The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE): A Summary of a Highly Successful Mission Currently Operating in the Cislunar Environment

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Delivering Innovation to Orbit™

CAPSTONE Mission Summary

What is CAPSTONE?

- A 12U CubeSat that will serve as the first spacecraft to enter into the Near Rectilinear Halo Orbit (NRHO) destined for Gateway, the Moon- orbiting outpost that is part of NASA's Artemis program.
- CAPSTONE is the first CubeSat to fly in cislunar space.
- Successfully launched on June 28th @ 5:55AM EDT aboard a 3-stage Rocket Lab Electron rocket from Mahia, NZ.
- ~4 months in deep space to arrive at its target insertion into the NRHO via a low-energy, deep space transfer.
- Insertion into the NRHO occurred on November 13, 2022. In the NRHO now for 203 days.
- Successfully completed the Primary Mission Phase (6 months in the NRHO) and completed 2 of 3 primary objectives.
- Scheduled to orbit this area around the Moon for another 12+ months to understand the characteristics of the orbit and perform additional technology demonstrations.
- Helping reduce risk for future spacecraft by validating innovative navigation technologies and verifying the dynamics of the NRHO.

CAPSTONE Mission Objectives

CAPSTONE

1) Validate and demonstrate NRHO/three-body Earth-Moon operations.

Objective 1 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 will include demonstrating navigation capabilities and validating station keeping simulations. **Complete**

2) Inform future lunar exploration requirements and operations such as for the Artemis Lunar Gateway.

Objective 2 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 will include the establishment of commercially available capacity to support NASA, commercial, and international lunar missions in the future. **On track**

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

Objective 3 is focused on demonstrating core technical components of the Cislunar Autonomous Positioning System (CAPS) in an orbital demonstration. This objective will include collaboration with the operations team at NASA Goddard Space Flight Center to demonstrate inter-spacecraft ranging between the CAPSTONE spacecraft and the Lunar Reconnaissance Orbiter in operation at the Moon. In addition to demonstrating key inter-spacecraft tracking, CAPSTONE will also enhance the technology readiness level of the CAPS software. **On track**

CAPSTONE Mission Timeline

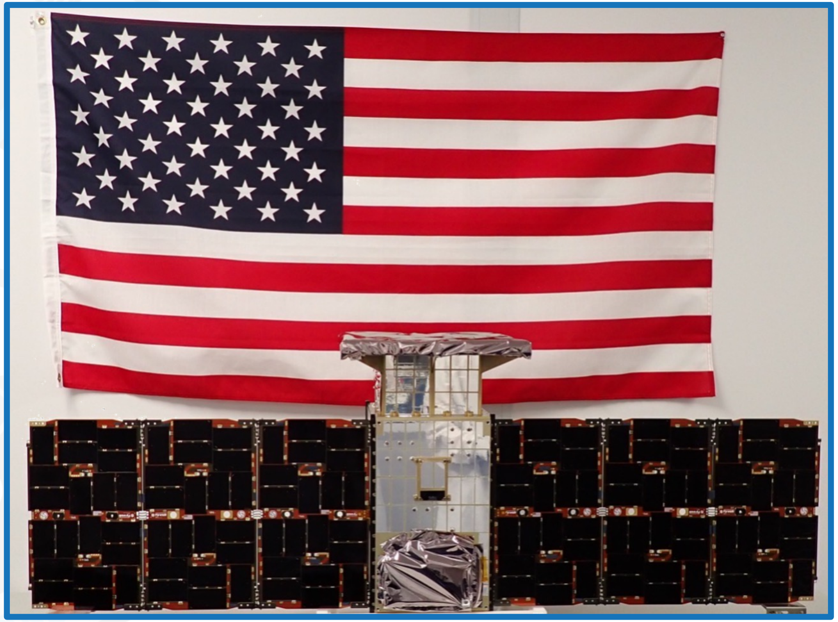
Months from Launch

Today: 6/6/23

1 2 3 4	5 6 7 8 9 10	11 12 13 14 15 16 17 18 19 20 21 22	23 24 25
L + 4 months: • Launch to LEO • Orbit raising • BLT & insertion into NRHO by CAPS-TONE S/C	• L + 5-10 months: Conduct primary demonstration operations for 6 months • NRHO operations and flight dynamics assessment • CAPSTONE to LRO cross-link experiment • One-way ranging with the CSAC	L + 10-22 months: Conduct technology enhancement operations for 12 months • Perform additional NRHO operations and autonomous system evaluation • Continued CAPSTONE to LRO and 1-way ranging experiments • Increase fidelity of CAPS system demonstration • Detailed demonstration of a one-way ranging experiment with the Chip Scale Atomic Clock (CSAC)	Possible follow-on Ops with other NASA or commercial assets End of mission (EOM) - Spacecraft disposal

