, enabling CAPSTONE to transition into an extended mission supporting additional technology demonstrations [2]. Overall, spacecraft health was excellent with few anomalies reported. By completing its initial demonstration objectives, the CAPSTONE spacecraft proved itself to be a capable piece of hardware. The mission teams demonstrated capability to operate the spacecraft in the distant orbit and establish stable long-duration operations. The flight experience and hardware provided a strong foundation for continued experimentation, enabling the proven spacecraft to serve as a reliable platform for extended testing, operational refinement, and technology maturation.

2.3 On-Orbit Assets as Reusable Infrastructure

Access to lunar orbits—particularly the NRHO—remains limited, and the absence of additional spacecraft operating in NRHO constrains opportunities for sustained experimentation in this strategically important regime. CAPSTONE's extended mission addresses this gap by transforming a one-time pathfinder into reusable cislunar infrastructure capable of supporting continued technology maturation. By serving as a persistent on-orbit testbed, CAPSTONE continues generating operational and scientific value well beyond its original mission. This increases the overall return on the United States' investment while enabling researchers to conduct flight experiments without incurring the cost, schedule risk, or technical overhead associated with developing and launching a new spacecraft.

Many early-stage technologies lack the resources required to mount independent missions. Leveraging an existing spacecraft dramatically lowers barriers to entry, enabling investigators to test payloads and software demonstrations that would otherwise be infeasible. This approach also avoids consolidating multiple experiments into a single new spacecraft platform, simplifying integration and accelerating test opportunities. In this way, CAPSTONE demonstrates how repurposing on-orbit spacecraft can provide flexible infrastructure for continuous learning in the cislunar environment.

2.4 Reuse of On-Orbit Assets: The Starling Example

NASA's Starling mission provides a compelling example of how SSDS is leveraging on-orbit assets as reusable infrastructure. Originally designed to demonstrate autonomous swarm behaviors among small satellites, Starling's successful primary mission completion enabled the spacecraft swarm to transition into a platform for continued experimentation in distributed autonomy, relative navigation, and inter-satellite communications. Rather than decommissioning the swarm at the end of the primary mission, NASA repurposed the spacecraft to support follow-on investigations, allowing researchers to test new software, algorithms, and cooperative behaviors directly on the existing flight systems. This programmatic model—transforming spacecraft into persistent, shared testbeds—reduces cost, lowers risk, and accelerates access to on-orbit experimentation. Extending Starling's operational life demonstrates how missions can evolve from single-use demonstrations into multi-user research infrastructure, providing sustained value to the broader space technology and research communities and maximizing return on investment.

3 EXTENDED MISSION PARTNERSHIP and EXPERIMENTATION-AS-A-SERVICE MODEL

3.1 Public-Private Partnership with Advanced Space

NASA's partnership with Advanced Space for the CAPSTONE mission represents a modern public-private collaboration model designed to accelerate innovation while reducing mission cost and risk. Through a Phase III SBIR contract, NASA entrusted Advanced Space with mission design, navigation, and operations. This allowed a small commercial company to execute a deep space technology demonstration. The arrangement leveraged NASA's strategic oversight and access to agency infrastructure—such as the DSN—while benefiting from the agility, rapid development cycles, and cost efficiencies characteristic of the private sector. The partnership distributed technical responsibility among NASA centers, industry partners, and commercial launch providers, illustrating a scalable architecture. By enabling Advanced Space to perform end-to-end mission roles, NASA demonstrated how public-private partnerships can cultivate national industrial capabilities in cislunar mission design, autonomous navigation, and spacecraft operations. CAPSTONE reduced risk for the Gateway program while simultaneously strengthening the commercial space ecosystem and expanding the pool of U.S. providers capable of operating in deep space.

3.2 Demonstration Overview

In collaboration with NASA's Goddard Space Flight Center in Greenbelt, Maryland and Advanced Space as the prime contractor, CAPSTONE is demonstrating technologies that enable autonomous and standards-based, interoperable communications and networking within the challenging cislunar environment.

