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CAPSTONE: An Ongoing Demonstration of Navigation and Autonomy Technologies in the Cislunar Domain

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ABSTRACT

NASA, Advanced Space, Terran Orbital, Rocket Lab, Stellar Exploration, JPL, the Space Dynamics Lab, and Tethers Unlimited have partnered to successfully develop, launch, and operate the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which is continuing serving as a dedicated precursor for Near Rectilinear Halo Orbit (NHRO) operations in cislunar space. Over the past 26 months, this low-cost, high-value mission has demonstrated an efficient, low-energy orbital transfer to the Moon, a successful insertion into the NRHO, and completion of ~21 months of successful operations in the NRHO while successfully demonstrating key technologies in support of the NASA Artemis program. These technologies include 1) The successful demonstration of the CAPS autonomous navigation technology using both two-way ranging with the Lunar Reconnaissance Orbiter (LRO) and one-way uplink ranging with the Deep Space Network 2) Successful demonstration of our Neural Net for Electric Propulsion (NNEP) technology for autonomous maneuver planning and execution within a neural net framework and 3) Successful demonstration of our Sigma Zero technology for anomaly detection and classification via a neural network model. This paper will include an overview of the current mission status, lessons learned from the almost two `1years of highly successful ongoing operations in the NRHO, a summary of the challenges encountered thus far, and overview of the successful results from the CAPS, NNEP, and Sigma Zero autonomous navigation technology demonstrations to date.

INTRODUCTION

The CAPSTONE mission is a pathfinder for Near Rectilinear Halo Orbit (NRHO) operations that will be vital for the future NASA Lunar Gateway activities. Launched on June 28, 2022, by a three stage Rocket Lab Electron rocket, and utilizing a highly capable 12U CubeSat, CAPSTONE has been successfully operating in the NRHO since November 13, 2022. The CAPSTONE spacecraft completed its baseline mission phase in May 2023 (6 months in the NRHO) and the Enhanced Mission phase (12 additional months in the NRHO) in May 2024. During that time, CAPSTONE has successfully completed ALL the mission's primary objectives defined in 2019 and continues to provide a vital platform for the demonstration of unique and mission enabling technologies in support of the NASA's Artemis program for return to the Moon.

Partnering with Terran Orbital, Stellar Exploration, Tethers Unlimited, the Space Dynamics Laboratory, and Rocket Lab as well as working closely with NASA through multiple centers, the CAPSTONE mission represents not only the first steps to laying the foundation of the Artemis Program but also a different way of collaboration. By utilizing the best features of commercial and governmental capabilities, this technology demonstration was executed in a rapid and low-cost mission not typically seen in more traditional NASA small-mission contracts.

Successful primary objectives achieved thus far for CAPSTONE include 1) semi-autonomous operations and orbital maintenance of a spacecraft in an NRHO, 2) collection of inter-spacecraft ranging data in support of the several, diverse autonomous navigation processes, and 3) execution of the Cislunar Autonomous Positioning System (CAPS) navigation software in an autonomous mode on-board the CAPSTONE spacecraft.

In addition to the orbital and operational focuses of this mission, the spacecraft has served as a technology demonstration testbed for several Advanced Space navigation and other NASA products developed via multiple NASA supported research efforts. These demonstrations include the CAPS autonomous navigation system, the Neural Networks for Enhanced Planning (NNEP) autonomous maneuver planning system, and the autonomous anomaly detection and correction system, Sigma Zero, applied to onboard navigation estimation systems.

Through interactions with spacecraft in the cislunar domain, the CAPS software enables cislunar missions to manage their navigation functions themselves and reduces the reliance on Earth based systems. This process has also demonstrated an innovative one-way ranging navigation approach utilizing a Chip Scale Atomic Clock (CSAC) in combination with autonomous navigation algorithms developed by JPL and implemented by Advanced Space for real-time onboard navigation.

As space missions trend toward operating in dynamically sensitive regimes and using constellations of small spacecraft, the need to automate operations increasingly becomes necessary. Using neural networks (NN) for onboard maneuver planning reduces the dependency on ground contacts and increases spacecraft robustness while delivering similar efficacy as ground team operations. NNEP leverages the powerful function approximation capabilities of NNs to learn the relationship between the spacecraft state and optimal control instructions. Ground computers generate tens of thousands of off-nominal trajectory corrections that cover the entire design space and train a NN using these samples. The NNEP framework can then be applied to real-time onboard maneuver planning and execution operations that require minimal computational overhead and fit easily within modern flight hardware.

Even with over 60 years of spacecraft orbit determination practice, hard-coded logic is insufficient to achieve complete autonomy. The hard-to-quantify "engineering intuition" remains an irreplaceable component of current practice. Machine learning is a natural fit for the core orbit determination problem: conditional probability estimation of nonlinear systems. Autonomous navigation is even more challenging onboard spacecraft where computation is constrained. Traditional algorithms are computationally intensive and quickly become infeasible in an onboard and operational environment. Machine learning shifts the computational heavy lifting to ground-based assets at training time and minimizes the requirements for onboard memory and compute capability. The Sigma Zero system has applied this methodology to the problem of autonomous orbit determination and anomaly correction, and this system has been successfully demonstrated on the CAPSTONE spacecraft.

The CAPSTONE mission is funded through NASA's Small Spacecraft Technology Program (SSTP), which is one of several programs in NASA's Space Technology Mission Directorate (STMD). SSTP is chartered to develop and demonstrate technologies to enhance and expand the capabilities of small spacecraft with a particular focus on enabling new mission architectures through the use of small spacecraft, expanding the reach of small spacecraft to new destinations, and augmenting future missions with support from small spacecraft.

This paper will provide an overview of the mission, through its objectives and operations, as well as insight into the technology demonstration payloads and systems and their significance to both this mission and future ones and provide an update on the ongoing mission operations to date.

MISSION OBJECTIVES

The CAPSTONE mission has objectives that will serve the interests of NASA, Advanced Space, and future participants in the cislunar ecosystem. Detailed below, the primary objectives cover science, technology, and mission operations as part of the overall demonstration that CAPSTONE will perform:

1. Validate and demonstrate NRHO / highly dynamic Earth-Moon Operations

The first mission objective is focused on mitigating technical uncertainties associated with operating in the uniquely beneficial and challenging orbital regime defined as Near Rectilinear Halo Orbits. This objective included demonstrating navigation capabilities and validating stationkeeping strategies and operational simulations. This objective directly supports future missions through the dissemination of operational information and by obtaining operational experience in this unique orbital regime.