CAPSTONE Spacecraft in Flight Configuration

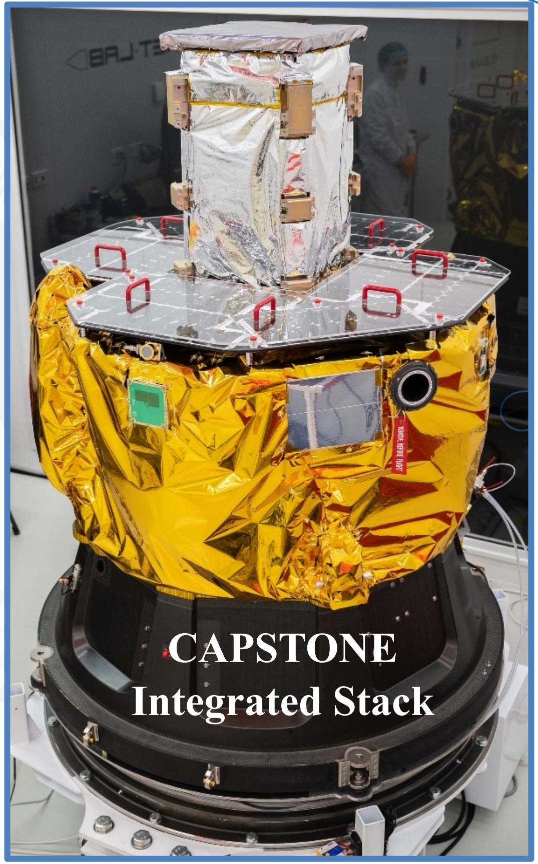
Subsystem	Value
Battery Modules	QTY 3x, 182 W-hr storage
Solar Panels	Deployable Fixed Angle Arrays, Peak Power 114W (BOL), 120 XTJ Prime cells
Space / Ground Radio	Iris Radio, 3.8W, operating at 8.45 GHZ downlink, 7.19 GHz receive
Space / Ground Antennas	X-band high gain & low gain patch antennas, on 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