4 SOFTWARE-DEFINED SATELLITE DEMONSTRATION

4.1 Brief Overview of Technology and Objectives

The software-defined satellite demonstration is fundamentally a demonstration of deep flight software and field programmable gate array (FPGA) patching. In ground-based systems, operating-system level updates and hardware upgrades are commonplace. These practices maintain the security and longevity of systems that we rely on. However, in flight environments, most spacecraft flight software updates are made at the application level. Flight software application updates may be sufficient for routine sustainment operations, but they can leave in place lower-level vulnerabilities, and they may not be sufficient to pivot a system to new objectives if necessary. The software-defined satellite demonstration showed that fully repurposing a spacecraft is possible using a combination of a new FPGA image, a new operating system image, and entirely new application software.

The CAPSTONE spacecraft architecture included a main flight computer and a payload flight computer. The updates required for the software-defined satellite demonstration were performed on the payload flight computer, allowing the spacecraft to be repurposed without compromising the critical communications interfaces present on the main flight computer.

The process of rewriting the payload flight computer began with development of an entirely new computer image. The FPGA bit file and bootloader were rebuilt, the Linux kernel was rebuilt with new settings, and the Linux user space and roots were rebuilt. These components were integrated into a combined image, uploaded, and written to NOR flash onboard the payload flight computer. Following this, new application software in the form of a new Core Flight System (cFS) [3] core binary was developed with a minimal set of modules. The cFS binary was uploaded separately and written to NAND flash onboard the payload flight computer. Notably, these updates were accomplished with a limited uplink data rate of just 2.2 kbps.

Initial success of this demonstration was accomplished when the new payload flight computer image was successfully programmed, and a checkout test confirmed that the updated software had loaded and the ground system was able to verify command and telemetry connection with the payload flight computer. The cFS architecture for this initial success is shown in Figure 1. After this initial success, additional cFS modules were added dynamically, ultimately instantiating a full cFS ecosystem on the payload flight computer. The cFS application suite at the conclusion of this demonstration, shown in Figure 2, included custom Command Ingest (CI) and Telemetry Output (TO) modules, reusable Scheduler (SCH), Health & Safety (HS), Data Storage (DS), Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP) noted CF in the figure, File Manager (FM), Stored Commands (SC), Checksum (CS), Shell modules, and Core Flight Executive (cFE), a component of the cFS. This full cFS suite served as the foundation for additional experimentation onboard CAPSTONE, including Autonomous Navigation, Guidance, and Control (autoNGC) and Delay Tolerant Networking (DTN) which are described in subsequent sections.

4.2 Future Implications of the Demonstration and Relevance to Future Architectures

The software-defined satellite demonstration has several important implications for the design and operation of future missions. As spacecraft become more capable and mission timelines extend, the ability to adapt, reconfigure, and repurpose assets in flight is increasingly valuable. This demonstration provides a concrete example of how flexible software and modular hardware can meaningfully expand mission utility while lowering risk and cost.

First, the demonstration highlights the power of modular architectures as an enabler of innovation. CAPSTONE benefited from both hardware and software modularity, which together provided a safe and extensible environment for experimentation. The addition of a dedicated payload flight computer—separate from the main flight computer—reduced risk by isolating new software from critical bus functions. This separation ensured that experimental autonomy functions could be tested without jeopardizing the spacecraft's core mission. On the software side, the use of the cFS framework created a robust foundation for iterative development. cFS allowed new components to be integrated incrementally, enabling the mission to expand from its initial demonstration objectives to a broader set of autonomous navigation and onboard processing experiments. This modular approach demonstrates how future missions can incorporate new capabilities over time rather than locking in all functionality at launch.