2. Inform future lunar exploration requirements and operations

The second CAPSTONE mission objective is focused on building experience operating in complex lunar orbital regimes to inform future lunar exploration requirements and operations, including human exploration flights with lower risk thresholds and higher certainty of success requirements. This includes the establishment of commercially available capacity to support NASA, commercial, and international lunar missions in the future. This objective also seeks to demonstrate the capacity of innovative NASA-industry approaches to rapidly bring capabilities to the Moon and challenge current expectations for cost and schedule.

3. Demonstrate and accelerate the infusion of the Cislunar Autonomous Positioning System (CAPS)

The third objective is focused on demonstrating core technical components of CAPS in an orbital demonstration. This objective includes collaboration with the Lunar Reconnaissance Orbiter (LRO) operations team at NASA Goddard Space Flight Center to demonstrate inter-spacecraft ranging between the CAPSTONE spacecraft and LRO currently in operation at the Moon. In addition to demonstrating key inter-spacecraft navigation in cislunar space, CAPSTONE is enhancing the technology readiness level of the CAPS software. This accelerated maturation permits this system to be available to support near term flight plans to the Moon and to be more widely adopted by future lunar missions and thus increase the value of this peer-to-peer navigation capability.

Since completing these primary objectives as part of the Enhanced mission phase, CAPSTONE has now been employed to demonstrate additional, autonomous spacecraft navigation, maneuver planning and operations technologies in further support of NASA objectives.

MISSION OVERVIEW

Mission Timeline/Contract

Proposed to NASA’s STMD and funded in mid-2019, the CAPSTONE mission was awarded a SBIR Phase III contract through NASA’s Small Spacecraft Technology Program (SSTP). This mission represents a new way of commercially partnering with NASA to enable rapid and cost-efficient technology demonstrations for highly condensed returns in experience to inform near-term operational needs. An initial level one objective of was to achieve launch readiness within 18-24 months of contract award however, because of COVID related supply chain issues affecting the entire spacecraft development and delays in the implementation and testing of both the spacecraft and the Rocket Lab Lunar Photo stage, the mission was actually launched in late June 2022 approximately 33 months after contract award.

Hardware

The CAPSTONE spacecraft is a 12U CubeSat (Figure 1, Table 1) that was designed built by Terran Orbital based on their existing commercial 12U satellite bus. In addition to the CAPS payload flight board, CAPSTONE also included a color commercial CMOS imager for generating images of the Earth and Moon, two communication systems (X-band and S-band) as well a CSAC for generating additional 1-way navigation data. The X-Band system, based on the Space Dynamics Lab (SDL) built Iris radio, is used to communicate with the ground though the Deep Space Network(DSN), while the S-Band system, built by TUI, performed numerous successful (and continues to perform) radiometric measurements with LRO to gather data for the CAPS payload. The mature SDL supplied Iris X-Band system is being used for both two-way communication and ranging as well as part of the 1-way ranging experiment, while the S-Band system will perform radiometric measurements with LRO to gather data for the CAPS payload using a S-Band patch array antenna.

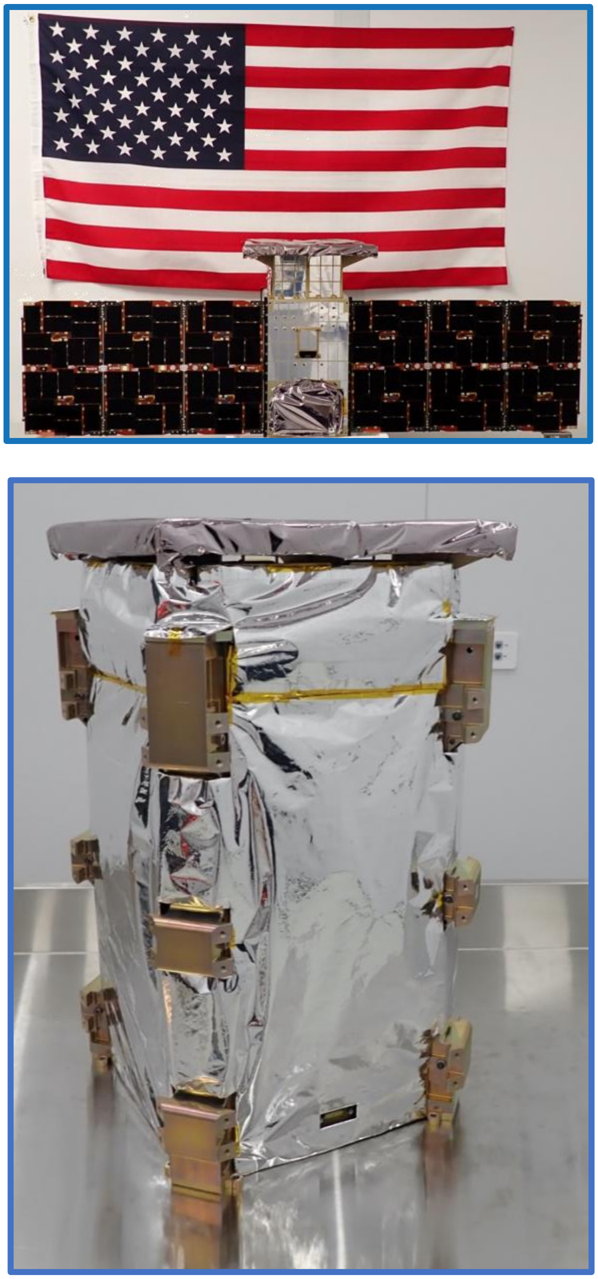
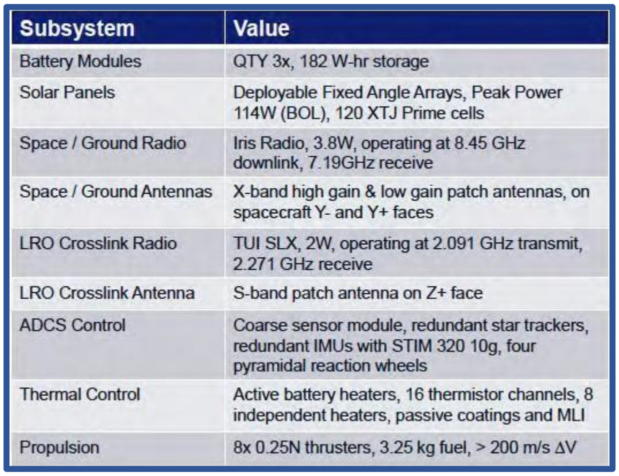


Figure 1: CAPSTONE spacecraft in a deployed (top) and stowed (bottom) configuration.