Rocket Lab Launch Support

Launch from LC-1, Mahia NZ

ROCKETLAB CAPSTONE



CAPSTONE Launch – Mahia, NZ

June 28, 2022, 2:55 AM PDT

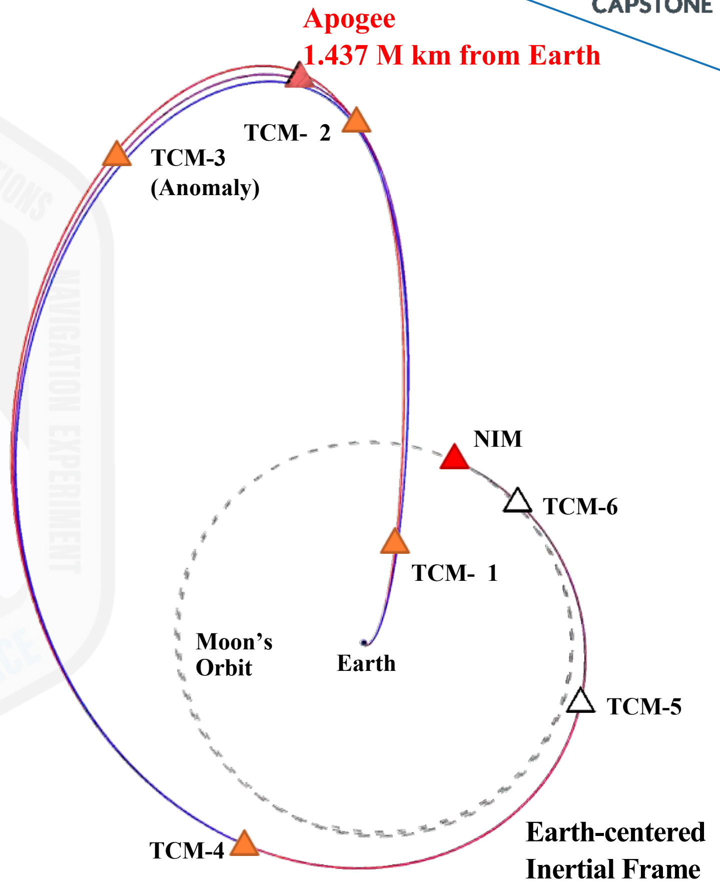
Initial Acquisition and LOS Anomaly

- Confirmation of downlink signal ~40 min after deployment on DSN Madrid
- Spacecraft detumbled and commissioned successfully
- Hand-off to Goldstone was successful
- **Minutes later lost signal on 04 July 2022 19:55 UTC**
- MOC continuously sent commands in the hope that something would get through
- DSN executed search pattern
- OD team processed navigation data to determine best DSN antenna pointing
- 06 July 2022 13:24 UTC – 2 days after LOS spacecraft performed an autonomous desaturation maneuver
- **Change in state machine allowed radio to reset and carrier lock re-achieved**
- Telemetry showed healthy spacecraft – nominal operations resumed
- **Root Cause of Anomaly**
  - Mis-formatted "peek" command sent to spacecraft during attempt to confirm status of PN regenerative ranging
  - Vulnerability in IRIS radio software led radio to lock-up and become unresponsive due to this command (has since been fixed)
  - Fault Detection, Isolation and Recovery (FDIR) was in place to detect and resolve the issue seen on the IRIS but a FSW issue in the FDIR prevented autonomous recovery

Low Energy, Ballistic Lunar Transfer (BLT)

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



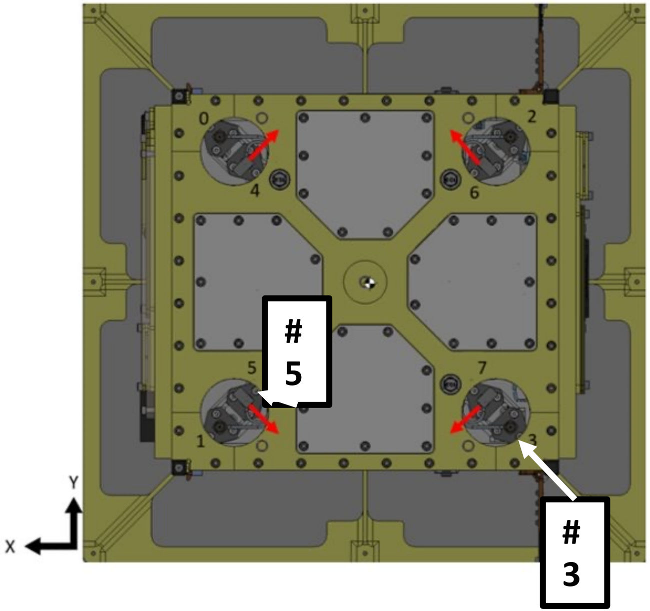
Stuck "Open" Thruster Anomaly – 9/8/23

- TCM-3 executed nominally
- During "braking" phase spacecraft spun up due to stuck "open" thruster
- Burn abort tripped due to excessive rates
- Spacecraft goes into safe mode
- Vehicle settled at rotation of ~70°/sec, pointing ~77° from the Sun
- Repeating ~5 min lock, ~50 min loss cycle as spacecraft charged enough to power on radio then lost power
- Propellant freezes (tank temp at -7C)
- Spacecraft team load sheds – able to run heaters enough to unfreeze the propellant after several weeks

Recovery – 10/12/23

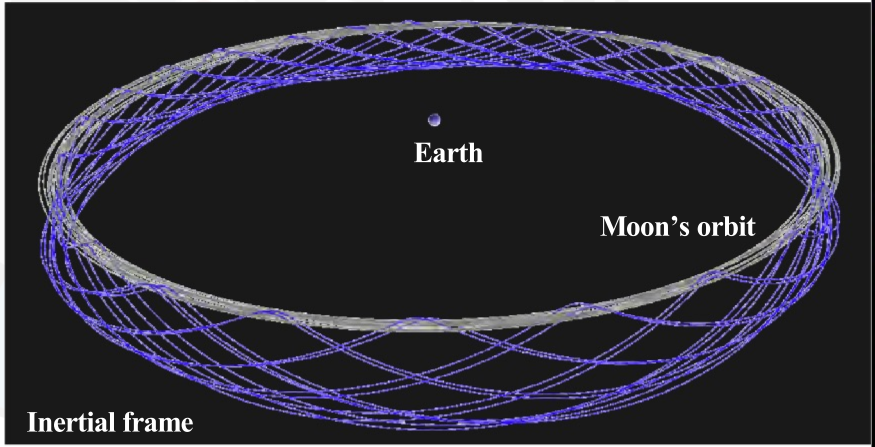
- With propellant unfrozen, the prop system was tested
- Spin rate increased to 105 deg/sec
- Narrow down stuck thruster to #3 (axial) or #5 (rotational)
- Terran Orbital GNC team builds detumble controller that is robust to stuck open thruster
- Oct-7 – Detumble maneuver completed successfully, regain constant communication with ground
- Oct-11 – Pressurization test executed to conclusively determine thruster #3 was stuck
- CAPSTONE completed >500k rotations during the anomaly!