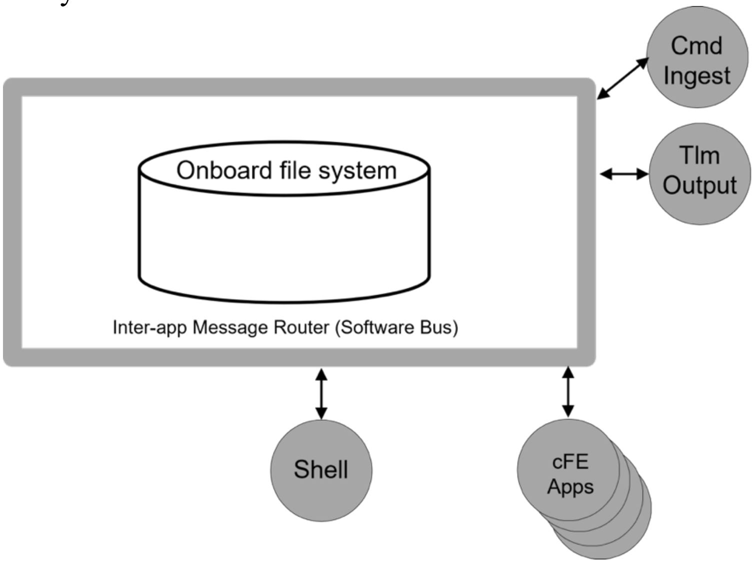

Figure 1. Initial Demonstration Core Flight Software Architecture

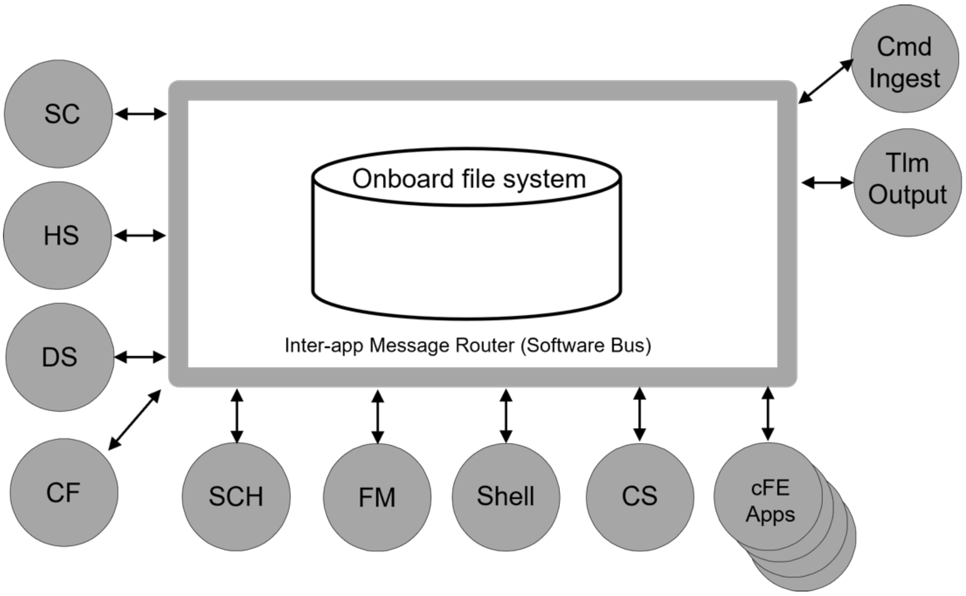

Figure 2. Final Demonstration Core Flight Software Architecture

Secondly, the demonstration challenges traditional assumptions about spacecraft lifecycles. Historically, spacecraft have been designed for a single primary mission, with post-primary operations limited to extended missions that use the existing hardware and software largely unchanged. The ability to reconfigure a spacecraft through software updates reinforces SSDS's testbed infrastructure concepts and suggests a new operational model in which a spacecraft's role can evolve significantly after launch. Instead of requiring new spacecraft for new mission concepts, operators may increasingly be able to upload entirely new capabilities to existing platforms. This creates opportunities for more frequent in-space experimentation, reduces the time-to-flight for emerging technologies, and maximizes the scientific and operational return from each asset. In effect, the spacecraft becomes a flexible on-orbit laboratory rather than a single-purpose tool. This also supports sustainability goals: extending the functional lifetime of spacecraft reduces demand for replacement missions and decreases the resource footprint associated with procurement, testing, and launch.

