The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE): A Highly Successful Mission Demonstrating Autonomous Navigation and Operations Technologies in the Cislunar Domain

Thomas G. Gardner
Chief Engineer
Advanced Space, LLC

CAPSTONE

NASA

Advanced SPACE

ROCKETLAB

TERRAN ORBITAL

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 **532 days**.
- Now scheduled to orbit this area in cislunar space for another **5+ months** to understand the characteristics of the orbit and perform autonomous operations and other technology demonstrations.
- Helping reduce risk for future spacecraft by validating innovative navigation technologies and verifying the dynamics of the NRHO.

CAPSTONE Mission Objectives

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. **Complete with additional data being accumulated**

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. **Complete with additional data being accumulated**

Artemis Project Relationship to CAPSTONE

CAPSTONE

- Advanced Space continues to supporting the Artemis program at NASA JSC with orbit design, navigation trades studies, and analysis related to the overall mission design, navigation, and operations planning for the Gateway Program and Artemis missions.

- This effort began ~5 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.

CAPSTONE Launch – Mahia, NZ
June 28, 2022, 2:55 AM PDT

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, 3.8 Watts, 1-way CSAC enabled FW
Space / Ground Antennas	X-band high gain & low gain patch antennas, on spacecraft Y- and Y+ faces
LRO Crosslink Radio	TUI SLX, 2 Watts
LRO Crosslink Antenna	S-band patch antenna on Z+ face
ADCS Control	Coarse sensor module, redundant star trackers, redundant IMUs, four pyramidal reaction wheels
Thermal Control	Active battery heaters, 16 thermistor channels, 8 independent heaters, passive coatings and MLI
Propulsion	8 x 0.25N thrusters, 3.25 kg fuel, >200 m/s ΔV

Within Dispenser on the Lunar Photon Upper Stage

Deployed Configuration

CAPSTONE Mission Timeline

Months from Launch

Today: 04/30/24

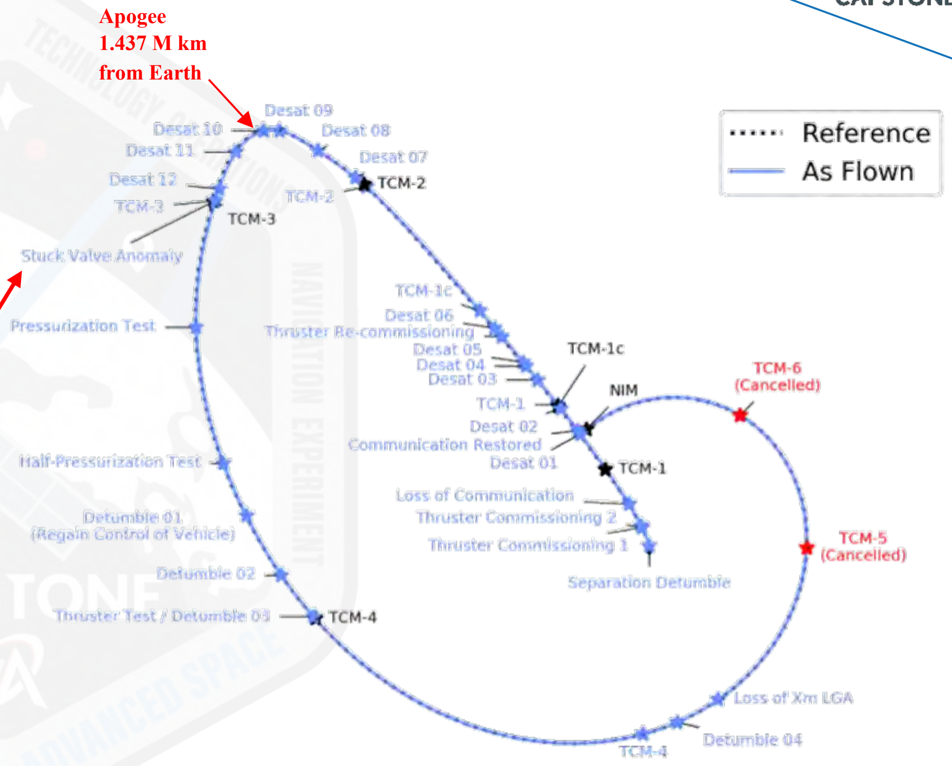
1 2 3 4	5 6 7 8 9 10 11	12 13 14 15 16 17 18 19 20 21 22	23 24 25 26
L + 4 months: • Launch to LEO • Orbit raising • BLT & insertion into NRHO by CAPS-TONE S/C	• L + 5-10 months: Conduct primary demonstration operations for 6 months • NRHO operations and flight dynamics assessment • CAPSTONE to LRO cross-link 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)	**Follow-on Technology Demonstrations:** **CAPS, autoNGC, TWTT** **Operations with other NASA or commercial assets** **End of mission (EOM) - Spacecraft disposal(?): NET 9/30/24**

