73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

IAC-22-B4,8,7,x74189

CAPSTONE: Pathfinder for the Lunar Gateway

Jeffrey S. Parker[a]*, Bradley Cheetham[a], Thomas Gardner[a], Michael Thompson[a], Alec Forsman[a], Ethan Kayser, Connor Ott[a], Arlen Kam[a,b], Sandeep Baskar[a], Matt Bolliger[a], Charles Cain[a], Michael Caudill[a], Sai Chikine[a], Lauren De Moudt[a], Andrew Koehler[a], Nathan Ré[a], and Jaquelyn Romano[a].

[a] *Advanced Space, 1400 W 122nd Ave Suite 200, Westminster, CO 80234,* parker@advancedspace.com
[b] *AKam Space, 321 Halaki St, Honolulu HI 96821*
* Corresponding Author

Abstract

Advanced Space and NASA have partnered to develop and launch the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which is serving as a pathfinder for Near Rectilinear Halo Orbit (NHRO) operations around the Moon. The NHRO is the intended orbit for the NASA's Gateway lunar orbital platform – as such the CAPSTONE mission is validating simulations and confirming operational planning for Gateway while also validating performance of navigation and stationkeeping for future operations. This paper summarizes the launch and early navigation operations of CAPSTONE, validating the low-energy approach to the Moon and preparing for arrival at the NRHO.

Keywords: CAPSTONE, NRHO, BLT, CubeSat, Lunar, Navigation

Acronyms/Abbreviations

The following acronyms/abbreviations are used in this paper:

Ballistic Lunar Transfer (BLT)
Chip Scale Atomic Clock (CSAC)
Cislunar Autonomous Positioning System (CAPS)
Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)
Deep Space Network (DSN)
Inertial Measurement Unit (IMU)
Insertion Correction Maneuver (ICM)
Lunar Reconnaissance Orbiter (LRO)
Navigation Team (NAV)
National Aeronautics and Space Administration (NASA)
NRHO Insertion Maneuver (NIM)
Near Rectilinear Halo Orbit (NRHO)
Orbit Determination (OD)
Orbit Maintenance Maneuver (OMM)
Reaction Control System (RCS)
Small Spacecraft Technology Program (SSTP)
Solar Radiation Pressure (SRP)
Trajectory Correction Maneuver (TCM)
Trajectory Interface Point (TIP)
Trans-Lunar Injection (TLI)

1. Introduction

Advanced Space and NASA have partnered to develop and launch the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which is serving as a pathfinder for Near Rectilinear Halo Orbit (NHRO) operations around the Moon. The NHRO is the intended orbit for the NASA's Gateway lunar orbital platform – as such the CAPSTONE mission is validating simulations and confirming operational planning for Gateway while also validating performance of navigation and station-keeping for future operations.

This low-cost, high-value mission has demonstrated an efficient low-energy orbital transfer to the Moon and will be demonstrating an insertion into the NRHO on November 13, 2022. It will thereafter demonstrate the operations within the NRHO that will reduce the risk of key exploration operations and technologies required for the future success of NASA's lunar exploration plans, including the planned human return to the lunar surface. This paper includes the current mission status leading up to launch, the operations underway, and lessons learned to date in order to inform future lunar exploration and scientific exploration.

CAPSTONE is a 12U cubesat developed, integrated, and tested by Tyvak Nanosatellite Systems carrying a payload communications system capable of cross-link radiometric tracking with the Lunar Reconnaissance Orbiter (LRO), a dedicated payload flight computer for software demonstration, and an imager. The crosslink radiometric tracking and software demonstration will provide critical demonstration of the Cislunar Autonomous Positioning System (CAPS) to enable peer-to-peer navigation for future lunar missions. CAPSTONE was launched on a Rocket Lab Electron launch vehicle with a Photon upper stage. The paper will describe the results of the launch and subsequent flight to the Moon.

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. 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 supporting small spacecraft.

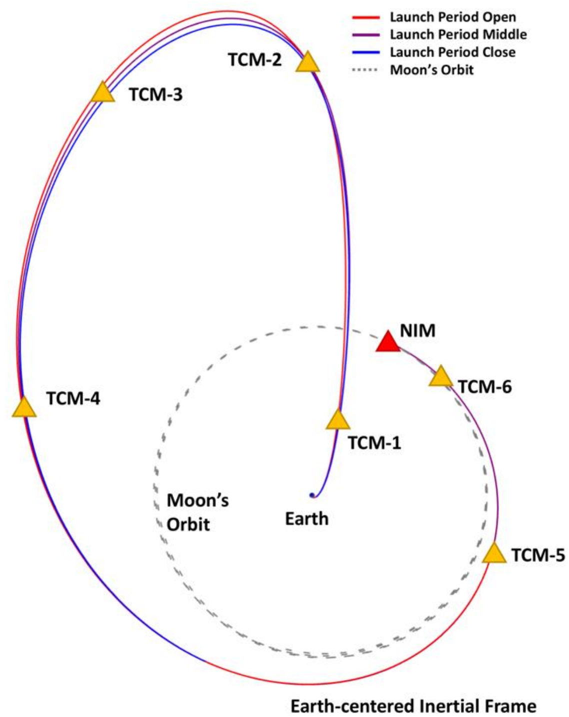

Figure 1. CAPSTONE's Ballistic Lunar Transfer to the NRHO.