Finally, the demonstration suggests potential shifts in spacecraft hardware design philosophy. Today, many spacecraft are purpose-built for narrowly defined mission objectives, resulting in specialized systems that cannot easily be reused or repurposed. The CAPSTONE experience hints at a future in which spacecraft architectures become more generalizable and software-configurable, similar to the evolution of terrestrial computing platforms. By including extensible hardware interfaces and additional "peripherals" that may not be required for the primary mission, designers enable room for innovation during later mission phases. These supplementary components—whether sensors, compute modules, or communication interfaces—create opportunities for follow-on work that may be impossible to predict at launch. Such design practices also support greater standardization across spacecraft classes, enabling economies of scale and lowering per-unit cost. As software increasingly determines mission capability, hardware can converge toward more uniform, flexible platforms that support a wide range of operational concepts.

5 AUTONOMOUS NAVIGATION, GUIDANCE, and CONTROL

5.1 Brief Overview of Technology and Objectives

autoNGC is a suite of software applications and libraries built on the cFS that provides onboard navigation, guidance, and control capabilities for spacecraft [4]. The software architecture allows customization and insertion of new capabilities, even in flight as demonstrated on CAPSTONE. The flight software suite includes the Goddard Enhanced Onboard Navigation System (GEONS) [5], a high-fidelity navigation flight software library that processes sensor measurements to estimate spacecraft position and velocity, onboard clock corrections, and measurement and force modeling parameters [5]. It utilizes an Extended Kalman Filter to sequentially provide improved state estimates as measurements are processed. The measurements that GEONS models include GPS observables, one-way and two-way ground station range and Doppler, satellite one-way and two-way crosslink range and Doppler, camera bearing angles, range measurements, accelerometer data, and attitude solutions. Another key library in autoNGC is cGIANT, a version of the advanced image processing tool, Goddard Image Analysis Navigation Tool (GIANT), that uses the cFS architecture [6]. GIANT extracts observables from images that can then be processed in GEONS for navigation. The widely available, common cFS software architecture of autoNGC leverages the existing cFS apps and standardizes integration with the rest of the spacecraft flight software. The cFS software bus provides a standardized plug-and-play interface for the addition of future algorithms and flight software and allows for ready integration into commercial spacecraft that use cFS.

The autoNGC flight experiment objectives are to demonstrate the following autonomous NGC functionalities using the resources and sensors available on CAPSTONE:

1. Real-time onboard filtering of two-way range and Doppler from DSN stations to estimate CAPSTONE's orbit
2. Real-time onboard formulation and filtering of one-way forward range and Doppler from DSN to estimate CAPSTONE's orbit
3. Real-time image processing of images of the Moon, Earth, planets, and asteroids captured by the star tracker for limb-based and celestial optical navigation to estimate CAPSTONE's orbit
4. Onboard maneuver planning for maintenance of CAPSTONE's orbit in the NRHO

Real-time onboard processing of navigation observables allows for faster response time for mission planning, including maneuvers. A common current operations workflow involves a ground team collecting several days of measurements, performing orbit estimation (typically using batch filtering methods), predicting forward in time, and uplinking the predicted ephemeris to the spacecraft. With real-time onboard processing, however, the spacecraft can make use of the most current and up-to-date estimate to make its decisions. This is demonstrated in the first and the fourth autoNGC experiments described above where the Maneuver Planning app computed the orbit maintenance maneuver using the onboard knowledge of the spacecraft state from real-time filtering of two-way measurements.

The autoNGC experiment was able to utilize the Iris radio to demonstrate both the two-way and one-way pseudo-noise range and Doppler measurements processing onboard for navigation. The Iris ranging telemetry contains the pulse-per-second data from the chip-scale atomic clock (CSAC) for accurate timing for onboard calculations of Doppler and range measurements which are filtered by the GEONS filter for navigation.

While the two-way DSN measurements require exclusively scheduled use of a ground station for coherent radiometric measurements, the one-way forward measurement capability allows for multiple spacecraft to make use of the same signal from a single ground station at the same time, increasing station availability. It also eliminates the latency associated with the two-way light-time delay. The second autoNGC experiment utilizes the telemetry from the Iris radio and the CSAC, as well as ground station data from the uplinked two-way measurements, to form the one-way measurements onboard that are then filtered by GEONS.

