Advanced SPACE

CAPSTONE™

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Delivering Innovation to Orbit™

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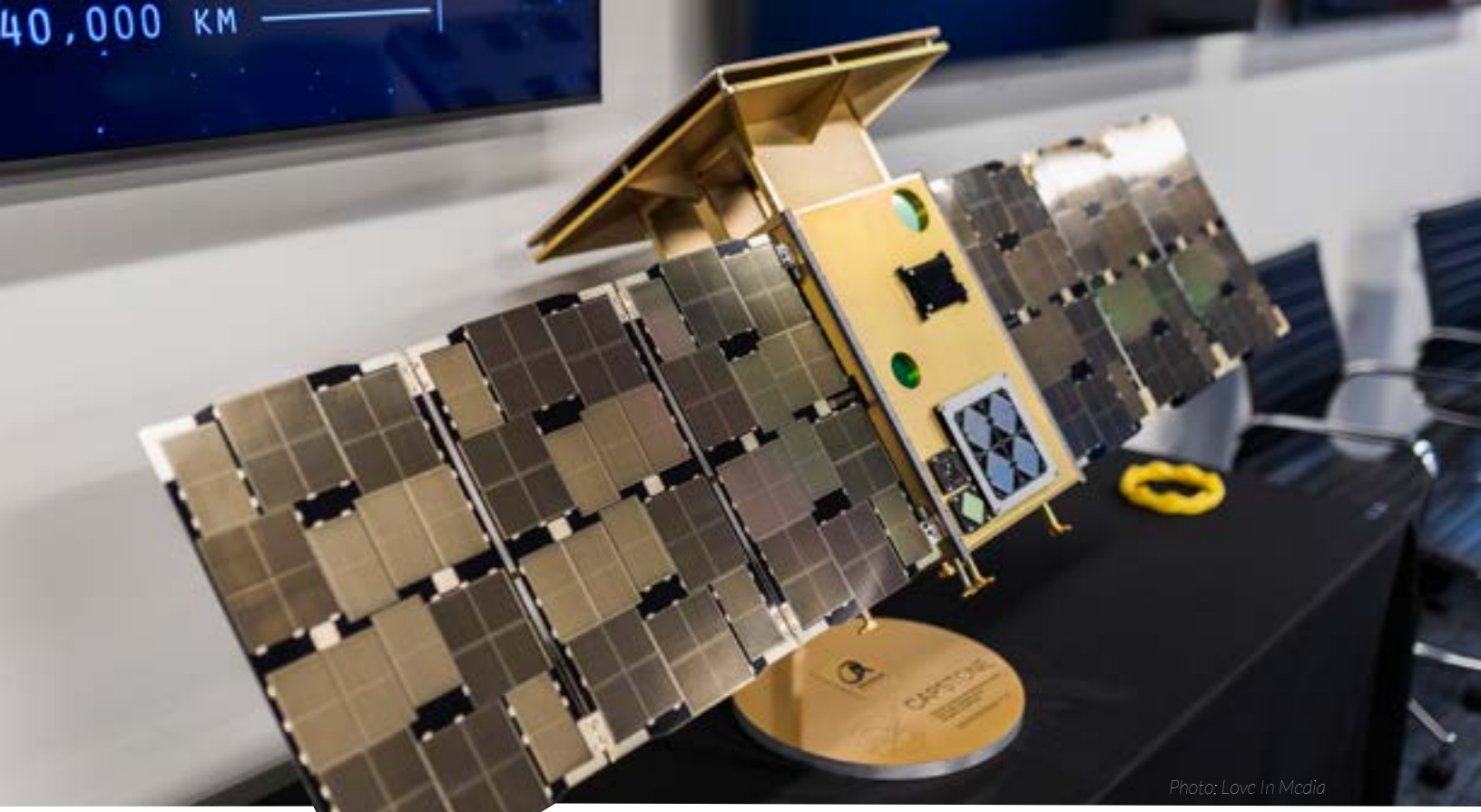


Full-scale model of CAPSTONE displays in Advanced Space's Operation Center (ASOC)

Mission Summary

Pathfinding Mission To The Moon

Advanced Space, LLC in Westminster, Colorado owns and operates the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment, CAPSTONE™ mission. CAPSTONE is made possible by small business collaboration across the country. CAPSTONE, a NASA-supported mission, is a small satellite, or CubeSat, that will be the first spacecraft to test a unique, elliptical lunar orbit that will support NASA's Moon missions under Artemis.