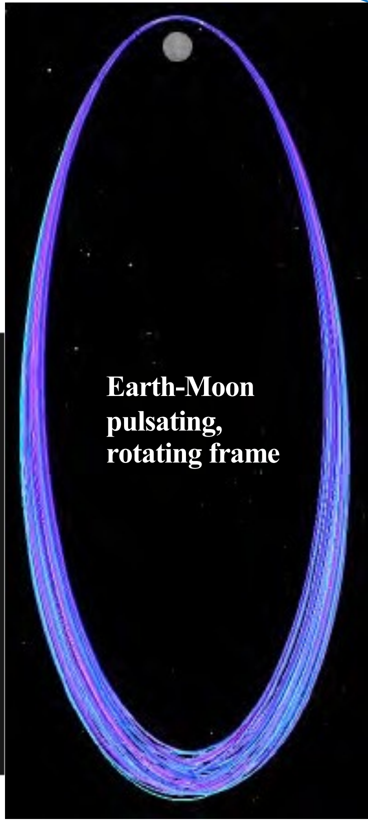
Red arrows show Thrust Vector



Near Rectilinear Halo Orbit (NRHO)

- The NRHO is the baselined plan for NASA's Gateway.
- This quasi-stable orbit minimizes the propellant required for orbit maintenance.
- Offers a continuous view of Earth
- Avoids and/or minimizes eclipses
- Provides coverage of both the lunar North and South Poles
- Orbital period ~6.5 days
- Perilune ~3,500 km
- Apolune ~71,000 km
- 9:2 Moon-Sun resonant orbit





Operations Status – 6/6/23

Currently in NRHO

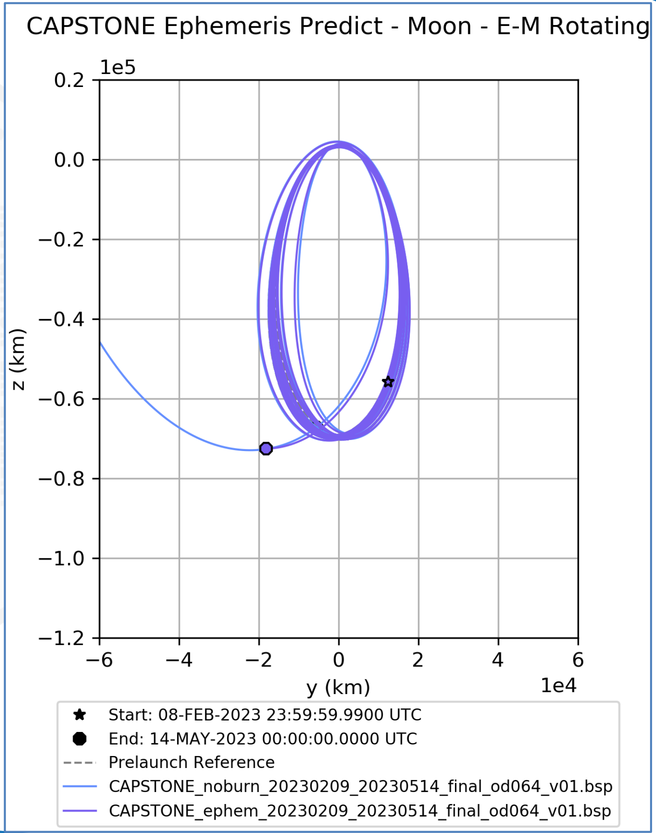
- Due to minimum maneuver magnitude threshold, only needed to execute OMMs 5, 10, 13, 18, 20, 21, 22, 26,28
- No issues through eclipses (6 thus far): ~60-75 min each.
- Executed 3 CAPS attempts
- Have reduced DSN passes – needed fewer than one a day

Milestones:

- Executed 69 OMMs to maintain NRHO
- Performed 3 CAPS Crosslink attempts with LRO

Upcoming events

- Next CAPS Crosslink attempts planned in mid-June
- CSAC one-way ranging navigation demonstration in mid-June