2. Mission Design

CAPSTONE utilizes a low-energy transfer to the Moon, known as a Ballistic Lunar Transfer (BLT), which makes it far more realizable to place a small spacecraft with limited propulsive capability into an orbit about the Moon. The launch vehicle must reach a slightly higher energy target – a C3 target of approximately -0.6 km^2/s^2 instead of -2.0 km^2/s^2 – but that amounts to a very small amount of additional lift capability. The low-energy transfer's benefits for CAPSTONE include the following:

- A very flexible mission design, providing numerous launch opportunities per month that arrive at the same target orbit. Hence, the orbit design only has to be produced once per launch period.
- Reduced operational intensity and risk; it takes about four months to reach the Moon, providing ample time to support operations. CAPSTONE observed this as it experienced an anomaly 12 hours after its Trans-Lunar Injection. This disruption had far less significant impacts to CAPSTONE because of the low-energy transfer than it would on a direct transfer to the Moon. Further, CAPSTONE had a lot of time to complete spacecraft commissioning before the primary science phase.
- Reduced fuel requirements: CAPSTONE requires only 17 m/s of Delta-V to enter the NRHO, and a low fuel cost to establish a wide launch period.

CAPSTONE's low-energy transfer is illustrated in Figure 1, shown in the inertial frame. One can see that the launch vehicle effectively placed CAPSTONE on a highly eccentric initial orbit that travelled well past the Moon. At that distance, the Sun's gravity pulls on CAPSTONE, raising CAPSTONE's orbital periapse and reducing its orbital inclination. The geometry is carefully balanced – requiring several trajectory correction maneuvers (TCMs) – such that when CAPSTONE arrives at the Moon, it arrives in the proper geometry that places it into the NRHO with minimal fuel.

CAPSTONE's NRHO is built the same as NASA's Gateway's proposed NRHO. It is a Southern halo orbit, which spends most of its time in view of the Southern Pole of the Moon. Being a halo orbit, CAPSTONE will always remain in view of Earth. The orbit is in a 9:2 resonance with the synodic motion of the Earth about the Sun, such that the spacecraft traverses the NRHO nine times when the Moon travels about the Earth twice in a synodic fashion, relative to the Sun. In this way, the spacecraft may avoid all passages through the Earth's shadow. The spacecraft does traverse through the Moon's shadow, but those durations are far shorter than Earth eclipses. The CAPSTONE NRHO is illustrated in Figure 2. Each revolution of the NRHO takes 6.5 days.

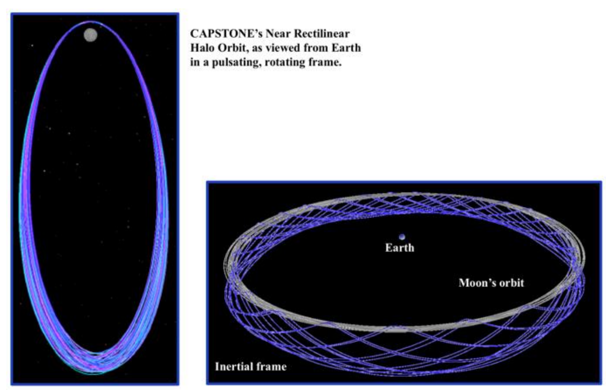

Figure 2. CAPSTONE's NRHO, viewed in the Earth-Moon rotating frame (left) and in the Earth-centered inertial frame (right).

Inserting into an NRHO is not the same as a conventional lunar or planetary orbit insertion for several reasons: first, it's a small maneuver, only ~17 m/s in size when arriving from a BLT; second, it is important to achieve the insertion's execution without too much undershoot *or* overshoot. That is, a mission to a low lunar orbit could be designed to target a 10-hour orbit and then reduce it from there via one or more orbit reduction maneuvers (i.e., favoring an *undershoot* to save fuel and add robustness). That strategy has been employed on most orbiters, including Apollo, GRAIL, Chandrayaan-1, and many others. The NRHO is a very specific orbit: one cannot just get close and adjust it a few orbits later. Rather, one has to arrive carefully and perform corrections very quickly. CAPSTONE is trailblazing these strategies for all future lunar missions and has worked hard to understand different approaches.

The approach settled on by the CAPSTONE navigation team is to execute the NRHO Insertion Maneuver (NIM) as accurately as possible, without bias. The NIM is designed such that a perfect maneuver will place the spacecraft right into the NRHO. Each previous TCM permits the NRHO maneuver magnitude to vary if needed, but all designs yield a deterministic orbit insertion. Navigation and maneuver execution errors will exist, so the spacecraft will not perfectly slip into the NRHO. As the spacecraft drifts away from the NRHO, two insertion correction maneuvers (ICM-1 and ICM-2) will be designed and executed to bring the spacecraft back onto the NRHO: ICM-1 targets a change in velocity that would bring the trajectory back to the reference at the time of ICM-2. Then ICM-2 adjusts the spacecraft's velocity to place the spacecraft immediately onto the NRHO. ICM-2 is nominally two days after NIM; ICM-3 is three days after that.

3. Spacecraft

CAPSTONE is a fully functional spacecraft in a small form factor; see Figure 3. It is a 12U spacecraft with an S-Band antenna sticking out one end (the top-right of Figure 3). It has a mass of 27 kg and fits within a 12U deployer, which is in turn mated to the upper stage of the launch vehicle. The spacecraft is 3-axis stabilized using two redundant inertial measurement units (IMUs), two star trackers, four momentum wheels, and eight reaction control system (RCS) thrusters. Four of the RCS thrusters point down (lower-left of Figure 3) and work together to produce translations with a net thrust of approximately 0.8 N. The RCS system duty cycles each thruster as needed to maintain three-axis stability during maneuvers. The propulsion system is a pump-fed monopropellant hydrazine system with an Isp of approximately 175-200 sec, depending on the pump speed. The spacecraft has two low gain X-band antennas and one high gain X-band antenna for communicating with the ground system. The S-band antenna has its own radio and performs radiometric tracking with the Lunar Reconnaissance Orbiter (LRO). The spacecraft has a chip scale atomic clock (CSAC) for clock stability, which is used for several navigation demonstrations. The spacecraft also has an imager, which has an extended goal of demonstrating optical navigation in several ways.