A complete Earth-independent orbit determination is provided by the optical navigation experiment. On CAPSTONE, autoNGC employs limb-based and celestial navigation techniques. One of the star trackers is used to capture extended body images of the Moon and Earth. cGIANT performs limb-based image-processing to extract bearing and range measurements to these bodies, which are then filtered by GEONS to update the estimate of the spacecraft orbit. For celestial navigation, the star tracker is occasionally used to capture images of other planets and asteroids against a background of stars. cGIANT estimates both the sensor attitude from the stars and extract bearing measurements to the celestial bodies for filtering by GEONS.

5.2 Limitations of Current Ground Infrastructure as a Programmatic Constraint and Autonomy for More Sustainable Operations

Operating cost scales with DSN pass time, staffing, and analysis overhead. Autonomy reduces pass frequency and duration needed for navigation, lets missions prioritize downlink of science products, and minimizes labor-intensive post-processing.

The inventory of ground stations to support the growing number of missions is limited. Scheduling them requires careful planning and negotiations among competing missions. Station visibility is a major constraint for obtaining navigation observables required to determine accurate orbits of the spacecraft for maneuver and mission planning. Autonomy can shift routine navigation, maneuver planning, and anomaly triage onboard, so spacecraft use of the DSN would be primarily for science and health data versus closed-loop operations. By producing real-time, onboard solutions, autoNGC reduces the need for frequent radiometric passes and detailed ground-in-the-loop image analysis.

The Navigation Team for a mission can be quite large especially if ground processing of optical images is required. Onboard optical navigation allows for a much smaller team to spot check the results of the onboard solution. Autonomy also enables new concepts of operations with a lighter ground footprint. CAPSTONE’s extended operations show months-long routine station-keeping and navigation in NRHO with increasing onboard capability—while teams focus on higher-level analysis instead of minute-by-minute command sequences. Autonomy shifts workload from flight controllers to onboard inference, changing the role of ground teams from operators to supervisors and experimenters. These capabilities shift operations from continuous command driven control to “manage by exception”, where human operators intervene only when the system flags anomalous behavior. This means fewer operators per mission and shorter staffed shifts, because the spacecraft can execute routine navigation and control without a real-time ground loop.

The autoNGC experiments on CAPSTONE will advance the flight software to technology readiness level 7 allowing for easier adoption by missions. Lessons learned from these early flight experiments will be applied to future updates of the flight software and in future flight experiments to increase the robustness of autoNGC for missions.

6 COMMUNICATIONS and NETWORKING DEMONSTRATIONS

6.1 Brief Overview of Technology and Objectives

To enable the extended experimentation campaign in flight, a new ground system was instantiated at NASA's Goddard Space Flight Center that integrated with the commercial ground station in Irvine, California. The Experiment Workflow Operations for CAPSTONE (EWOC) establishes a virtual tunnel to the CAPSTONE Mission Operations Center (MOC) to allow for a real-time command and telemetry connection between the EWOC and the spacecraft. The EWOC was designed to interface with the existing MOC communication protocols in order to require as few changes as possible in the MOC itself. Additionally, the EWOC combines two distinct ground system software packages in order to minimize re-development by individual experiment teams. Figure 3 illustrates this communications path.