The spacecraft hosts a monopropellant hydrazine propulsion system designed and developed by Stellar Exploration, Inc., providing over 240 m/s of total ΔV with eight 0.25-Newton thrusters. Four are used for translational maneuvers and attitude control, and four are used for attitude control and momentum desaturation.

Table 1: CAPSTONE S/C Key Characteristics



Subsystem	Value
Battery Modules	QTY 3x, 182 W-hr storage
Solar Panels	Deployable Fixed Angle Arrays, Peak Power 114W (BOL), 120 XTJ Prime cells
Space / Ground Radio	Iris Radio, 3.8W, operating at 8.45 GHz downlink, 7.19GHz receive
Space / Ground Antennas	X-band high gain & low gain patch antennas, on spacecraft Y- and Y+ faces
LRO Crosslink Radio	TUI SLX, 2W, operating at 2.091 GHz transmit, 2.271 GHz receive
LRO Crosslink Antenna	S-band patch antenna on Z+ face
ADCS Control	Coarse sensor module, redundant star trackers, redundant IMUs with STIM 320 10g, four pyramidal reaction wheels
Thermal Control	Active battery heaters, 16 thermistor channels, 8 independent heaters, passive coatings and MLI
Propulsion	8x 0.25N thrusters, 3.25 kg fuel, > 200 m/s ΔV

Payloads

Technology demonstration system software, such as CAPS, NNEP and Sigma Zero, is hosted on a separate flight computer from the spacecraft's primary redundant flight computer boards and operates distinctly from that C&DH system. Being hosted on a separate board allows for technology demonstration software to be updated throughout the demonstration as observations are returned, without disrupting the operations of the primary flight computer(s).

As an example of additional technology demonstrations not part of the original mission objectives, the CAPS payload development received follow-on funding through a Phase II-E SBIR award to support development and integration of an additional component added to the CAPSTONE spacecraft design. An integrated Chip Scale Atomic Clock (CSAC) is providing an additional data 1-way ranging type using the Iris X-Band radio for navigation measurements to support CAPS when other methods are not readily available. A significant part of this demonstration is the ongoing testing of the capability of CAPS to ingest these CSAC time tagged uplink measurements from the DSN the demonstrating a unique, new approach to navigation without the need for two-way communications with the spacecraft.

Operations Overview Thus Far

The mission launched on June 28th, 2022. After an approximate four-month, low energy deep space transfer, and a series of Trajectory Correction Maneuvers (TCMs), the spacecraft inserted into the NRHO on November 13, 2022. Since that time, the spacecraft has completed its Baseline Mission phase on May 13th, 2023, its Enhanced Mission phase on May 15th, 2024 and for the past 3 months has been in the Extended mission phase that could last up to an additional year based on ongoing technology experiments and the continued availability of the full functionality of the spacecraft.

Launch

The CAPSTONE spacecraft launch (Figure 3) was carried out on a dedicated three-stage Electron, a launch vehicle developed by Rocket Lab that includes the first ever use of the Lunar Photon upper stage (Figure 2). After launching into a low Earth orbit from the Rocket Lab LC-1 on Mahia Peninsula, NZ at a latitude of approximately -39°, the Lunar Photon third stage performed a series of apogee raising maneuvers to achieve the Trans-Lunar Injection (TLI) characteristic energy, C3, of approximately -0.6 km^2/s^2 that put the spacecraft on its deep-space Ballistic Lunar Transfer (BLT) trajectory. A true ballistic BLT (no deterministic maneuvers) requires an instantaneous Sun-Earth-Moon geometry; however, for CAPSTONE a deterministic apogee maneuver was required in order to build the flexible Trans Lunar Injection (TLI) launch period, as well as target a constant, specific NRHO arrival time and geometry.[1,2]

BLT Maneuver

From the post-launch TLI deployment state, the spacecraft traversed the low-energy Ballistic Lunar Transfer (BLT), which is a very energy-efficient means of transferring from the LEO environment to an orbit near or about the Moon. BLTs are a type of low-energy transfer in which a spacecraft travels to an apogee of 1-1.5 million kilometers to utilize the Sun's gravity to modify the spacecraft's orbital perigee and inclination.[1,2] For CAPSTONE, this effect is used to decrease the inclination from a launch inclination of ~39° to an inclination in line with the Moon's orbital plane, as well as raise the spacecraft's perigee to the radius of the Moon. This reduced the required deterministic spacecraft ΔV to approximately 60 m/s, compared to the 350-550 m/s required for a direct transfer into an NRHO. This reduction in spacecraft ΔV enabled the mission to be achieved with a 12U-class CubeSat. The trade-off is that the TLI C3 energy of approximately -0.6 km^2/s^2 is higher than -2.0 km^2/s^2, the value needed for a direct transfer. The BLT for CAPSTONE required approximately four months of time to traverse, which is substantially longer than a direct transfer. This extended transfer duration provided for significant advantages from an operational perspective. First, there was ample time to characterize and navigate the spacecraft performance and then perform well-timed trajectory correction maneuvers that allows for a consistent entry time into the NRHO. Additionally, several anomalies with the spacecraft occurred during the transfer (described below) and the extended transfer time allowed the operation team to mitigate and resolve those issues prior to the time-critical NRHO Insertion Maneuver (NIM).

Figure 2: The CAPSTONE Spacecraft/Dispenser - Lunar Photon (gold MLI) Integrated Stack

Trajectory Correction Maneuvers

CAPSTONE performed 5 out of 7 planned Trajectory Correction Maneuvers (TCMs) (Figure 4) in order to clean up launch vehicle errors, target the insertion maneuver timing to achieve an Earth-eclipse free NRHO, as well as correct for navigation and maneuver execution errors. Given that the CAPSTONE spacecraft must achieve both a specific state and epoch after insertion to achieve an Earth-eclipse free NRHO, the TCMs and insertion maneuvers were designed using a three-burn optimization, rather than a simple one or two-burn targeter. Each correction maneuver was designed to minimize the sum of the ΔVs of the current TCM, the next TCM, and the insertion maneuver to achieve a state along the reference NRHO (and corresponding epoch). The final TCM was not redesigned, but rather executed as it is designed in the previous TCM's optimization. The insertion maneuver initial epoch is also part of the optimization, while the TCMs are fixed in time.