Low Energy, Ballistic Lunar Transfer (BLT)

CAPSTONE

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



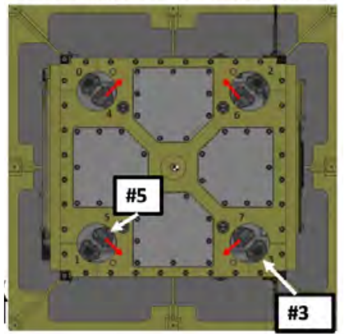
Stuck "Open" Thruster Anomaly

- 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
- Narrowed down stuck thruster to #3 (axial) or #5 (rotational)
- Terran Orbital (Tyvak) GNC team builds detumble controller robust to stuck “open” thruster
- 10/7/22 – Detumble maneuver completed successfully, regain constant communication with ground.
- 10/11/22 – Pressurization test executed conclusively determined thruster #3 was stuck open
- CAPSTONE completed >500k rotations during the anomaly!

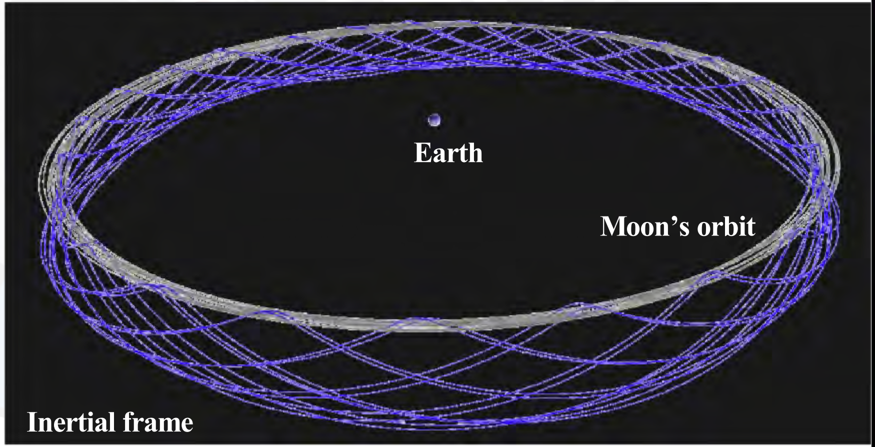
Red arrows show Thrust Vector

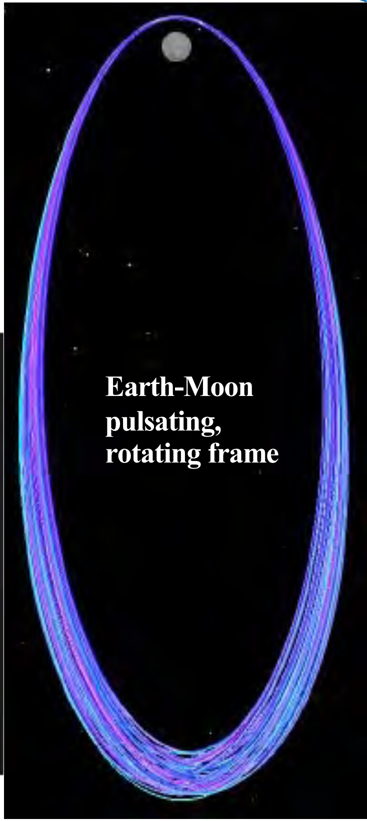


Extensive Details Provided in SmallSat 2023 Paper/Presentation:
CAPSTONE - Recovery and Operations of a Tumbling Small Satellite in Deep Space (SSC23-WVII-06)