Figure 3. The CAPSTONE Spacecraft in front of the Moon.

4. Navigation System

One of CAPSTONE's objectives is to advance the state of the art of navigation at the Moon; navigation is at the heart of the mission. The early part of CAPSTONE's mission is all ground-based radiometric navigation: CAPSTONE has an X-band radio that is used to establish two-way coherent radiometric tracking with the Deep Space Network and with Morehead State. The majority of CAPSTONE's tracking has been two-way Doppler, but some has included two-way turn-around pseudonoise (PN) ranging. The ground communication tracking schedule is illustrated in the schedule below.

The ground-based navigation filters estimate the spacecraft state, an SRP scale factor, desaturation and trajectory correction maneuvers, per-pass range biases, stochastic accelerations, and other parameters as necessary. Additionally, there are a number of parameters which are considered – their uncertainties are used to inflate the state covariance, but their values are not solved. These include ground station locations, Solar System GM values, Earth-Moon ephemerides, Earth and Lunar spherical harmonics, earth orientation parameters, and media calibrations.

5. Flight Operations

The CAPSTONE mission timeline is shown in Figure 4, which illustrates the navigation activities that have and are taking place during the mission.

3.1 Launch Operations

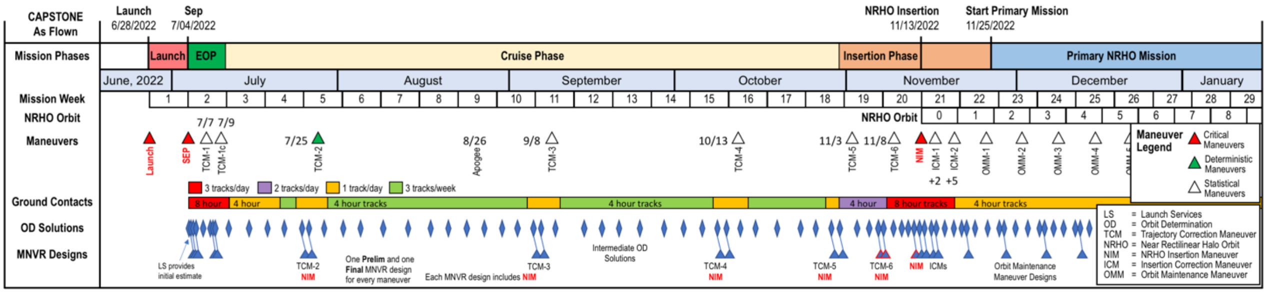

Figure 4. CAPSTONE's Operational Timeline

The launch operations were conducted by Rocket Lab and included a ride aboard an Electron launch vehicle into low Earth orbit, followed by a series of apogee raise maneuvers conducted by a Lunar Photon upper stage. The result was that the CAPSTONE spacecraft was deployed on July 4, 2022 and passed through the Trajectory Interface Point (TIP) within acceptable tolerance.

The CAPSTONE team developed the set of TIP targets and their associated tolerances using a series of Monte Carlos. The set includes the deployment orbital energy, characterized by the launch C3 value at the TIP time, with a tolerance of 0.1 km^2/s^2. The periapse and apoapse radii are not constrained, though it is assumed that the periapse is relatively low, and Rocket Lab's targeted deployment periapse was indeed relatively low. Next, the orbital orientation is specified via Inclination, Argument of Periapse, and the Right Ascension of the Ascending Node, all in Earth-centered EME2000 coordinates. Each of these orientation parameters had a tolerance of 1.0 degrees. The targets vary for every launch opportunity in the launch period; the launch period is illustrated in Figure 5.

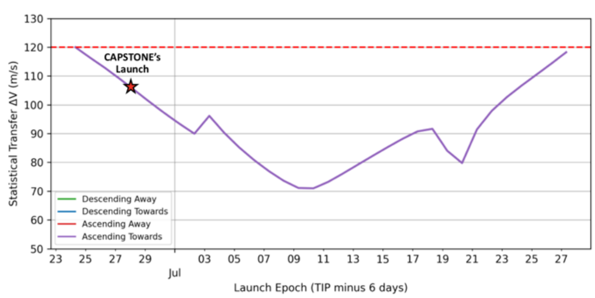

Figure 5. The CAPSTONE Launch Period, extending from late June through July, 2022

CAPSTONE's Electron launch vehicle successfully lifted off on June 28, 2022 and placed the upper stage with CAPSTONE attached into a low Earth orbit. The upper stage autonomously executed two maneuvers to circularize in an orbit about the Earth above the atmosphere. The upper stage then proceeded to execute a series of apogee raising maneuvers, to achieve CAPSTONE's required energy with little finite burn losses.

The TIP targets for the launch opportunity, as well as the estimates provided by Rocket Lab and by the CAPSTONE Navigation team are summarized in Table 1. Rocket Lab used flight data to estimate the separation; CAPSTONE used tracking data collected between July 4 and 7 to produce the estimate.

Table 1. The TIP state targets and estimates produced by Rocket Lab (RL) and the CAPSTONE Navigation team (NAV).

	Target	Tol	RL Estimate	NAV Estimate
Epoch	7/4/22 08:09:38.816 UTC	60 min	7/4/22 07:28:02.012 UTC	7/4/22 07:28:02.012 UTC
C3 (km^2/s^2)	-0.677	0.1	-0.727	-0.693
Inc (deg)	38.979	1.0	39.125	39.151
AOP (deg)	344.523	1.0	344.536	344.552
RAAN (deg)	-37.876	1.0	-38.386	-38.389

3.2 Initial Acquisition

Rocket Lab deployed CAPSTONE on a successful trajectory. Having said that, CAPSTONE's trajectory in space was not precisely where it was predicted to be. Figure 6 illustrates the expectation of the launch vehicle's deployment distribution, as viewed from an observer in Madrid, Spain, approximately 30 minutes after separation at a distance of approximately 17,323 kilometers. One can see that the 3-sigma envelope is far wider than the beam pattern of the 34-m Deep Space Network (DSN) antennas, which have a half-power beamwidth of about 0.033 deg. The width of CAPSTONE's dispersion is partly a result of being close to the Earth.