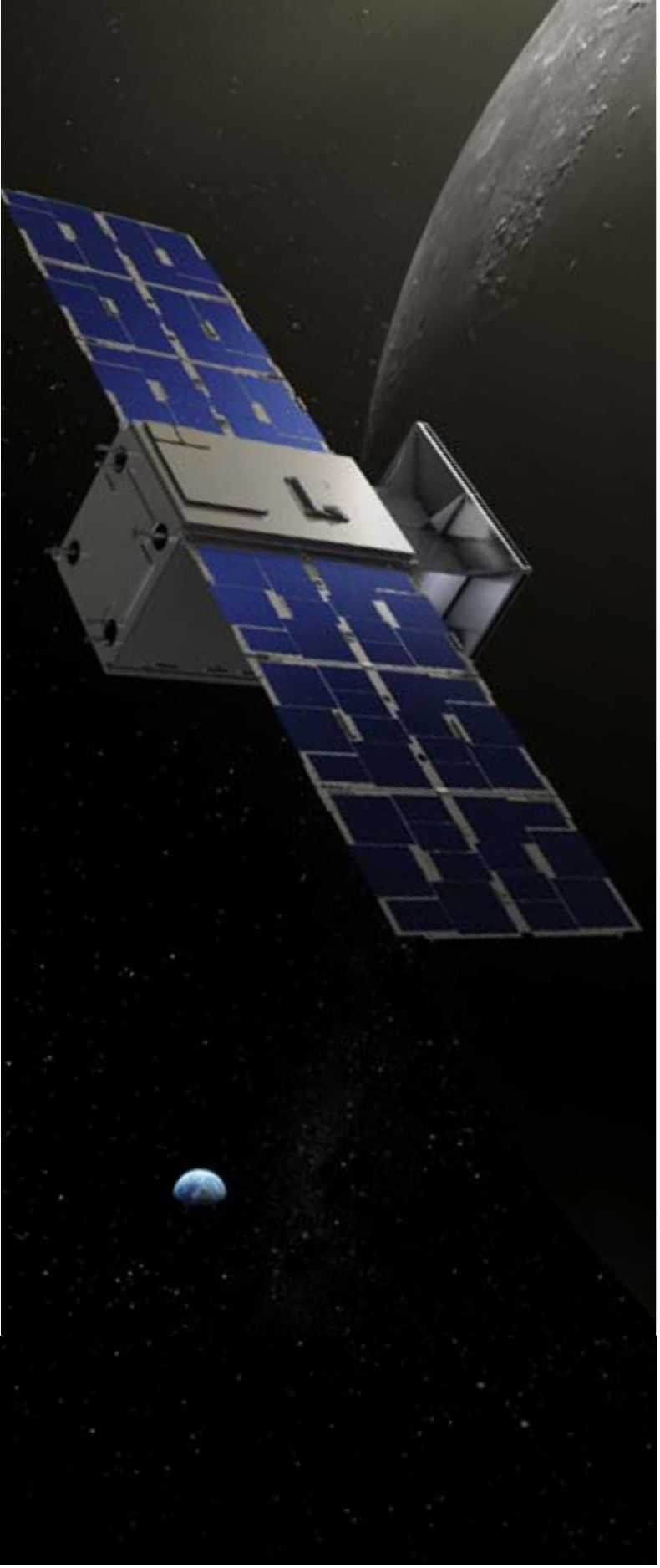
"We are proud of this mission and grateful to NASA for its support. This mission really showcases the benefits of collaboration between NASA and industry."

Bradley Cheetham
Advanced Space CEO & CAPSTONE PI

Launch to Mission

CAPSTONE went from an idea to a NASA SBIR funded contract in mid-2019. From there, the clock was ticking – while the average mission can take years to design, develop, manufacture, and launch, CAPSTONE mission plans represent an extraordinary pace from contract to launch readiness. This is possible through dedicated efforts from Advanced Space, close collaboration with customers and suppliers, and a laser focus on the core drivers of schedule and capabilities. The rapid timeline benefits from NASA investment and expertise as well as commercial investment from key suppliers. CAPSTONE shows how NASA partnerships with commercial innovators contribute to its future exploration endeavors.

Launching in 2022, on a Rocket Lab Electron, CAPSTONE is expected to be one of the first cislunar small spacecraft. The spacecraft was built by Terran Orbital Corporation. After several days of maneuvering to achieve its ballistic translunar injection, the CAPSTONE spacecraft will separate from the launch vehicle upper stage and begin its journey to the Moon. This will be the first mission for Electron beyond LEO and the CAPSTONE spacecraft will be the only payload launched on this flight. The injection accuracy is a critical start to the next phase of the mission.



Mission Objectives

CAPSTONE's primary mission is to pioneer a new and challenging lunar orbit to help inform future operations for NASA's new lunar space station, Gateway, as part of the Artemis program. The secondary objective is to test and demonstrate the cis-lunar autonomous positioning system, CAPS™, technology which will enable navigation services for the Moon using one to two satellites instead of using 20+ satellites for Earth based GPS. Several Commercial and Civil spacecraft are expected to arrive at the Moon in the next few years. However, there are only a few massive dishes that have the signal strength to reach the Moon. CAPS™ will reduce the amount of calls that need to be sent back home to Earth.