Figure 3 – CAPSTONE Launch

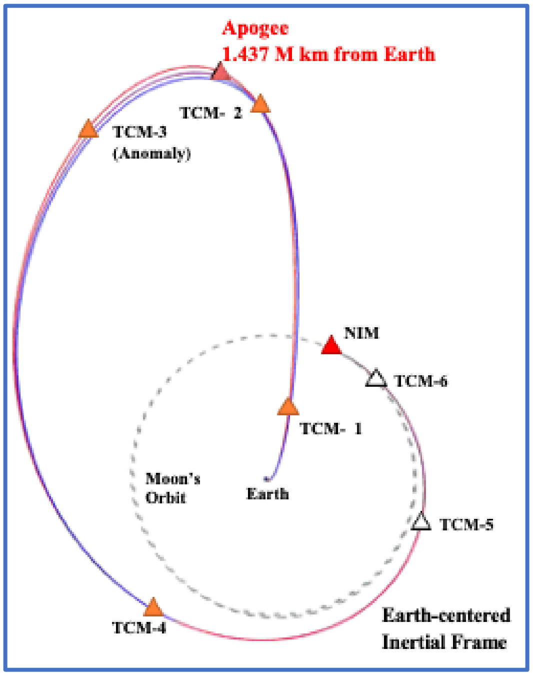


Figure 4: TCM Placement in the Earth-Centered EME2000 Frame

Table 2: CAPSTONE's as Executed TCM/ICMs

Maneuver	Designed ΔV (m/s)	Estimated ΔV (m/s)	Estimated Error
TCM-1a	20.002	19.81	<1%
TCM-1c	1.631	1.618	<1%
TCM-2a/b	40.116	39.97	<1%
TCM-3*	2.271	2.417	~6.4%
TCM-4	4.190	4.372	~4.3%
TCM-5/6	1.284/1.852	N/A	N/A
NIM	17.944	18.07	<1%
ICM-1	4.268	4.222	1.15%
ICM-2	3.843	3.838	<1%

*Post-maneuver anomaly

As shown in Table 2, each of the first 3 TCM was executed with 1% of predicted ΔV planned. *However, an anomaly occurred during the TCM-3 maneuver that resulted in a significant change in the overall mission plan.* First, the date and location for TCM-4 was changed substantially while the spacecraft operations team worked to first resolve the anomaly and its resultant impact on the spacecraft systems. Second, TCM-4 was executed at a much larger ΔV maneuver than originally planned and this re-planned optimization allowed for TCMs 5 and 6 to be subsequentially cancelled. The optimization process employed allowed both of these maneuvers to be skipped as well at the NIM to be executed well within the planned pre-launch error estimate.

TCM-3 Anomaly Overview

On September 8th, 2022, TCM-3 was executed nominally as planned in order to adjust the approach trajectory to the NRHO insertion point and correct any residual errors from the relatively large deterministic TCM-2. During the "braking" phase after the successful completion of the maneuver, the spacecraft unexpectedly spun up due to stuck "open" thruster valve. As a result, the spacecraft "burn abort" fault protection was "tripped" due to excessive rates and spacecraft went into a "Safe Mode" state.

As a result of this anomaly, the vehicle settled into a state with at rotation of ~70°/sec with angular momentum vector pointing ~77° from the Sun. Due to this orientation and spin rate, the spacecraft established a repeating communication pattern of ~5 minutes of communication lock followed by ~50 min loss of signal cycle as spacecraft charged enough to power on radio and then lost power. As a result of power load shedding, the propellant tank heaters were turned off and, as a result of this action, the hydrazine propellant froze (with tank temp at -7C).

After significant analysis of the telemetry that was slowly downloaded within the 5-minute blocks, it was determined that one of the 0.25N thruster valves had "stuck" in the "open" state. Thus, anytime the main propellant valve opened, an uncontrolled thruster firing would occur that would not allow any controlled de-spin of the spacecraft in order to return it to its nominal 3-axis controlled state. Several weeks of analysis and troubleshooting then occurred and a path forward was decided to attempt to return the spacecraft to normal, if possibly degraded, operations.

First, it was determined that as the orbit progressed, it became more able to run the heaters enough to unfreeze the propellant after several weeks due to the decreasing angle from the solar panels normal vector to the Sun line. With the propellant unfrozen, the prop subsystem was tested several times to more closely identify which thruster valve that was "stuck" open. As a result of these tests, the spin rate actually increased to ~105 deg/sec but the operations and GNC teams were able to narrow down which thruster was stuck, #3 (axial) or #5 (rotational).

The Terran Orbital GNC team then re-mapped the thruster controller logic and developed a detumble controller that was robust to and compensated for the stuck open thruster. On October 7th (approximately one month after the TCM-3 anomaly occurred) the detumble maneuver was completed successfully and the spacecraft re-gained full 3-axis control and aligned the spacecraft antennas in order to regain constant communication with ground. On October 11th a pressurization test was executed to conclusively determine that the valve for thruster #3 was the one stuck "open" and that led to finalizing the design and testing for the re-mapped TCM controller logic. It is estimated that during the anomaly analysis and resolution phase, CAPSTONE completed >500K rotations as an unintended spin stabilized spacecraft.

On October 27th, or approximately 2 weeks after the original planned timeline, TCM-4 was successfully executed. As a result, this event fully proved the re-mapped GNC controller was viable going forward also and aligned the spacecraft for insertion into the NRHO ~3 weeks later. Additionally, it was determined that the new minimum ΔV threshold for a TCM was substantially increased in order to minimize the impact of the stuck axial thruster and as a result, the originally planned TCMs 5 and 6 were cancelled because they did not meet this new minimum lower limit.

This is fundamentally why it was very fortunate that the anomaly that followed TCM-3 occurred when it did as it gave the spacecraft operations team over 2 full months to 1) Resolve the unplanned state that the spacecraft was put into as a result of the thruster issue 2) To re-map the spacecraft GNC commands to mitigate the impact of the stuck thruster valve and 3) to redesign the maneuver plan for the remaining TCMs, the time critical NIM and the subsequent post-NIM ICMs. If the anomaly had happened at the planned TCM-4, TCM-5, or TCM-6 times in the mission, it is unlikely that the NRHO insertion could have been achieved successfully. This provided further supporting evidence of the benefit of the BLT mission design approach for mission operations risk mitigation.