The DSN and CAPSTONE teams developed search patterns to use to help identify where the spacecraft is in the sky, if the signal were too weak. In flight operations, the signal was deemed too weak. Therefore, two searches were conducted: one coarse and one fine to really identify where the spacecraft was within the search pattern. Figure 7 illustrates the coarse search pattern with the dispersion as it appeared 120 minutes after TIP. The dispersion has rotated since Figure 6 as the trajectories pass over Madrid's zenith. The orange dot is the navigation reconstruction of the trajectory, supporting the DSN's conclusion that Node 7 was near the actual trajectory.

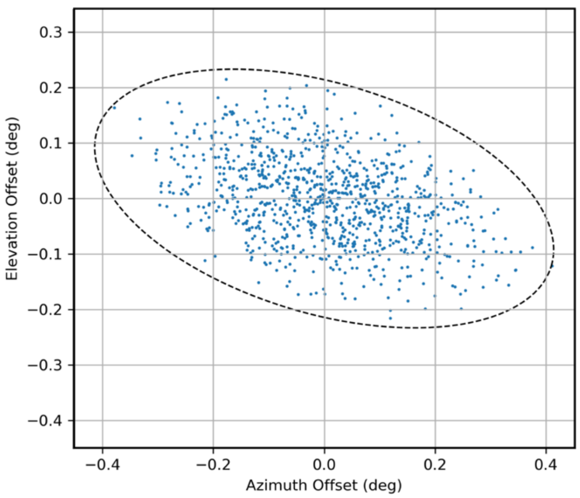

Figure 6. CAPSTONE's expected deployment dispersion, as predicted 12 hours before deployment, viewed from Madrid 30 min after deployment.

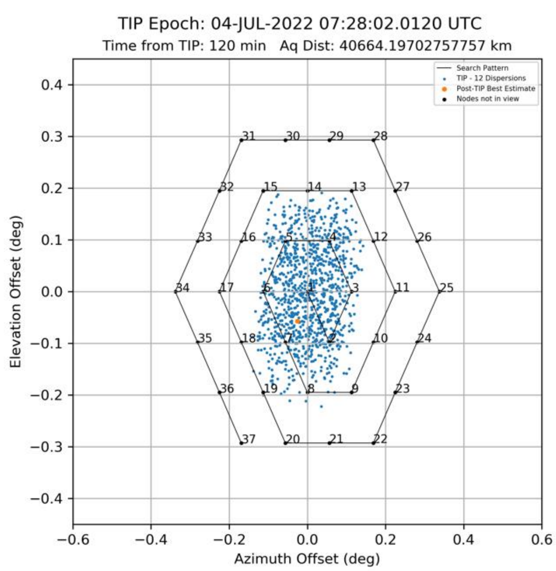

Figure 7. An illustration of the DSN's coarse search pattern for CAPSTONE's initial acquisition.

CAPSTONE was acquired with two antennas within the Madrid DSN complex, DSS-55 was prime and DSS-54 was backup. The primary antenna remained on the best predict available; the backup antenna performed the search patterns and provided substantial flexibility to execute the acquisition of signal. While searching, the DSN identified a 20-dB improvement in the signal through the coarse and fine searches, and the best offset was loaded to the prime antenna. This was a successful demonstration of the DSN's capacity to search and acquire a spacecraft within an expected deployment dispersion.

Approximately 90 minutes after separation, Rocket Lab had a better estimate of the actual deployment state of CAPSTONE and delivered it to the CAPSTONE Nav team. Since the DSN was tracking the signal well, it was determined that the DSN would not replace the frequency profile of its current working trajectory with the new one, in order to maintain constant communication with the spacecraft, but the spatial pointing of the prime antenna would be updated to the new trajectory predict.

The CAPSTONE Navigation team produced the first official post-separation solution, od001, using the first two hours of Madrid tracking, which yielded a good trajectory predict for the backup antenna to use, in case the prime antenna began drifting away from the spacecraft.

The sequence of activities focused on navigation that CAPSTONE experienced during initial acquisition is summarized as follows. Numerous spacecraft activities were executed that were unrelated to the navigation and hence excluded from this timeline.

- 7:18 UTC: Rocket Lab confirms CAPSTONE is deployed. The CAPSTONE vehicle performs its power-on sequence, detumbles, and initializes communications.
- 8:00 UTC: DSN confirms downlink of CAPSTONE's signal.
- 8:08 UTC: DSN gives readiness to begin commanding. Two-way communication proceeds. The connection experiences periodic drops and losses of lock. It is determined that CAPSTONE is in a null between the main lobe and a side lobe.
- 8:37 UTC: DSN begins coarse search on backup antenna. This requires 25 minutes to complete.
- 9:30 UTC: DSN begins fine search on backup antenna.
- 10:10 UTC: DSN determines that Offset Node 7 yields the best signal (20 dB improvement). DSN loads that offset onto the prime antenna, keeping backup centered on the reference predict.
- 10:50 UTC: DSN loads the post-separation predict onto the prime in pointing only, maintaining signal lock.
- 11:35 UTC: od001 delivered and loaded to the backup antenna.
- 11:57 UTC: CAPSTONE performs the first of two thruster tests, pulsing all 8 thrusters and consuming 1-2 mg of propellant.
- 12:20 UTC: CAPSTONE performs the second thruster test, firing three pairs of thrusters.
- 14:28 UTC: od002 delivered, including estimates through thruster tests.

- 16:27 and 16:39 UTC: observed two small shifts in Doppler, attributed to outgassing.
- 18:35 UTC: Goldstone track begins; Goldstone uses the od002 predict.
- 18:55 UTC: Madrid track ends.