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





OMM Design Performance thru OMM-45

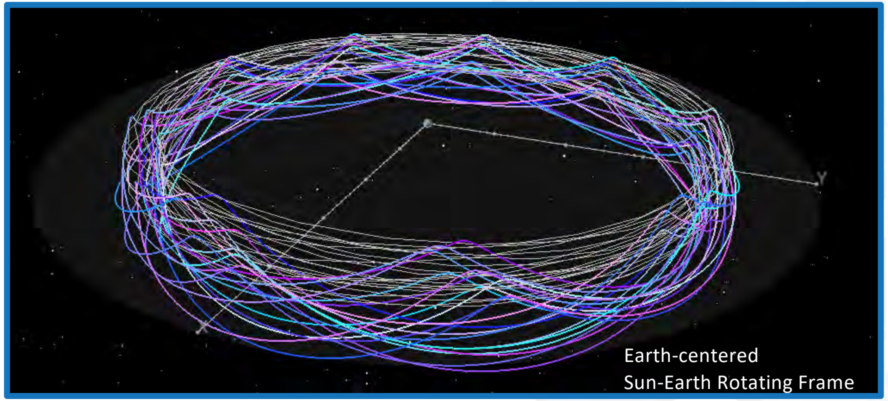
Maneuver	Operational Design (cm/s)	Estimated Delta-V (cm/s)	% Error
OMM-05	61.92	63.37	2.3%
OMM-10	31.43	32.03	1.9%
OMM-13	18.70	18.52	1.0%
OMM-18	44.99	42.73	5.0%
OMM-20	15.53	16.54	6.5%
OMM-22	6.40	7.40	15.6%
OMM-26	19.71	17.72	10.1%
OMM-28	13.10	14.37	9.7%
OMM-32	13.42	13.50	0.6%
OMM-36	13.17	13.54	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%
Total	**610.33**	**649.74**	**15.1%**

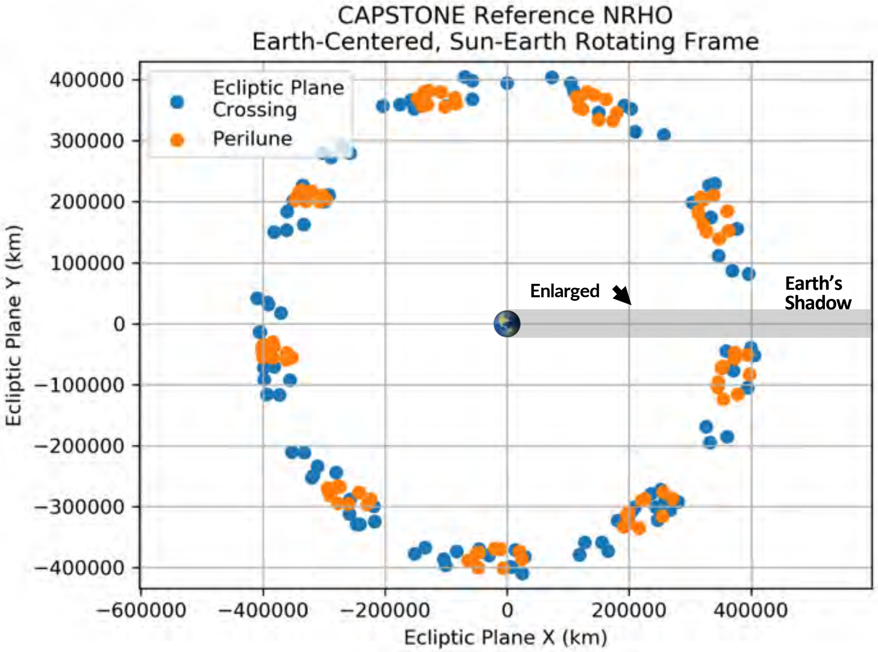
- OMMs were originally planned once per orbit: ~ every 6.5 days.
- During operations, OMMs are placed within the 24 hours preceding a true anomaly of 200 degrees and done during DSN tracking passes.
- Pre-launch analysis showed that OMM delta-Vs should be between 0 and 50 cm/s.
- Due to the stuck thruster, potential OMMs are often canceled reduce maneuver execution errors.
- The operations team has settled on a cadence of executing OMMs that are between 10-50 cm/s.
- Balances between low execution error while maintaining proximity to the reference trajectory.