OMM Design Performance thru OMM-20

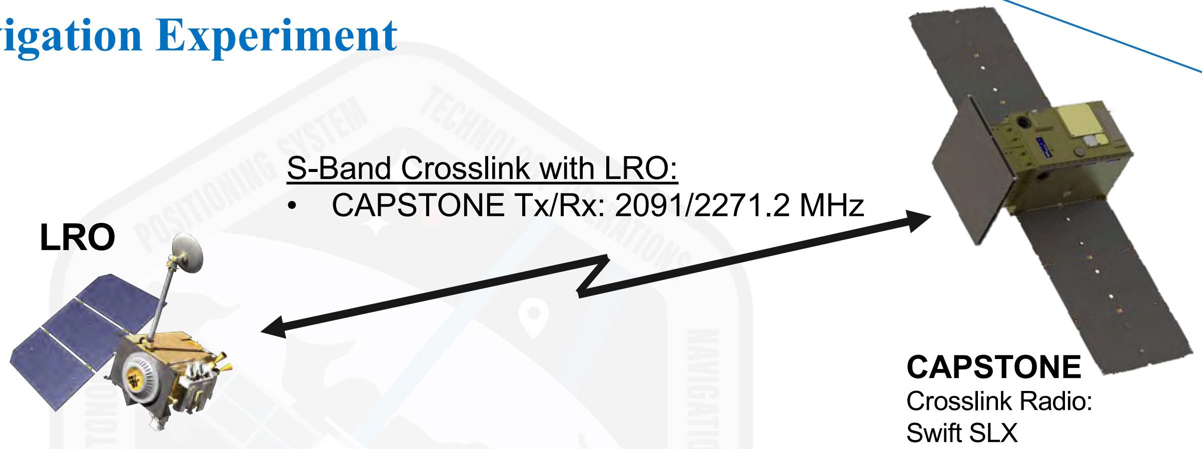
OMM	Design (m/s)	Reconstruction (m/s)
1-4	0.0503	Skipped
5	**0.6192**	**0.6337 +/- 3.439e-3**
6-9	0.2492	Skipped
10	**0.3143**	**0.3203 +/- 1.242e-6**
11-12	0.2062	Skipped
13	**0.1868**	**0.1852 +/- 3.734e-6**
14-17	0.3224	Skipped
18	**0.4499**	**0.4273 +/- 0.01493**
20	**0.1553**	**0.1654 +/- 2.218e-3**

OMM Design Process:

- Does the OMM, as designed, achieve the targets?
- Does the performing the OMM keep CAPSTONE in the NRHO longer than if skipped?
- 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)
- Despite skipping many OMMs, the stationkeeping strategy keeps the spacecraft near the design reference

CAPSTONE CAPS Demonstration

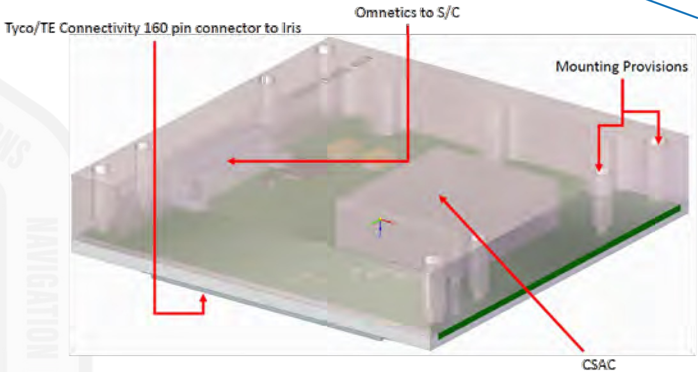
Autonomous Absolute Navigation Experiment



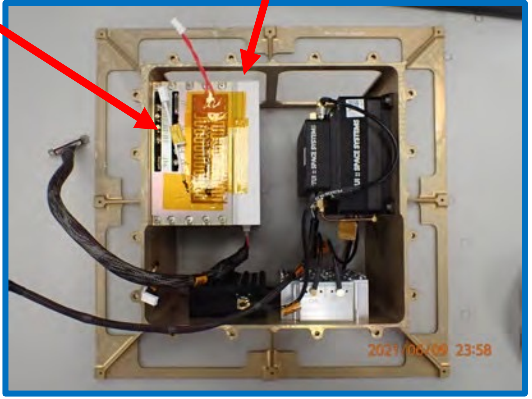
- The cross-link experiment between CAPSTONE and the LRO spacecraft will evaluate ranging capability.
- The Cis-Lunar Autonomous Positioning System (CAPS) will be demonstrated for lunar missions to utilize automated navigation solutions to reduce ground segment burden and enhance future mission operations.
- To date, CAPSTONE has performed 3 ranging passes with the LRO spacecraft in order to generate absolute estimates of spacecraft position and velocity.
- Results thus far have been uneven but promising. Working to adjust the CAPSTONE S-Band radio modulation and the ranging signal to get better measurements.