Insertion into NRHO

Given the primary mission objective of demonstrating NRHO stationkeeping and operations to inform future lunar exploration, on November 13, 2022 CAPSTONE was inserted into the same sized orbit targeted by the Lunar Gateway: a 9:2 resonant, southern L2 NRHO (Figure 5). For every two lunar synodic periods, approximately 29.53 days each, CAPSTONE will complete 9 revolutions in the NRHO.

There are four families of NRHOs, distinguished by the location of their apolune. The apolune may be stretched towards either the L1 or L2 Earth-Moon Lagrange point, and may be either above (northern) or below (southern), the lunar orbital plane. A 9:2 resonant NRHO only exists in the L2 family, and the southern trajectory was chosen to maximize the in support of the Lunar Gateway's planned time over the lunar south pole, an area specifically of interest to the Artemis program's lunar exploration plans.

The CAPSTONE NRHO reference orbit has been designed to avoid Earth induced solar eclipses (Figure 6) for the duration of the Primary, Enhanced, and now Extended missions (~30 months), as well as align the epoch of the first perilune with the low-energy transfer to minimize the ΔV required to achieve the NRHO. Although periodic in the circular restricted three-body problem, a multi-shoot method was used to build an Earth-eclipse free, multi-revolution NRHO with minimal discontinuities in the ephemeris model.

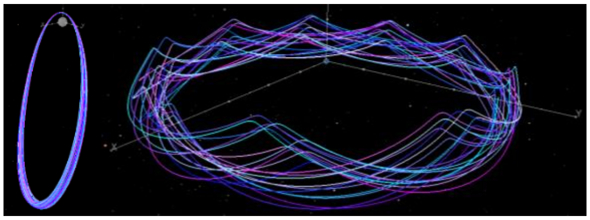


Figure 5: NRHO Reference Orbit in the Earth-Moon Rotating (left) frame and Sun-Earth Rotating (right) frame

As the spacecraft arrived at the Moon, it targeted the reference NRHO periapse passage, and the spacecraft was precisely inserted into the NRHO. Planetary missions are often robust to large maneuver execution errors upon insertion into a capture orbit because the capture orbit simply must be safe and otherwise a good transition to the science orbit via additional maneuvers. CAPSTONE's insertion was quite different from this model. First, the NRHO Insertion Maneuver (NIM) was ~17 m/s, quite a small maneuver compared with conventional planetary orbit insertions. Second, this maneuver must very accurately target the NRHO. If the post-NIM state, mapped to the nearest periapse, is more than 5 m/s different from the NRHO periapse state, the resulting orbit is far different from the reference NRHO, and the mission must then spend a significant amount of fuel to return to the reference NRHO. One way in which CAPSTONE's orbit insertion was similar to a conventional planetary insertions is that the NIM is considered a critical event maneuver: aka it must be performed approximately as designed or else the mission is substantially impacted.

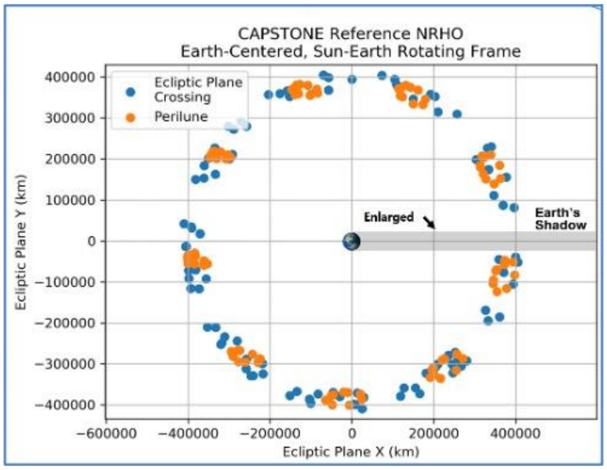


Figure 6: Illustration of the CAPSTONE Reference NRHO's phasing to avoid Earth eclipses

Post-NIM Maneuvers

CAPSTONE introduced two maneuvers (Table 2) following NIM: ICM-1 was performed one day later to clean up NIM execution errors; ICM-2 was performed three days after ICM-1 to complete the insertion process into the reference NRHO. These two Insertion Cleanup Maneuvers (ICMs) allowed the mission designers six degrees of freedom to achieve a six-state at the time of ICM-2, i.e., they compose a two-burn transfer from the post-NIM orbit to the reference NRHO and were performed relatively soon after NIM in order to avoid exponentially increasing ΔV cost. Some separation was desirable between the two ICMs to give the spacecraft time to drift from the post-NIM orbit to the reference NRHO, but it was desirable to achieve the transfer prior to the next periapse passage since periapse passages are very sensitive to orbital errors.

Daily Operations – Orbit Maintenance Maneuver (OMM) Design

The orbit maintenance strategy for CAPSTONE is both informing and responding to projected NASA's Lunar Gateway requirements. CAPSTONE's orbit maintenance maneuvers (OMM) are based on the "X-axis crossing control" strategy—a low-cost, robust method of maintaining NRHOs for long durations.[3-5] Each maneuver is designed to achieve a target 6.5 revolutions downstream (that is, at the seventh perilune crossing), where the target is the X-velocity of the reference orbit (NRO) in the Earth-Moon rotating frame at that perilune. This strategy is low-cost from both a ΔV and navigation perspective and effective at maintaining the NRHO-like motion, but the spacecraft drifts away from the reference over time. This drift is realized not only in the position and velocity states of the spacecraft, but also the phasing. Such a drift is undesirable because the NRHO for CAPSTONE was designed to avoid Earth induced solar eclipses by targeting strict phasing.

Different approaches to correct this drift have been developed.[6,7] Some of these strategies implement a two-burn sequence to correct the phasing, while others implement small augmentations to the traditional X-axis crossing algorithm.[8] The current OMM approach baselined for CAPSTONE supplements the traditional X-axis crossing control algorithm by adding an epoch constraint to the maneuver targets. This constraint requires the perilune passage time of the controlled spacecraft to match the perilune passage time of the reference spacecraft to some tolerance.

Other OMM augmentations were considered as well. These augmentations incorporated different aspects of phase-control strategies presented in literature, such as where in the NRHO the OMM is performed. In these cases, where the location of the maneuver was changed, the same epoch constraint as discussed in the CAPSTONE baseline OMM strategy are still implemented.[6] The additional maneuver locations chosen were 160º and 200º osculating true anomaly (in the Earth-Moon rotating frame).