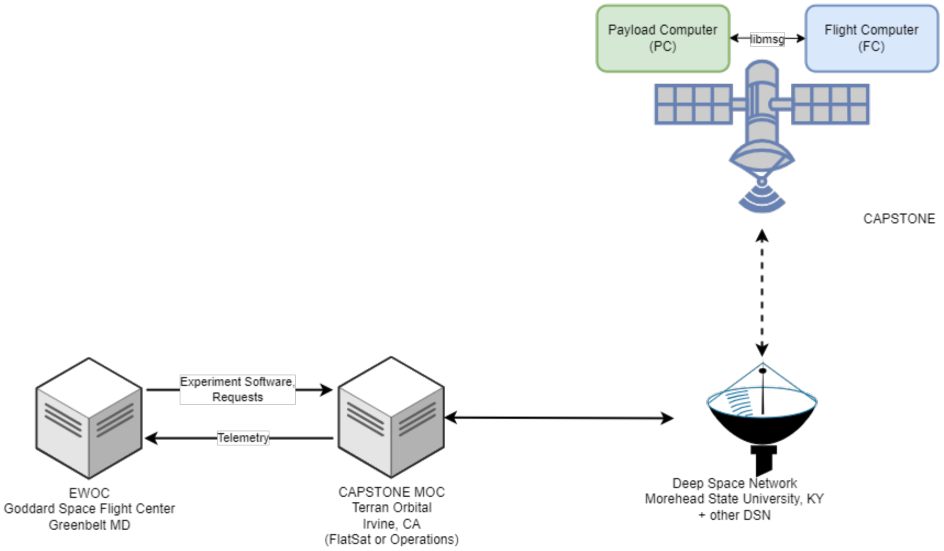

Figure 3. Ground-to-Flight Communication Path

The DTN demonstration directly addresses the unique communication challenges of cislunar and deep space environments. In these environments, communication between spacecraft and ground systems is limited by large light-time delays and limited contact times. The DTN demo shows an approach to mitigating these challenges using the Internet Engineering Task Force and CCSDS Bundle Protocol (BP) specifications Request for Comments 9171 and CCSDS 734.2-B-1 respectively. The CAPSTONE DTN demonstration includes two flight software components and a corresponding ground segment built into the EWOC. The flight and ground nodes share two architectural components: BPLib is a C-language library that implements the RFC-9171 standard and BPNode is a cFS application that uses BPLib to create a DTN node. Both BPLib and BPNode are released as open-source software. See Figures 4 and 5 for the flight and ground cFS architecture for the DTN demonstration. This DTN experiment has successfully instantiated the first DTN node at the Moon. To date, the DTN experiment has performed:

- Real-time file uploads to the spacecraft, also using the Bundle Protocol in combination with CFDP
- Real-time file downloads from the spacecraft, also using the Bundle Protocol in combination with CFDP
- Store-and-forward file download from the spacecraft