CSAC 1-Way Ranging Experiment

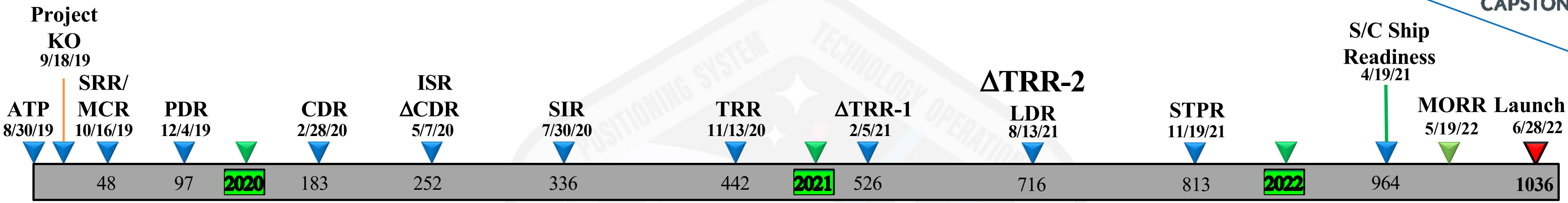
- A **Chip Scale Atomic Clock (CSAC)** has been added to Iris X-Band radio in order to support a 1-Way ranging experiment during the CAPSTONE mission.
- Collaboration with JPL to develop the Iris interface to the CSAC
- JPL has tested the ranging function and the firmware interface in their Iris testbed.
- Tyvak completed the integration of the CSAC board package, the Iris transponder and the spacecraft SW interface in July 2021.
- Advanced Space developed the 1-way ranging (uplink) navigation measurement processing software and delivered the flight SW for test in October 2021
- Goal/plan is to test the 1-way ranging with the CSAC/Iris (DSN to spacecraft) during the enhanced mission phase.



CSAC Board Package



CAPSTONE Development Timeline



1. Baseline schedule at ATP: 548 days (18 months)
2. Re-baseline 1 : 655 days (22 months) - Launch Vehicle Readiness, Spacecraft HW Development Issues
3. Re-baseline 2 : 782 days (26 months) - Launch Vehicle Readiness, Spacecraft HW Development Issues
4. Re-baseline 3 : 933 days (30 months) - Launch Vehicle Readiness, Spacecraft Testing
5. Re-baseline 4 : 974 days (32 months) - Launch Vehicle Readiness, Spacecraft Testing
6. Re-baseline 5: 1036 days (34 months) - Launch Vehicle Readiness, Spacecraft Testing Close-out

Fully 8 months of the ~16-month launch delay were due to **complications due to COVID**: Supply chain, personnel, launch vehicle upper stage testing and development. The remaining 8 months are due to **risk realizations** for the spacecraft and launch vehicle HW development and implementation.

CAPSTONE: Key Lessons Learned – 1 of 2

- 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.)
    - Low-cost, CubeSat missions often rely on COTS components and alleged "plug and play" designs that are often not as developed as advertised.
    - A clear understanding of the unique requirements vs. capabilities for a unique mission needs to be better defined and detailed out BEFORE schedules and budgets are estimated and agreed to.
    - Ground system requirements and operations are often not well understood until well after ATP and the 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.
- 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.

CAPSTONE: Key Lessons Learned – 2 of 2

- Regulatory approvals often require far more time and resources that expected
  - Frequency approval 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.
  - Multiple government agencies, who often don't communicate with each other, are involved in getting final launch approval, i.e., New Zealand Space Agency (NZSA)
  - Items like Planetary Protection, Orbital Debris, Range Safety requirements for launch, and transport requirements for an overseas launch (aka Rocket Lab in NZ) are <u>not well understood</u> by most space systems development teams and require significant oversight by project management.
- Selling the project is great. Implementing and executing the project is ALWAYS harder, takes 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 is <u>often underestimated</u> as well.
  - COVID aside, several key challenges were not well understood by the team until well into the project and costly adjustments had to be made to mitigate these issues.
  - Between the launch vehicle upper stage issues and the the unique spacecraft requirements impact on a COTS design, the mission launched ~**16 months** after it was initially planned.