3.3 Communications Anomaly

The DSN handed commanding from Madrid to Goldstone at 18:45 UTC, which differed only in two ways: first, the uplink power was increased from 200 W, used with Madrid at close ranges, to 1 kW; second, the pass was configured to include ranging. Once the handover was complete, the spacecraft ceased providing command receipt verifications. After about 35 minutes, the power was reduced back to 200 W and commands immediately began being received and verified. However, a configuration error on the radio produced erratic Doppler shifts that were unusable from a navigation perspective – the radio had lost coherency and was not turning around the signal at the exact correct ratio. A series of cascading events caused an anomaly on the spacecraft and the signal disappeared.

The CAPSTONE team set up an anomaly resolution process to work out what caused the loss of signal and how to recover. Meanwhile the navigation team continued to work with the DSN to search for any trace of CAPSTONE's signal in a wide range of frequencies and angular dispersions. Over the next day the spacecraft team worked out how to recover the radio while the navigation team continued to examine the tracking data. Fortunately, the navigation team was able to conclude that the trajectory uncertainty confidently fell within the DSN's 34-m beamwidth for the subsequent week, saving the DSN efforts at continued angular searches. Simultaneously the spacecraft team identified the source of the anomaly.

On July 6, 2022, after 43 hours of silence, the spacecraft autonomously restarted the radio and the DSN reacquired the signal. The spacecraft was located exactly where the predictions expected it and the spacecraft was healthy. The radio was reconfigured and tracking resumed and has continued successfully to the time of this paper.

The navigation plan called for od001 to include 2-3 hours of Madrid tracking data, od002 to include approximately 5 hours of tracking, and then od003 would wait until a data cutoff that included at least two hours of tracking on Goldstone. Without Goldstone tracking data, and in the presence of the anomaly, the NAV team built od003 using all of the Madrid tracking data in an effort to provide the best possible estimate of the spacecraft's trajectory.

Figure 8 illustrates the Doppler residuals as the spacecraft was re-acquired after the anomaly, showcasing just how small the Doppler residuals were compared to this od003 delivery; the single track of Madrid Doppler data even with thruster commissioning and outgassing was sufficient to predict CAPSTONE's location in space for a long time. Figure 9 illustrates the Doppler residuals after processing the same tracking data shown in Figure 8, which amounted to od006.

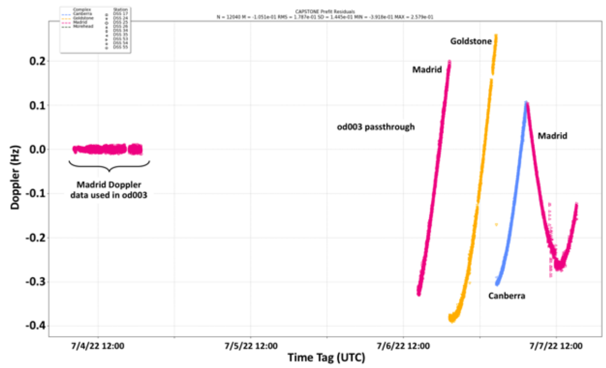

Figure 8. The od003 passthrough; the Madrid Doppler data on the left produced od003; the residuals shown on the right illustrate how small the Doppler errors were using od003.

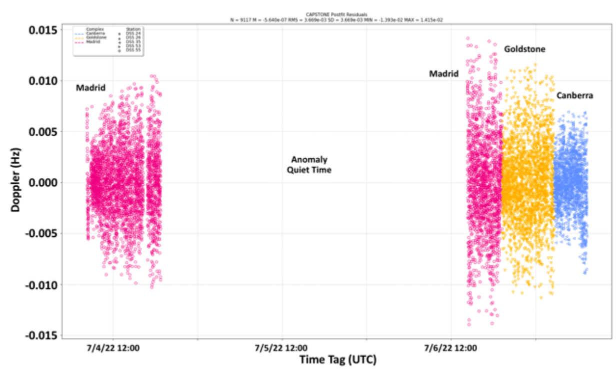

Figure 9. The postfit Doppler residuals after processing od006, including these tracking arcs.

3.4 Design and Execution of TCM-1

CAPSTONE scheduled its first trajectory correction maneuver, TCM-1, to be performed 30 hours after deployment; the sooner the better to correct energy errors in the deployment trajectory. Figure 10 illustrates the timeline of navigation activities leading up to TCM-1. This was developed with the DSN and spacecraft team with the following logic:

- All early DSN tracks would be supported by an orbit determination (OD) delivery at least two hours earlier. Hence, od002 supports the Goldstone pass; od004 supports the Canberra pass; etc.
- The preliminary TCM-1 design would use a data cutoff that included at least two hours of tracking on Goldstone.
- Each maneuver design would have at least two stations to uplink it for redundancy.

Given these rules, the preliminary and final TCM-1 designs were ready after 20 hours of operations. This permitted time for a *Late Update* design as well, reviewing the tracking from Canberra to see if the design needed a final update, albeit with fewer redundancies built in.