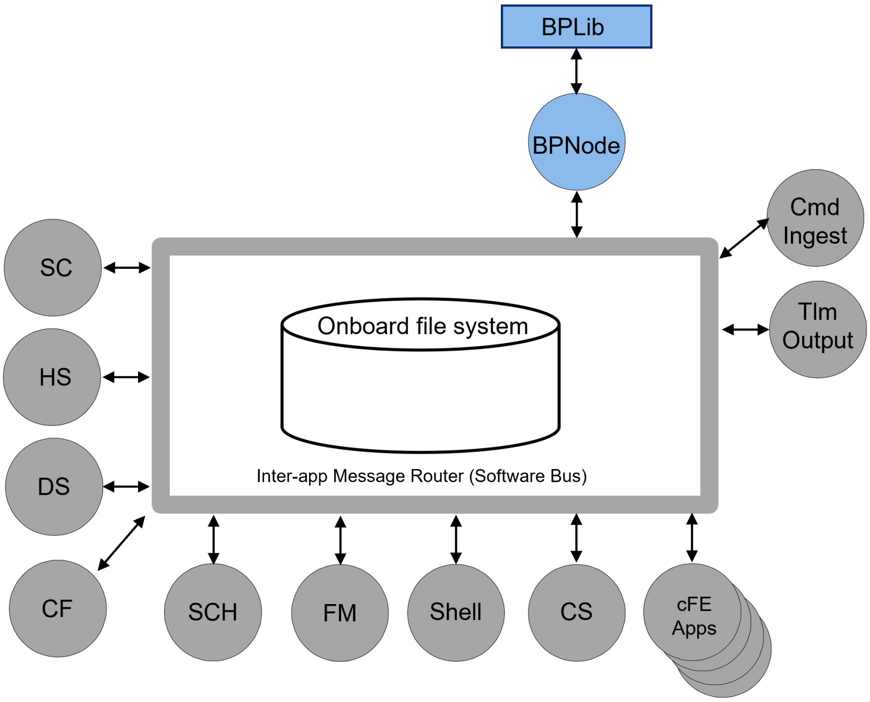

Figure 4. Delay Tolerant Networking in the CAPSTONE Flight Software Architecture

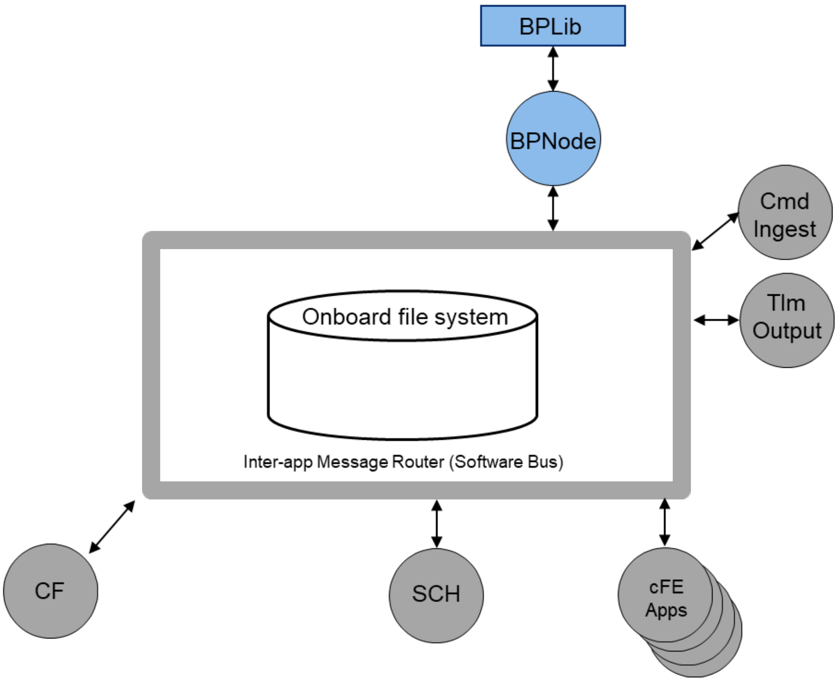

Figure 5. Delay Tolerant Networking Ground Node Architecture

6.2 CAPSTONE Serves as a Platform to Test Future Communications Concepts

The CAPSTONE EWOC and MOC integration shows that legacy ground systems can potentially support new mission concepts. The use of standard protocols such as CCSDS promotes greater interoperability and can enable integrations between ground systems even if they were not part of the original mission objectives.

The DTN technology is vital for creating a robust and reliable communications network in cislunar space and beyond. Communication networks are a foundational infrastructure technology required to enable future missions. The DTN demonstration onboard CAPSTONE shows not only that DTN nodes can be instantiated in lunar orbit and beyond, but also that existing spacecraft can be repurposed as DTN nodes, potentially increasing the speed at which communications infrastructure can be put in place.

7 CROSS-CUTTING PROGRAMMATIC LESSONS and RECOMMENDATIONS from NRHO / CISLUNAR DEMONSTRATIONS

Upon initiation of the CAPSTONE extended mission, the joint NASA – commercial team adopted a flat organizational structure, with individual experimenters working with both Advanced Space and their subcontractor Terran Orbital directly to standup experimentation. While progress was rapid because of the direct lines of communication preventing information bottlenecks or misinterpretation during second part information dissemination, resources were not efficiently used during the initial phases. The initial assumption was that differing experiment readiness levels would naturally facilitate resource deconfliction. Over time, it became apparent that the private partner was not positioned with the authority needed to mediate among the NASA experiment groups. Revision of the communication channels within the group allowed for more efficient use of resources. Coordination between the public (NASA) and private (Advanced Space and its subcontractor Terran Orbital) partners would be handled via a NASA civil servant coordinator and the project manager from Advanced Space. An additional layer of organization allowed for better coordination among the experimenters as it assisted with prioritization. This construct allowed Advanced Space to right size subcontractor resources for the experimenter requests.