Avoiding Earth Eclipses

Body	Number of Events	Average Duration	Max Duration
Earth	0	0	0
Luna	20	53.0 min	75.2 min

Requirement: < 90 min





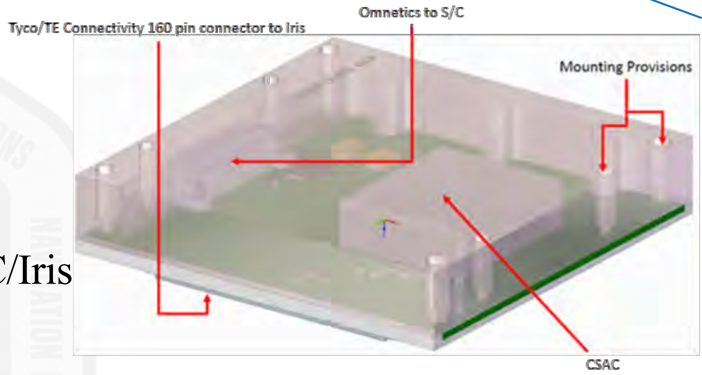
CAPSTONE CAPS Demonstration

Autonomous Absolute Navigation Experiment

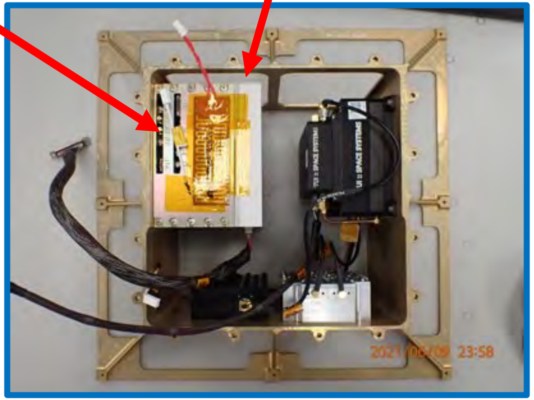
- The Cis-Lunar Autonomous Positioning System (CAPS) is demonstrating automated navigation solutions to reduce ground segment burden and enhance future mission operations.
- Crosslink Measurements:
  - Radiometric observables between spacecraft in cislunar space
  - Asymmetric gravity fields can provide absolute observability of both spacecraft
  - CAPSTONE is equipped with an S-band radio capable of crosslink ranging with the Lunar Reconnaissance Orbiter's (LRO) High Gain Antenna (HGA)
  - Crosslink measurements possible: Window of ~9 hours near perilune in each 6.5-day NRHO rev
  - There are usually 1-3 passes of 30-60 minutes possible each perilune
- Crosslink Status:
  - CAPSTONE has attempted 5 successful ranging/doppler crosslinks with LRO
  - Recently completed update to CAPSTONE's S-Band radio modulation and ranging signal to improve measurements and better mission planning to resolve inter-spacecraft timing conflicts.
  - Evaluating measurement sets to tune the onboard navigation filter to support autonomous navigation experiment tests in the coming months.