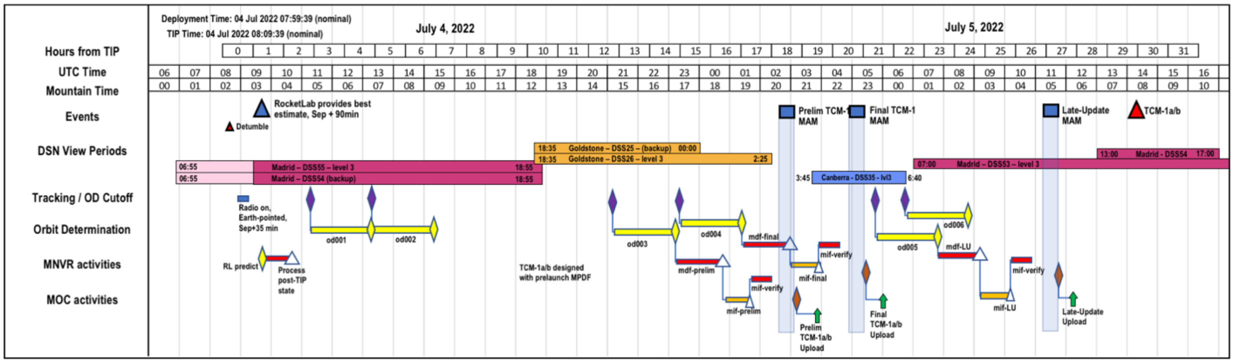

Figure 10. The navigation activities that were scheduled to take place to support TCM-1.

The communications anomaly delayed TCM-1 from being executed July 5 14:10 UTC to July 7 15:30 UTC, yielding a 49-hour delay from the original time. The same strategies were employed to ensure that the navigation solutions were sound.

The Delta-V cost of TCM-1 is directly dependent on the launch vehicle deployment error and the time between the trans-lunar injection and TCM-1. The errors experienced with CAPSTONE were well within the tolerance, so the size of TCM-1 was well within the budget. The TCM-1 maneuver was also a great demonstration of the main engine and would become a source of calibration of the system. Thus, it was desirable to ensure TCM-1 was larger than 2 m/s but no larger than 20 m/s, since the system was not yet calibrated and could add large errors. Thus, the expected design logic flowed as follows:

- If TCM-1 is < 2 m/s, delay TCM-1 until > 2 m/s
- If TCM-1 is 2-10 m/s, execute it in one maneuver.
- If TCM-1 is 10-20 m/s, execute it in two pieces: the first performs ~90% and the second finishes the maneuver and cleans up error of the first half.
- If TCM-1 is > 20 m/s, execute it in three pieces. The first ~90% is executed in two equal halves with little time separation between them; then a third piece is executed two days later to clean up errors and finish the maneuver.

Thus, TCM-1a and TCM-1b are the first two pieces, where TCM-1b is often not used; TCM-1c is executed two days later if needed.

Table 2 summarizes the evolution of the size and design of TCM-1 as the mission took place. CAPSTONE had several pre-separation predictions, including one at TIP-63 hours and one at TIP-12 hours. Those were pretty steady. Then the trans-lunar injection maneuver produced maneuver execution errors that introduced further error in the trajectory. The post-separation errors include those and spring deployment mismodeling.

Table 2. The evolution of the TCM-1 design as information arrived.

Traj	Notes	TCM-1 Design
TIP-63 hr predict	Early predict about the expected separation state	8.69 m/s
TIP-12 hr predict	Official prediction pre-separation	8.68 m/s
SEP+90 min	Post-separation predict using a single maneuver	15.23 m/s
od001	TCM-1 executed as a single maneuver at TIP+30 hrs	15.39 m/s
od002	TCM-1 executed as a single maneuver at TIP+30 hrs	15.28 m/s
od002	TCM-1 executed as a single maneuver at TIP+54 hrs	18.90 m/s
od003	TCM-1 executed as a single maneuver at TIP+79 hrs	22.28 m/s
od004	TCM-1 prelim design, executed as TCM-1a and TCM-1c (on 7/9/22)	1a: 20.00 m/s 1c: 1.92 m/s

TCM-1a was executed on 7/7/2022 at 15:30 UTC, commanded to execute 20.00 m/s; TCM-1b was cancelled. Post-maneuver OD estimates TCM-1a achieved approximately 19.81 m/s of Delta-V. Additional commissioning activities ended up delaying TCM-1c to 7/12/2022, though with very minimal cost. Given the maneuver execution error and a re-optimization of TCM-1c, TCM-2, and NIM, the design of TCM-1c ended up being 1.62 m/s in size.

After all activities transpired, the delay in TCM-1 of 49 hours increased the TCM-1 cost from approximately 15.4 m/s to a total of 21.6 m/s, including TCM-1a and TCM-1c.

3.5 Entering Cruise

With TCM-1a and TCM-1c successfully executed, the spacecraft entered its cruise phase along the ballistic lunar transfer. Figure 11 illustrates the ground contact schedule that was realized through the end of July.

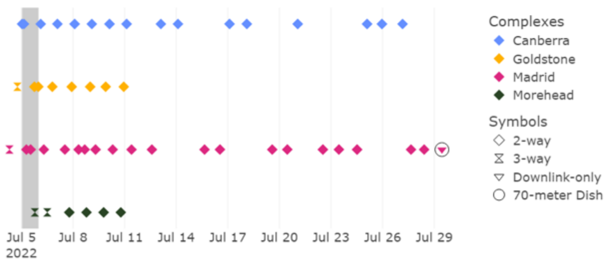

Figure 11. CAPSTONE's early ground contact schedule.

The cruise along the ballistic lunar transfer requires a much lower cadence of ground contacts than early operations, dropping down to as few as two contacts per week. The ground contact schedule is enhanced to one contact per day for a week around each maneuver, including TCM-2, which was scheduled for July 25.

3.6 TCM-2

CAPSTONE's second TCM, TCM-2, is the only deterministic correction maneuver on the cruise, which provides for an extended launch period. TCM-2 was part of the optimization of TCM-1, so its design changed throughout CAPSTONE's flight. Table 3 summarizes the evolution of the TCM-2 design.

Table 3. The evolution of the TCM-2 design as information arrived.