CAPSTONE Mission Status – 6/6/23

CAPSTONE

- **CAPSTONE has successfully operated in the NRHO since 11/13/22 (203 days)**
- All Orbital Maintenance Maneuvers (OMM's) have successfully executed as planned. Multiple planned OMM's have been cancelled cancelled due to process of stepping down ΔV to find a lower bound threshold.
- OMM cadence reduced due to minimum OMM ΔV based on the updated Terran controller implemented for the post-TCM-3 valve anomaly.
- Due to updated maneuver performance, further threshold reductions are expected to reduce the minimum OMM < 5 cm/sec.
- Two anomalies has occurred since NRHO insertion: Loss of commanding on uplink occurred on Jan. 26th and Feb 17. Suspect SEU on the Iris firmware as the root cause. Commanding restored on Feb 6th and Mar 1st when Command Loss Timer reset the spacecraft.
- First CAPS pass attempt occurred on 18 Jan. LRO received a signal, but no ranging data was observed. Two additional passes have been successfully executed with data collected but the ranging data was not well characterized.
- Next CAPS pass attempt (lower range to LRO) is planned for mid-June. Working the TUI on adjustments to the ranging modulation to improve the measurement quality.
- CAPS SW Version 0.5 continues development and will be part of potential in flight SW updates to improve the accuracy of the navigation estimate and correct issues observed in the initial experiment's results.

AIAA 2022 SmallSat "Mission of the Year"

Awarded at 2022 SmallSat Conference – 8/10/22

Questions and Additional Information?

Email: gardner@advancedspace.com

AdvancedSpace.com/missions/capstone

NASA.gov/directorates/spacetech/small_spacecraft/capstone

Thank-you!

(CAPSTONE)

Cislunar Autonomous Positioning System Technology, Operations, and Navigation Experiment

Demonstrating an innovative spacecraft-to-spacecraft navigation solution at the Moon from a near rectilinear halo orbit slated for Artemis' Gateway.

The CAPSTONE mission is managed by NASA's Small Spacecraft Technology Program. NASA's Advanced Exploration Systems funds the launch and supports mission operations. The mission is developed and operated by Advanced Space, LLC.

Back-up

Artemis Project Relationship to CAPSTONE

- Advanced Space is currently (independent of CAPSTONE) supporting the Artemis program at NASA JSC with orbit design and navigation trades studies and analysis related to the overall mission design and operation planning for the Gateway Program.
- This effort began ~3 years ago to support analysis and understanding of orbit transfers, orbit operations, navigation and OMM (Orbit Maintenance Maneuver) planning in the Near Rectilinear Halo Orbit (NRHO).
- This existing work, and these existing relationships provide an expedited transition of lessons learned and knowledge between programs/activities.
- A major objective of CAPSTONE is the validation of those analysis efforts in support of development and planning for the Gateway Program.

***"The purpose of flight research is to separate the real from the imagined problems and to make known the overlooked and the unexpected."* - Hugh L. Dryden**

CAPSTONE Quantifiable Objectives

- Demonstrate a rapid and affordable lunar mission by reaching initial launch readiness no later than 18 months from authority to proceed (contract award: 8/30/19, COVID delays not withstanding). 33 months.
- The CAPSTONE mission shall demonstrate a low-energy transfer to cis-lunar space requiring no more than 120 m/s ΔV when provided a -0.6 km^2/sec^2 C3 that can be achieved by a commercial small launch vehicle. Fully executed successfully – 94.21 m/sec (actual through ICM-2).
- For comparison to the predicted value, measure the ΔV to within +/- 3 m/s for insertion into a 9:2 synodic resonant lunar NRHO. Fully executed successfully on 11/19/22 (< 1% error).
- For comparison to predicted values, collect spacecraft position data to within +/- 10 km, collect spacecraft velocity data to within +/- 10 cm/s, and measure the required station keeping budget to within +/- 1 m/s ΔV over a minimum of 6 orbits a 9:2 synodic resonant lunar NRHO. Ongoing. Thus far: 7.5 cm/sec per rev of the 24 NRHO orbits.
- The CAPSTONE mission shall test the CAPS system's ability to generate a navigation solution to within 10 km in position and 10 cm/s in velocity without Earth-based tracking data by comparing the onboard flight software solution with ground-based results for at least 5 tracking passes with the measured signal noise on the LRO crosslink factored in. Ongoing. 3 attempts thus far. Partially successful. Next CAPS pass attempt on 5/9/23.
- Document operational experience and lessons learned for insertion into and operation in a lunar NRHO and directly transfer that experience and lessons to the NASA Gateway team. Reviewed with multiple JSC Gateway team(s) in April 2023. Reviewing with NASA GSFC (original SBIR sponsor) June 19-20.