CSAC 1-Way Ranging Experiment

- A **Chip Scale Atomic Clock (CSAC)** was added to Iris X-Band radio to support a 1-Way ranging experiment during the CAPSTONE mission.
- JPL had tested the ranging function and the firmware interface
- Advanced Space developed the 1-way ranging (uplink) navigation measurement processing software as part of the CAPS SW development.
- Now performing ongoing testing of the 1-way ranging with the CSAC/Iris (DSN to spacecraft) during the ongoing Enhanced mission phase.
- One-way data can be obtained on the spacecraft while simultaneously getting traditional two-way data on the ground
- **One-Way Status:**
  - One-Way data is now being gathered on every tracking pass and used on the ground to compare navigation data received from both one- and two-way tracking.
  - Working on updates to the onboard filter tuning and processing to demonstrate autonomous navigation on board with on the 1-way measurement data.



CSAC Board Package



CAPSTONE Quantifiable Objectives

CAPSTONE

- 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 – C3: -0.693 km2/sec2, Transfer ΔV 97.05 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 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. Error < 1%.
- 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. Completed the required 5 successful ranging/doppler data collection passes (over 1000 measurements). Filter tuning and accuracy assessment ongoing.
- Document lessons learned for operations in a NRHO and transfer that experience and lessons to the NASA Gateway team. Reviewed with multiple JSC Gateway team(s); April 2023. Reviewed with NASA GSFC; June 2023. Reviewed with JPL: July 2023. Reviewed with STMD/HQ: February 2024. Final report planned for September 2024.

Sigma Zero - Navigation Anomaly Classification
NASA SBIR Phase 2

CAPSTONE

Goal: reduce human intervention by an order of magnitude in spacecraft orbit determination

Technical Approach:

- Transformer neural network models specialized to extract useful information from sequences of spacecraft navigation data.
- Adapt state-of-the-art methods from natural language processing; apply them to sparse, multivariate, high-precision numerical data.
- Flight software implemented as core Flight System (cFS) app
- Inputs at a series of 10's-1,000's of epochs:
  - Estimated spacecraft state
  - Ground station state
  - Post-fit residuals
  - Measurement type
- **Outputs:**
  - Probability distribution function across 9 anomaly classes
- **Test campaign used "pre-canned" simulated data**
  - **Test 1:** 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

- **Procedure:**
  - Run on lab board at Advanced Space office with equivalent CPU
  - Run on Flat Sat at Terran Orbital
  - Upload files to SV
  - Run on CAPSTONE
  - Downlink results as telemetry packets & compare with known truth

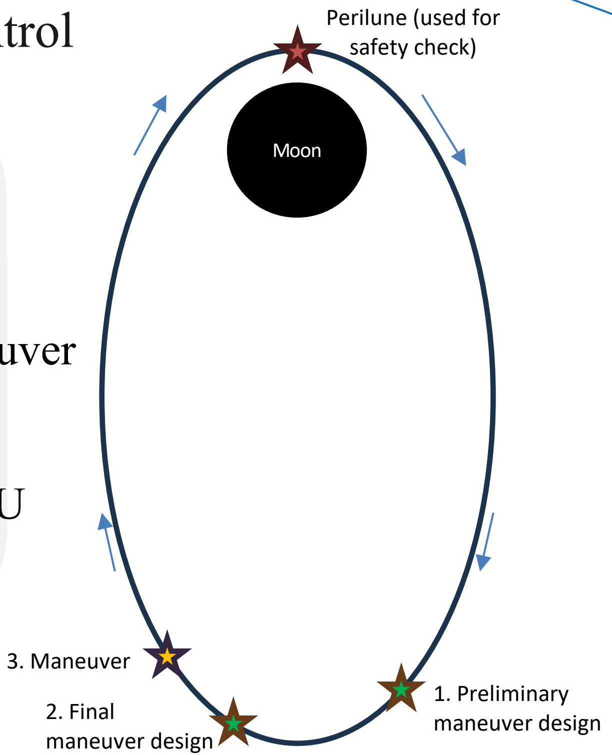
- **Elements of Sigma Zero tested on CAPSTONE**

- **Navigation Anomaly Detector**
  - Given a set of measurements and/or measurement residuals, identify if something went wrong.