Traj	Notes	TCM-2 Design
Pre-launch	Pre-launch deterministic component	37.83 m/s
TIP-63 hr predict	Early predict about the expected separation state	36.96 m/s
TIP-12 hr predict	Official prediction pre-separation	36.96 m/s
od002	TCM-1 executed as a single maneuver at TIP+30 hrs	37.78 m/s
od003	TCM-1 executed as a single maneuver at TIP+79 hrs	38.49 m/s
od005	Final TCM-1a design	39.26 m/s
od008	Final TCM-1c design	40.18 m/s
od011	Final TCM-2 design	2a: 19.94 m/s 2b: 20.18 m/s

The final TCM-2 design was a net Delta-V of approximately 40 m/s, optimized to minimize the total amount of fuel spent, including TCM-2, TCM-3, and NIM, where all design features of TCM-2 and TCM-3 could vary, as well as the maneuver magnitude of NIM. The TCM-2 design shown here includes a small 0.28 m/s TCM-3, and small adjustments in NIM.

It was determined to break TCM-2 into two halves: TCM-2a and TCM-2b, each approximately 20 m/s. Each of these would also be a dress rehearsal for NIM, since they are almost the same size. Each of these halves was executed as a critical maneuver in order to exercise all functionality of the flight software to conduct a critical maneuver.

The Doppler residuals of the tracking data yielding the TCM-2 design are shown in Figure 12.

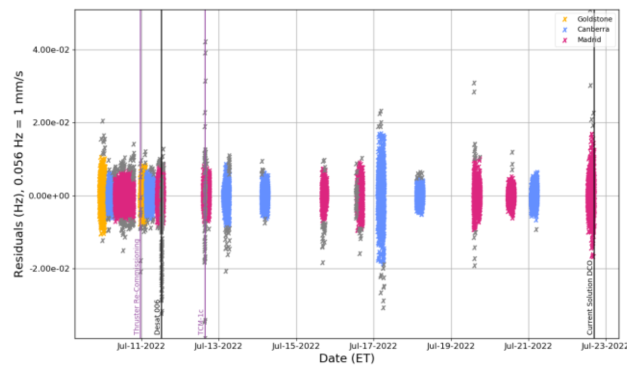

Figure 12. The Doppler residuals for the ground tracking arcs that led to the design of TCM-2.

TCM-2a and TCM-2b executed nominally on July 25, 2022 and the spacecraft continues to operate well en route to TCM-3.

6. Navigation Details

CAPSTONE has encountered a number of challenges and solved each puzzle to the point that the residuals are clean, Gaussian stochastics. Each is addressed here.

6.1 Propulsion System Bake-off

The CAPSTONE navigation team noticed even in the very first pass that the residuals after the propulsion system performed a firing (desaturation, commissioning, or later translational maneuvers) would not sit still for some time. The first pass was not enough time to work out all of the details, especially in the presence of outgassing. The tracking passes after TCM-1a and TCM-1c provided the first real look at this, and TCM-2 confirmed it. The hydrazine propulsion system left some small residual hydrazine in the system, such that after a maneuver was complete, a small amount of hydrazine would continue decomposing in the system and continue propelling the spacecraft. This has been referred to as the hydrazine bake-off and requires a small filter modification to support cleanly. This effect is also seen in spacecraft telemetry as an unexpected accumulation of momentum in the hours after the thrusters are used.

Any time the propulsion system is used above and beyond a desaturation maneuver, the navigation team adds stochastic acceleration parameters in the Body-X direction (corresponding with the translational direction). They are only estimated in the Body-X direction because CAPSTONE slowly rotates about the X boresight, averaging out perturbations in the Y and Z direction. It has been observed that the stochastic acceleration parameters often estimate to non-zero values for as much as 12 hours after a maneuver. Thus, stochastic acceleration parameters are added with a batch size of one hour for 12 consecutive hours. For TCM-2, the stochastics are only added after TCM-2b. This does add more parameters to the filter, but the solutions clearly benefit with the addition.

6.2 Communications Anomaly

The communications anomaly was clearly a challenge, and navigation could not be discounted as the culprit until proven so. This was accomplished in a number of ways. First, the initial Madrid tracking data fit incredibly well, especially after the stochastic acceleration parameters were introduced. Second, after very close scrutiny, 90 seconds of tracking data on Goldstone was discovered once the commanding sequences were closely studied; it is believed that those 90 seconds include proper, coherent, two-way Doppler measurements and they fit the od003 passthrough as expected. Third, the data on Goldstone other than those 90 seconds was scrutinized and believed to not valid coherent two-way data due to offsets of multiple kHz in the returned signal compared to the expected values, which helped assuage concerns that the solution simply was not fitting otherwise correct tracking data. Once all of these artifacts were compiled then the navigation team could relax to some degree with the understanding that the navigation solution was as well constructed as possible.

6.3 Solar Radiation Pressure

The early filter setup solved for a solar radiation pressure (SRP) scale factor that was well below a value of 1.0, indicating that some physical characteristic in the SRP model was incorrect. The navigation team worked with the spacecraft team and compiled evidence to suggest that one solar panel did not immediately deploy fully. Upon executing further deployment exercises and tests, the SRP scale factor jumped to a value very close to 1.0. The spacecraft team corroborated the hypothesis that the solar panel completed its deployment. This experience further supported close communication between all teams to compile all evidence to understand the state of the spacecraft.

6.4 Morehead Configurations

CAPSTONE is the first spacecraft to navigate beyond the orbit of the Moon using tracking data provided by the Morehead State ground station, DSS-17. As such, Morehead needed some configuration updates, including an update to its location on Earth and updates to media calibrations, which are provided by the DSN for DSN complex, but not for Morehead State University. Advanced Space produces media calibrations to support the radiometric tracking with DSS-17, and Advanced Space has estimated its position with new precision. Periodic updates to the station location and unique processing configurations have been provided to secondary payloads on Artemis-I, some of which will heavily rely on DSS-17 for navigation.