Experimenters were cognizant of the age of the platform; all were eager to be scheduled first in the event of a system critical failure that would end use of the testbed prematurely. This additional organization layer allowed for prioritization amongst the teams with major criteria being testing readiness. In the event that a test campaign was not mature enough to be deployed during its scheduled slot, other experiments were moved forward to prevent downtime of the testbed. Also, in line with the notion of using a testbed beyond its operational design lifetime operating in a harsh environment while still seeking to demonstrate results, each experiment was divided into Crawl, Walk, Run campaigns. Each would build upon and further demonstrate capability to the one prior. Intermediate goals were stand alone and sufficiently modest to make them tractable, and the time between campaigns was used to further refine the test as well as allow for testing on flatsat simulators.

8 CONCLUSIONS and FUTURE WORK

The CAPSTONE campaign builds upon the work performed during its primary mission, with advances in software architecture, autonomous navigation, and communications informing future cislunar and deep space architectures. Combined with “Software Defined Satellite” techniques validated during the extension, CAPSTONE pushes further the ability of a post primary mission spacecraft to be used as a testbed to demonstrate capabilities not previously envisioned for the on-orbit asset. Coordination lessons between public and private partners, and within teams of experimenters will inform future demonstration opportunities. The CAPSTONE spacecraft remains in excellent health, and further opportunities to conduct experimentation continue. The spacecraft will be transitioned to enable the platform to serve a new cohort of experimenters.

NASA's Exploration Systems Development Mission Directorate and Space Technology Mission Directorate, in conjunction with Advanced Space as a primary private partner, are developing the CAPSTONE 02 concept to perform further Artemis risk reduction, environment characterization, and autonomous navigation demonstrations. Baked into its architecture is the opportunity for extended missions.

9 ACKNOWLEDGEMENTS

The authors acknowledge the support of NASA's Space Technology Mission Directorate and the Exploration Systems Development Mission Directorate, whose sponsorship enabled the CAPSTONE mission and its extended operations. The authors also recognize the contributions of the CAPSTONE mission teams, including personnel from NASA's Ames Research Center, NASA's Goddard Space Flight Center, Advanced Space, Terran Orbital, Rocket Lab, and other partner organizations whose efforts made this mission possible and advanced the state of the art of small spacecraft capabilities in deep space.

10 REFERENCES

[1] Agasid, E., Hunter, R., & Cheetham, B. *Cislunar autonomous positioning system technology operations and navigation experiment (CAPSTONE) pathfinder for Artemis Gateway*. In Proceedings of SPIE, Vol. 13546, Small Satellites Systems and Services Symposium (4S 2024). https://doi.org/10.1117/12.3060896

[2] Gardner, T., Cheetham, B., Parker, J., Forsman, A., Kayser, E., Thompson, M., Ott, C., DeMoudt, L., Caudill, M., Bolliger, M., & Kam A. (2023). *CAPSTONE: A summary of a highly successful mission in the cislunar environment* (SSC23-I-04). Proceedings of the Small Satellite Conference, Utah State University.
https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5595&context=smallsat

[3] Prajapati, A. (2026) *NASA cFS 2.0 and Beyond. NASA Technical Reports Server (NTRS). https://ntrs.nasa.gov/citations/20250011773*

[4] Hur-Diaz, S., Azimi, B., Romeo, M., Liounis, A., Stacey, N., Pritchett, R., Crum, G., & Semper, S. (2024). *Autonomous Navigation, Guidance, and Control Software in a Low SWaP Box. NASA Technical Reports Server (NTRS)*. https://ntrs.nasa.gov/citations/20240008867

[5] NASA. *Goddard Enhanced Onboard Navigation System (GEONS)* V3.1(GSC-19476-1). NASA Software Catalog. https://software.nasa.gov/software/GSC-19476-1

[6] Liounis, A. J., Gnam, C., Swenson, J., Getzandanner, K., Small, J., & Lyzhoft, J. (2022). *The Goddard Image Analysis and Navigation Tool* (Version 1.0.3) [Computer software]. GitHub. https://github.com/nasa/giant