- **Navigation Anomaly Classifier**
  - Determine the most probable cause(s) of an anomaly
  - Anomaly could be a maneuver, hardware malfunction, unplanned reaction wheel desaturation, unmodeled dynamics, bad data, etc.

Neural Networks for Easy Planning (NNEP)
NASA SBIR Phase 2

- Model: Small feedforward Neural Network to map state to control
- Flight software implemented as core Flight System (cFS) app
- Inputs: epoch, estimated state
- Outputs: maneuver design, results of Safety Check
- Test campaign planned for Q2 2024:
  - Use historical real state estimates from earlier CAPSTONE ops
  - Compare NNEP onboard maneuver designs with historical maneuver designs
- Procedure plan:
  1. Run on lab board at Advanced Space office with equivalent CPU
  2. Run on Flat Sat at Terran Orbital
  3. Upload files to SV
  4. Run on CAPSTONE
  5. Downlink results as telemetry packets & compare with truth



CAPSTONE Current Mission Status

4/30/24

CAPSTONE

- **CAPSTONE has successfully operated in the NRHO since 11/13/22 (532 days)**
- All Orbital Maintenance Maneuvers (OMM's) have successfully executed as planned.
- OMM cadence reduced due to minimum OMM ΔV based on the updated Terran controller implemented for the post-TCM-3 valve anomaly.
- **CAPSTONE has used 45% of its initial fuel.**
- Five(5) successful ranging/doppler CAPS passes have been completed.
- Ongoing CAPS pass attempts are planned for each periapse with suitable geometry. (lower range to LRO, acceptable antenna limits). TUI on adjustments to the ranging modulation FW have improved the measurement quality.
- CAPS SW continues development and will be part of payload flight SW updates to improve the accuracy of the navigation estimate and correct issues observed in the initial experiment's results.
- **CAPSTONE's mission is funded by NASA through September 2024**
- Continued work with Gateway team to demonstrate operational activities
  - Simulating a "noisy" spacecraft
  - Rendezvous demonstrations and proximity operations in 3-body orbits
  - Changing phasing in the NRHO
- Have or are planning to demonstrated autonomous onboard maneuver planning/execution software
- **Exploring other extended mission options with multiple stakeholders: NASA GSFC, AFRL, Other DoD**

CAPSTONE: Key Lessons Learned

CAPSTONE

- For a CubeSat mission with a clear set of mission goals, a better understanding of the system requirements is needed well before the PDR
- Low-cost, CubeSat missions often rely on COTS components. Alleged "plug and play" designs are often not as developed as advertised.
- Ground system requirements and operations are often not well understood until well after ATP. Plugging into existing ground architectures is not as simple as it is often advertised and is often underestimated.
- Regulatory approvals often require far more time and resources that expected. Frequency approval for cislunar or deep space missions is currently a labyrinth of requirements and approvals. Extensive attention of the time and the detailed requirements is needed for full approval – i.e. Planetary Protection, Orbital Debris, Range Safety requirements for launch, overseas launch (aka Rocket Lab, NZSA).
- 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 but were underestimated. Between the launch vehicle upper stage issues, COVID, and the spacecraft requirements impact on a COTS design, the mission launched ~**16 months** later than planned
- Lessons learned are being applied to other Advanced Space projects with NASA, AFRL and others: Low cost, high value missions are not only possible but are being embraced but multiple stakeholders.

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.

CAPSTONE vs Gateway in the NRHO

	CAPSTONE	Gateway
Mass	~25 kg	16,000-60,000+ kg
SRP Area	0.05 to 0.5 m^2	350 to 480+ m^2
Thrust	4 N (0.88 N effective) pre-anomaly 2 N (0.09 N effective) post-anomaly	2-3 N (SEP) 88 N (RCS)
Minimum Impulse	4 cm/s pre-anomaly 60 cm/s post-anomaly ~ 10 cm/s today	3 cm/s (currently assumed OMM minimum threshold)
Desaturation Maneuvers	Up to one per revolution in NRHO Executed with OMM or near apolune Typically < 2 cm/s	1-10 per rev while uncrewed (simplified model) Active RCS assist while crewed