OMMs as Implemented

As a result of the re-mapped maneuver GNC, a modified OMM strategy was developed in order to mitigate and negative effects of the “stuck” open thruster valve during each OMM. Thus, for each already pre-planned OMM, 4 questions are asked within the Operations and Navigation teams as to whether an OMM was required to be executed relative to the original OMM plan:

1. Does the OMM, as designed, achieve the targets?
2. Does the performing the OMM keep CAPSTONE in the NRHO longer than if skipped?
3. When including navigation uncertainty and maneuver execution errors, does the OMM still effectively move the downstream state towards the target or is the effect lost in the uncertainty?
4. Despite skipping many OMMs, does the stationkeeping strategy keeps the spacecraft near the design reference?

As a result of this process, thus far (at the time of this paper’s writing) over 26 OMM’s have been successfully executed by the spacecraft (Table 3) and many more of the pre-launch planned ones (which were to occur on each NRHO) that have been skipped. As noted in the table, recent maneuvers have been impacted by recent issues with the propulsion system pump speed that have increased maneuver execution errors, either by underperformance due to time-out issues in the command control software or fault detection by the pump controller. Compensation has been developed and implemented for the maneuvers that occurred after early June, 2024. The spacecraft and operations team continue to operate at this cadence along with the support of the DSN for the routine communication and navigation tracking passes.

NAVIGATION

CAPSTONE has navigated during the transit to and in the NRHO with radiometric measurements from the Deep Space Network and one affiliated dish at Morehead State University. There are multiple navigation-related technology demonstrations onboard the spacecraft, but traditional, two-way radiometric measurements with the ground are the primary method of navigation for CAPSTONE. This is the same paradigm that will be used by NASA’s Lunar Gateway.

Measurements taken with the DSN-affiliated 21-meter dish at Morehead State University have been shown to be on the order of ~40% noisier than the 34-meter dishes at the Deep Space Network and are de-weighted accordingly within the navigation filter. Additionally, as part of another technology demonstration, the DSN has proposed having CAPSTONE demonstrate an experimental CONOP of Delta-DOR measurements using pseudo noise tones instead of typical DOR tones.

Table 3: CAPSTONE's as Implemented OMMs

Maneuver	Design DV (cm/s)	Estimated DV (cm/s)	Error (%)
OMM-05	61.92	63.37	2.3%
OMM-10	31.43	32.03	1.9%
OMM-13	18.70	18.52	1.0%
OMM-18	44.99	42.73	5.0%
OMM-20	15.53	16.54	6.5%
OMM-22	6.40	7.40	15.6%
OMM-26	19.71	17.72	10.1%
OMM-28	13.10	14.37	9.7%
OMM-32	13.42	13.50	0.6%
OMM-36	13.17	13.54	2.8%
OMM-39	13.15	14.56	10.7%
OMM-43	34.00	30.88	9.2%
OMM-45	13.31	10.9	18.1%
OMM-49	38.5	46.55	20.9%
OMM-52	75.71	78.83	4.1%
OMM-53	4.98	6.22	24.9%
OMM-56	4.70	10.81	130.0%
OMM-60	49.26	55.13	11.9%
OMM-62	23.35	28.89	23.7%
OMM-64	23.37	26.04	11.4%
OMM-66	8.76	10.54	20.3%
OMM-71	39.36	46.91	19.2%
OMM-72	16.11	16.52	2.5%
OMM-76	27.40	27.24	0.6%
OMM-81	74.12	12.68*	82.89% *
OMM-82	61.02	31.96*	47.62% *
Total	**745.47**	**694.38**	**18.98%**

Orbit determination is performed in the Advanced Space Flight Dynamics System (FDS), which is a system of driving scripts and organizational tools wrapped around JPL’s MONTE software. The orbit determination setup allows for the input of high-fidelity dynamic models, media calibration models, and measurement files from the DSN. State estimates, estimates of other parameters, associated uncertainties, and trajectory runouts are generated which are then passed along to downstream processes such as maneuver design and payload planning. Orbit determination is performed nearly daily assuming that there is new data to process. Orbit determinations are delivered, meaning that they are given an official “stamp of approval”, and forwarded along to downstream users, approximately 1-2 times per week. An OD is delivered prior to every OMM design, and there are sometimes additional deliveries to support payload activities.

The far, the CAPSTONE mission has met all navigation requirements at the time of maneuver designs across the entire timeline of the mission thus far including TCM-

1a, TCM-1c, TCM-2, TCM-3, TCM-4, NIM, ICM-1, ICM-2, and NRHO OMM's 5-82 and beyond (Table 4). Additionally, the navigation approach has successfully executed through several off-nominal and unplanned spacecraft behaviors including propellent "bake-off" for the entire mission and the full line-leaks that occurred after the thruster valve anomaly resolution. The navigation team has consistently and accurately estimated the perturbations after each thruster event, like the ongoing reaction wheel desaturation maneuvers that occur on a routine basis during each orbit. As shown in Table 4, navigation errors post-ICM-2 in the NRHO have been nominal and well within the expected predicted NRHO performance.

In summary, the navigation teams at Advanced Space with support from the Terran Orbital spacecraft team and the DSN, have accurately navigated CAPSTONE for over two years, through a wide variety of conditions. Though all these conditions, the navigation solutions have met the needs of the mission and been in line with pre-launch expectations. Results, raw data, and best practices have been shared with many NASA centers and other interested parties including the Jet Propulsion Laboratory, Goddard Space Flight Center, Glenn Research Center, the Gateway and Artemis systems teams at Johnson Space Center, and several CLPS provider teams.

Table 4 – CAPSTONE Navigation Performance Results through the initial OMMs

Mission Phase	Position Error - 3s (km)	Velocity Error - 3s (cm/sec)
Deployment to TCM-2 (Doppler only)	~10	~1
TCM-2 to TCM-3	~10	~1-5
TCM-3 to Anomaly Recovery (Spin-stabilized, Doppler only)	~5-20	~0.8 - 2
Anomaly Recovery to NIM	~1-3	~0.5 - 1
Post-NIM (Leadup to ICM-1, high tracking cadence)	~0.2-1	~0.3 - 0.5
Initial Post-ICM 1, 2	~1	5
NRHO Operations to date	<1	<1

CISLUNAR AUTONOMOUS POSITIONING SYSTEM (CAPS)

CAPS is a unique innovation that operationalizes, and leverages investments made in algorithms, flight computers, and radios over the past decade. At its foundation, CAPS starts with the algorithms and logic of automated navigation layered on top of an innovative approach to absolute orbit determination that requires only relative radiometric ranging and Doppler measurements. In its most streamlined implementation, CAPS is a software innovation that can be incorporated on any future spacecraft.