6.5 Mass Tracking

The CAPSTONE mission has been consuming mass at a rate within expectations. The detumble from the launch vehicle required approximately 1.5 mg of propellant; each of the two early thruster tests consumed 1-2 mg of propellant; each desaturation event has consumed a small amount of propellant. Figure 13 illustrates the as-flown mass estimate over time, tracked with the prelaunch mass allocations. The prelaunch mass allocations amount to the mass drops in a DV99 sense.

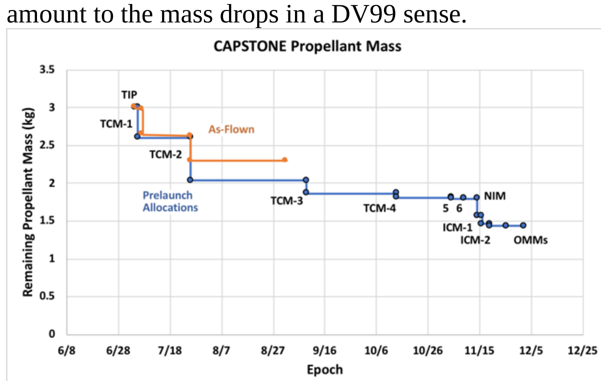

Figure 13. The mass of the remaining propellant onboard CAPSTONE over time.

7. Discussion

The CAPSTONE mission has demonstrated the value in taking a BLT to the Moon from an operational perspective. CAPSTONE has maintained very low operational cost and has avoided high-risk situations by having the time to properly assess issues as they arise. The communication anomaly may have ended the mission if CAPSTONE were on a direct transfer to the Moon, but as it was, CAPSTONE only expended a small amount of additional Delta-V to catch up after the anomaly. CAPSTONE has executed the majority of its Delta-V to transfer to the Moon: only small navigation adjustments remain to reach the NRHO insertion.

8. Conclusions

CAPSTONE is pathfinding the mission design and navigation for missions to the lunar NRHO in support of

NASA's Gateway and all missions that support this exploration. CAPSTONE has already demonstrated many key benefits of the Ballistic Lunar Transfer (BLT) and is en route to demonstrating the delicate insertion into the NRHO. The routine operations within the NRHO will follow, further paving the way for Gateway and others.

Acknowledgements

The CAPSTONE team is indebted to NASA's Small Spacecraft Technology Program and specifically to Chris Baker, Elwood Agasid, and Roger Hunter at NASA for their support. Special thanks to Diane Davis and her team for the two-way support with NASA's Gateway program.

References

[1] Parker, J. S. & Andersonn, R. L., "Low-Energy Lunar Trajectory Design," (John Wiley and Sons, 2014).

[2] Parker, J. S., "Low-Energy Ballistic Lunar Transfers," *University of Colorado Boulder*, 2007.

[3] Howell, K. C., Breakwell, J. V. "Almost Rectilinear Halo Orbits," *Celest. Mech,* 1984.

[4] Zimovan, E. M., Howell, K. C. & Davis, D. C. "Near Rectilinear Halo Orbits and Their Application in Cis-Lunar Space." in Advances in the Astronautical Sciences (2017). doi:10.1111/j.1744- 6171.2010.00231.x

[5] Parrish, N. P., Kayser, E., Udupa, S., Parker, J. S., Cheetham, B. W., Davis, D. C., "Survey of Ballistic Lunar Transfers to Near Rectilinear Halo Orbit," AAS 19-740.

[6] Davis, D., C., Khoury, F. S., Howell, K. C., Sweeney D. J., "Phase Control and Eclipse Avoidance in Near Rectilinear Halo Orbits," *AAS Guidance Navigation and Control Conference, Breckenridge, CO,* 2019. AAS 20-047.

[7] Williams, J., Lee, D. E., Whitley, R. J., Bokelmann, K. A., Davis, D. C., Berry, C. F. "Targeting Cislunar Near Rectilinear Halo Orbits for Human Space Exploration," AAS 17-267.

[8] Davis, D. C., S. A. Bhatt, K. C. Howell, J. Jang, R. L. Whitley, F. D. Clark, D. Guzzetti, E. M. Zimovan, and G. H. Barton, "Orbit Maintenance and Navigation of Human Spacecraft at Cislunar Near Rectilinear Halo Orbits," *27th AAS/AIAA Space Flight Mechanics Meeting, San Antonio, Texas*, February 2017.

[9] Guzzetti, D., E. M. Zimovan, K. C. Howell, and D. C. Davis, "Stationkeeping Methodologies for Spacecraft in Lunar Near Rectilinear Halo Orbits," *AAS/AIAA Spaceflight Mechanics Meeting, San Antonio, Texas*, February 2017.

[10] Newman, C. P., D. C. Davis, R. J. Whitley, J. R. Guinn, and M. S. Ryne, "Stationkeeping, Orbit Determination, and Attitude Control for Spacecraft in Near Rectilinear Halo Orbit," *AAS/AIAA Astrodynamics Specialists Conference, Snowbird, Utah*, August 2018.

[11] Parrish, N. L., Bolliger, M. J., Kayser, E. K., Thompson, M. R., Parker, J. S., Cheetham, B. W., Davis, D. C., Sweeney, D. J., "Near Rectilinear Halo Orbit Determination with Simulated DSN Observations," *AIAA Scitech 2020 Forum, Orlando, FL,* January 2020. AIAA 2020-1700.

[12] J. S. Parker, J. Smith, A. Forsman, C. Rabotin, C. Cain, and B. Cheetham, "The Cislunar Autonomous Positioning System (CAPS)," *42nd Annual AAS Guidance and Control Conference, Breckenridge, CO*, 2019. AAS 19-094.

[13] Davis, D. C., Boudad, K. K., Phillips, S. M. & Howell, K. C. "Disposal, Deployment, and Debris in Near Rectilinear Halo Orbits," *AAS/AIAA Astrodynamics Specialist Conference*, 2019