Navigation Highlights
Separation through NRHO Operations

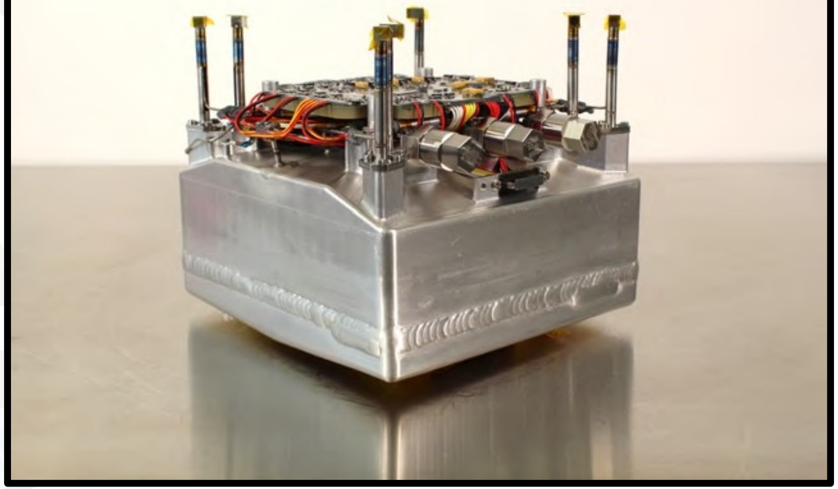
- Met all navigation requirements *at the time of maneuver designs*
  - TCM-1a, TCM-1c, TCM-2, TCM-3, TCM-4, NIM, ICM-1, ICM-2, OMM-5, OMM-10, OMM-13)
- Navigation through propellent “bake-off” for the entire mission and full line-leaks after the thruster valve anomaly
  - Consistently estimating perturbations after each thruster event
- Navigation during anomalous spin-stabilized period
  - Calibrated out transmit frequency bias due to spin – two separate biases as a function of which antenna was being utilized
- Navigation Post-ICM-2 in the NRHO has been nominal and well within the expected predicted NRHO performance.

CAPSTONE Orbit Determination Performance
Position, Velocity

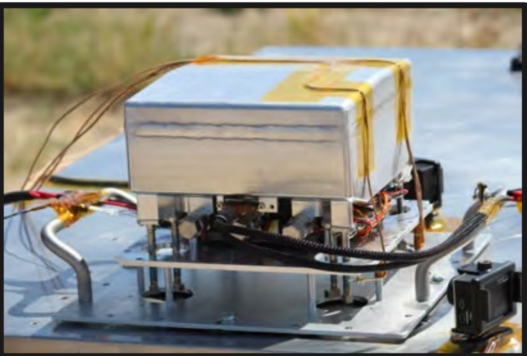
- Deployment to TCM-2 (Doppler only)
  - ~10 km, ~1 cm/s 3-sigma
- TCM-2 to TCM-3
  - ~10 km, ~1-5 cm/s 3-sigma
- TCM-3 to Anomaly Recovery (Spin-stabilized, Doppler only)
  - ~5-20 km, ~0.8-2 cm/s 3-sigma
- Anomaly Recovery to NIM
  - ~1-3 km, ~0.5-1 cm/s 3-sigma
- Post-NIM (Leadup to ICM-1, high tracking cadence)
  - ~0.2-1 km, ~0.3-0.5 cm/s 3-sigma
- Post-ICM 1, 2
  - ~1 km, 5 cm/s 3-sigma
- Post-OMM 10
  - ~0.8 km, ~1 cm/s 3-sigma
- Post-OMM 13
  - ~1.207 km, ~1.43 cm/s 3-sigma

CAPSTONE Propulsion System

Subsystem/Spec	Value
Dimensions	2U X 2U footprint for 12U spacecraft
Fuel Capacity	Variable height for fuel load ~3-6kg
ΔV	~220 meters/sec
Thrusters	8 thrusters with 0.25 N thrust (200 sec Isp)
Attitude Control	Translational & 3-DOF rotational capability
Propellant	Hydrazine with catalyst decomposition
Pressurization	Electric gear pump
Launch Safety	91-710 compliant, propellant tank not pressurized at launch, fully welded and sealed



CAPSTONE Propulsion Flight Unit



CAPSTONE ETU System Testing

Mission Operations Architecture

Tyvak Mission Operations Center (MOC): spacecraft operation, monitoring, commanding

Advanced Space Operations Center (ASOC): orbit determination, maneuver planning, payload activity planning