SBIR Development

From 2017 to 2021 the CAPS development was supported via a NASA SBIR Phase 1-2 contract through the NASA Goddard Space Flight Center. In this timeframe, the software was developed and tested in a lab environment that readied it for further integration and ultimately flight testing. With the Phase II concluding mid-2020, the CAPS research and development was funded for continuation through a Phase II-E and a Phase III SBIR set of awards. The intent for these awards was the ongoing development and support of the software as it approaches demonstration on the CAPSTONE mission. Part of these funding extensions also have expanded the data types ingestible by CAPS, thereby widening its navigation capabilities in the cislunar environment.

Crosslink

To demonstrate and accelerate the infusion of the Cislunar Autonomous Positioning System (CAPS), CAPSTONE has to date performed the required 5 successful crosslink communication passes with the Lunar Reconnaissance Orbiter (LRO) using the TUI radio-based S-band telecommunication system. The tracking passes occur when CAPSTONE is nearer to periapse, as LRO is in a polar, low lunar orbit and within the communication range of the S-Band telecom system on the spacecraft (~6000 km). The availability of these passes has been more limited than expected due to dependencies on a number of factors, including each spacecraft's power availability, their relative distances, lunar occultations, pointing constraints, and LRO ongoing science operational priorities. The limited successful tracking passes have provided the necessary two-way, coherent range and Doppler measurements to the CAPS flight software onboard CAPSTONE.

The flight software has demonstrated CAPS in flight successfully several times thus far, while also downlinking the CAPSTONE-LRO crosslink data to the ground for further refinement, validation, and CAPS filter tuning and development. The objective for CAPSTONE is to accelerate the infusion of autonomous spacecraft navigation, where such crosslink tracking may support the navigation needs of both spacecraft in the link. The CAPS FSW continues development and has been and will= be part of in-flight FSW updates to improve the accuracy of the navigation estimate and correct issues observed in the initial experiment's results. Eventually, during the current ongoing extended mission phase, the goal is for the CAPS software to provide full autonomous navigation onboard the CAPSTONE spacecraft thus demonstrating this capability for future cislunar mission applications.

NNEP

As space missions trend toward operating in dynamically sensitive regimes and using constellations of small spacecraft, the need to automate operations increasingly becomes necessary. Using neural networks (NN) for onboard maneuver planning reduces the dependency on ground contacts and increases spacecraft robustness while delivering similar efficacy as ground team operations. NNEP leverages the powerful function approximation capabilities of NNs to learn the relationship between the spacecraft state and optimal control instructions for commanding maneuvers.

A test campaign using the NNEP embedded software was executed on CAPSTONE during Q3 of 2024. Using historical real state estimates from earlier CAPSTONE operations, results were compared between the NNEP autonomous onboard maneuver designs with historical maneuver designs done on the ground. This software was then executed on the spacecraft in order to evaluate the results in an actual in-flight environment. Evaluation of these results is still ongoing with the goal of planned updates to the NNEP algorithms and onboard software that would lead to an autonomous real time maneuver test using the spacecraft propulsion with the NNEP software on the spacecraft in the 4th quarter of 2024

SIGMA ZERO

Autonomous navigation is even more challenging onboard spacecraft where computation is constrained. Traditional algorithms are computationally intensive and quickly become infeasible in an onboard and operational environment. Machine learning shifts the computational heavy lifting to ground-based assets at training time and minimizes the requirements for onboard memory and compute capability. The Sigma Zero system has applied this methodology to the problem of autonomous orbit determination and anomaly correction, and this system has been successfully demonstrated on the CAPSTONE spacecraft.

The overall goal of the Sigma Zero technology is to reduce human intervention by an order of magnitude in spacecraft orbit determination. To that end, a test campaign was developed and executed on the CAPSTONE spacecraft using the Sigma Zero embedded software implementation of real-time error detection and correction through the use of transformer neural network (NN) models specialized to extract useful information from sequences of spacecraft navigation data.

This process adapts state-of-the-art methods from natural language processing; applies them to sparse, multivariate, high-precision numerical data (like navigation measurements) and are implemented is flight software implemented as core Flight System (cFS) application;

The inputs at a series of 10's-1,000's of epochs include:

- Estimated spacecraft state
- Ground station state
- Post-fit residuals
- Measurement type

The resultant output is a probability distribution function across 9 anomaly classes that results in an autonomous corrected navigation estimate

The test campaign used "pre-canned" simulated data on the spacecraft for the following:

- Test 1: a single input file representing an unexpected finite burn maneuver
- Test 2: 9 input files, 1 for each of: nominal, drag mismodel, SRP mismodel, gravity field mismodel, finite burn mismodel, desaturation maneuver, spinning, radio dropout, outgassing

Thus far, elements of Sigma Zero tested on CAPSTONE include the following:

1. A Navigation Anomaly Detector: Given a set of measurements and/or measurement residuals, identify if something went wrong.
2. A Navigation Anomaly Classifier: Determine the most probable cause(s) of an anomaly. The Anomaly could be a maneuver, hardware malfunction, unplanned reaction wheel desaturation, unmodeled dynamics, bad data, etc.

Using the information from this process, the spacecraft system controller is able to take autonomous action to correct for these anomalies through maneuver execution or other actions in order to mitigate any risks the anomalies may cause to the mission operations or overall success.

OTHER PLANNED TECHNOLOGY DEMONSTRATIONS

In addition to CAPS, NNEP, Sigma Zero, several other technology demonstrations related to spacecraft autonomy, Position, Navigation and Timing (PNT), relay operations, and other spacecraft operations autonomy are being planned for CAPSTONE during the enhanced mission phase. These include, but are not limited, to the following:

- AutoNGC (NASA GSFC) navigation demonstration.
- Software encrypted data relay networking demonstration.
- LRO data relay for possible support for future farside or other lunar surface missions.
- Delay Tolerant Network Demonstration
- Two Way Time Transfer (TWTT) demonstration.
- Integrating of NNP to demonstrate autonomous navigation (ACPE) with autonomous maneuver planning and execution.
- NRHO Rendezvous Proximity Operations demonstrations (RPOd), perhaps with Gateway or an Artemis mission.

As the Enhanced mission phase proceeds and depending on spacecraft availability and operational complexity, each of these has the possibility of execution within the next 8-10 months.

CURRENT MISSION STATUS

Currently, the CAPSTONE spacecraft is operating nominally and has more the 45% of fuel remaining for ongoing operations. All operations systems at the Terran Mission Operations Center (MOC) for spacecraft TT&C and at the Advanced Space Operations Center (ASOC) for navigation and flight dynamics management continue to perform well. Coordination with the LRO operations team will continue through at least September, 2024 and both the CAPSTONE and LRO teams are ready to support the ongoing inter-spacecraft ranging operations in support of the CAPS on-orbit autonomous navigation demonstration.

CAPSTONE has successfully operated in the NRHO since 11/13/22 (630 days). In general, Orbital Maintenance Maneuvers (OMM's) have executed as planned with the exception being for recent issues with the propulsion system pump in the April-May 2024 timeframe that have since been resolved. Multiple planned OMM's continue to be cancelled due to process of only applying ΔV when above a pre-determined threshold required for orbit stability. OMM cadence has been reduced due to minimum OMM ΔV based on the updated Terran Orbital GNC controller implemented for the post-TCM-3 valve anomaly and adjusted for pump speed variations.

Several minor anomalies have occurred since NRHO insertion including loss of commanding on uplink do to suspected Single Event Upsets (SEUs) on the Iris firmware, maneuver timeouts due to the aforementioned pump speed controller issues, and other minor issues with SW commands that have not affected mission performance.

SUMMARY OF KEY LESSONS LEARNED TO DATE

As result of the development, implementation, and operations execution of the CAPSTONE mission, quite a few key "lessons learned" have been identified by the mission team and these are summarized below:

1) For a CubeSat/Small Sat based mission with a clear set of mission goals, a better understanding of the overall system requirements is needed well before the PDR and certainly as part of the spacecraft acquisition process (i.e., RFP, contract requirements, deliverables, etc.)
2) Low-cost, CubeSat missions often rely on COTS components and alleged "plug and play" designs that are often not as developed as promoted by suppliers or as advertised. Several of the original components and subsystems had to be re-worked based on the deficiencies that emerged during the development process.
3) A clear understanding of the unique mission requirements vs. the flight system capabilities for a unique mission needs to be better defined and detailed out BEFORE schedules and budgets are estimated and agreed with all stakeholders.
4) Ground system requirements and operations are often not well understood until well after Authority to Proceed (ATP) and the resultant complications related to those can drive schedule and costs that were not well considered. Plugging into existing ground architectures is not as simple as it is often advertised and the complexities of interface testing with those system is often underestimated.
5) Having a better understanding of vendor capabilities, heritage and past performance is important to understand prior to contract award and execution. Smaller, lower cost vendors often underestimate or underbid the costs and scope of the required work, and this leads to headaches and delays when inevitable problem arise.
6) Regulatory approvals often require far more time and resources that expected. As an example, the frequency approval process for cislunar or deep space missions is often a labyrinth of requirements and approvals that require extensive attention to the detailed requirements and the time it takes to receive full approval.
7) Multiple government agencies, who often don't communicate with each other, are involved in getting final launch approval. In the case of CAPSTONE, this included the i.e., New Zealand Space Agency (NZSA) who had never had an interplanetary launch from their territory and thus a

new licensing process needed to be implemented for the CAPSTONE mission.

8) Items like Planetary Protection, Orbital Debris, Range Safety requirements for launch, and transport requirements for an overseas launch (aka Rocket Lab in NZ) are not well understood by most space systems development teams and require significant oversight by project management.
9) Selling the project is great. Implementing and executing the project is ALWAYS harder, takes far longer and costs more that most everyone thinks. CAPSTONE was sold as a low cost, fast paced cislunar mission to deliver data and results to NASA in ~20-24 months. The reserves were considered adequate and that, as in the case for CAPSTONE, is often underestimated as well.
10) COVID impacts aside, several key challenges were not well understood by the team until well into the development of the project and costly adjustments had to be made to mitigate these issues. Between the launch vehicle upper stage issues and the unique spacecraft requirements impact on a COTS design, the mission launched ~16 months after it was initially planned, or 33 months after the mission was awarded by NASA.

Advanced Space along with the team members Terran Orbital, Stellar Exploration, SDL, Tethers Unlimited, the DSN, and Morehead State have thus far assembled and presented these lessons learned in numerous forums in the form of presentations, papers, and technical interchange meetings. This has been especially valuable to the NASA teams who are formulating and implementing the Artemis missions for the future human return to the Moon. It is hoped that these lessons will be applied to future missions like CAPSTONE in order to reduce the overall risks, costs, and schedule requirements for these important missions.

AN AUTONOMY ENABLED FUTURE VISION

As cislunar space is poised for significant increases in mission activity, missions large and small are inherently constrained by the current limitations of ground tracking systems such as DSN, the Near Space Network (NSN) Many of these missions will be operating in orbital regimes that would nominally require frequent tracking and station keeping, which drives the demand for navigation even higher. NASA’s Artemis Program of lunar exploration will return US astronauts to the Moon and lay a foundation for development of lunar resources. The Artemis Program lunar architecture now in development includes major elements such as the Orion space capsule, the Lunar Gateway, several human and robotic lunar landers (including several Commercial Lunar Lander Services (CLPS) systems) and the Space Launch System (SLS). Gateway will serve as a departure point for human excursions to the surface of the Moon. Many of these projects are now in development and can benefit from the capabilities CAPSTONE has demonstrated for their operational autonomy requirements.

Advanced Space foresees a future of increasing scientific, exploration, and commercial activity within cislunar space. Future missions operated by NASA, commercial entities, and international agencies will face increasing congestion due to limited communication and navigation infrastructure Thus the need for fully autonomous, onboard spacecraft operations will be vital to this vast expansion of missions and operations in the cislunar space environment.

CONCLUSIONS

As the Moon becomes the focus of more entities – whether governmental, commercial, or international – it is becoming imperative that there is a stronger understanding of the nuances and difficulties faced by future spacecraft as they enter this new environment. Not only is CAPSTONE providing and operational platform for important technology demonstrations and rapid feedback the on operational challenges soon to be faced by the future Lunar Gateway and other Artemis Program missions, but it is doing so in a way that is expedited via commercial strengths in schedule, cost, and risk management. It is the goal of the Advanced Space CAPSTONE team that these technology demonstrations will not only support Artemis operations and maturation but will also model a new way of commercial partnerships for NASA and other agencies to pursue in support of their directives.

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