- Demonstrate entering and maintaining this unique orbit, near rectilinear halo orbit (NRHO) that provides a highly-efficient path to the Moon's surface and back
- Verify the characteristics of a cis-lunar near rectilinear halo orbit for future spacecraft
- Demonstrate spacecraft-to-spacecraft navigation services that allow future spacecraft to determine their location relative to the Moon without relying exclusively on tracking from Earth
- Explore use of one-way ranging through the Chips Scale Atomic Clock (CSAC)
- Lay a foundation for commercial support of future lunar operations
- Gain experience with small dedicated launches of CubeSats beyond low-Earth orbit, to the Moon, and beyond and beyond

Mission Timeframe

- **Launch** on June 28, 2022
- **6 days** after launch is separation from the launch vehicle and CAPSTONE will head to the Moon
- **4 months** of flight from launch and transfer to arrival at the Moon
- **6 months** of primary operations to complete objectives
- **12+ months** of enhanced mission lifetime dependent on fuel reserves, new objectives/operations plan, and other circumstances.

CAPSTONE Mission Partners

National Aeronautics and Space Administration (NASA)

CAPSTONE's development is supported by the Space Technology Mission Directorate via the Small Spacecraft Technology program and the Small Business Innovation Research program based at NASA's Ames Research Center in California's Silicon Valley. The Artemis Campaign Development Division within NASA's Exploration Systems Mission Directorate funds the launch and supports mission operations. NASA's Launch Services Program at Kennedy Space Center in Florida is responsible for launch management and NASA Goddard Space Flight Center who was instrumental in their support of the CAPS technology being used in the mission.

Terran Orbital Corporation

Spacecraft design, development and implementation, hardware manufacturing, assembly, testing and mission operations support. Terran Orbital is the manufacturing partner in drafting the hardware that will fly CAPSTONE. Along with producing the major bus subsystems and machining the satellite bus, they are responsible for the assembly and testing of the spacecraft, as well as integration to the launch vehicle.

Advanced Space, LLC

Owner and operator of the CAPSTONE mission. Developers of the proprietary CAPS, Cislunar Autonomous Positioning System, technology being demonstrated using peer-to-peer navigation.

Stellar Exploration, Inc.

Propulsion system was designed, tested, and manufactured by Stellar Exploration, Inc. located in California. The system was initially supported by NASA's SBIR program.

Jet Propulsion Laboratory

Communication, tracking, and telemetry downlink via NASA's Deep Space Network, Iris radio design and groundbreaking 1-way navigation algorithms.

Rocket Lab USA, Inc.

Launch provider launching CAPSTONE on a three-stage Electron launch vehicle.

Orion Space Solutions

Chip Scale Atomic Clock (CSAC) hardware provider

Tethers Unlimited, Inc.

Cross Link radio provider

Space Dynamics Lab

Iris radio and navigation firmware provider.

Separation & Arrival

Separation occurs L+6 days, (6 days after launch). At this point, CAPSTONE takes its first steps on its long journey and flies on its own, marking the start of its mission. At separation we will begin sending commands to the spacecraft for maneuvers, navigation, and status updates.

Ballistic Lunar Transfer (BLT)

Transfer starts out with a critical 72 hours where the spacecraft will turn on, boot up, get a navigation solution, and execute its first maneuver. This start to the transfer is very important, from this key beginning the transfer to the Moon will leverage a highly efficient trajectory that utilizes solar gravity to get to the Moon while requiring very little fuel. The transfer is called a Ballistic Lunar Transfer, from injection by the launch vehicle it will travel to approximately 1.5 million km from the Earth. During the transfer the spacecraft plans to take images using the on-board camera and will execute several maneuvers to correct for errors and target a precise orbit insertion at the Moon. This transfer approach has been used by spacecraft in the past and is likely to be used by many missions in the future. Advanced Space specializes in these highly dynamic orbit designs and operations which have enabled CAPSTONE and will support future programs as well.

BLTs are a type of low-energy transfer in which a spacecraft launches 1-2 million kilometers away from the Earth (where the Sun's gravity perturbation becomes dominant), then returns to Earth with a larger radius of perigee than before and a different geocentric orbit plane. When designed with the proper geometry, it is possible to choose the perigee to coincide with the Moon's orbit, bringing the spacecraft into the vicinity of the Moon. BLTs have favorable properties for uncrewed launches to orbits in the vicinity of the Moon, such as dramatically reduced spacecraft ΔV requirements and increased mass delivered to the NRHO. This type of transfer could be used to deliver space station modules, lander elements, and other cargo to lunar orbit.

Why a BLT? The fuel required for a spacecraft to insert into lunar orbit from a BLT is much less than a standard lunar transfer. From a design standpoint, this means that the spacecraft can carry less fuel, deliver heavier payloads, and have a simpler propulsion system. Demonstrating a BLT as a viable way to arrive and enter the very specific Near Rectilinear Halo Orbit (NRHO) will be beneficial for large future missions that will need to be delivered to the Moon in preparation of the Lunar Gateway.

Near Rectilinear Halo Orbit (NRHO)

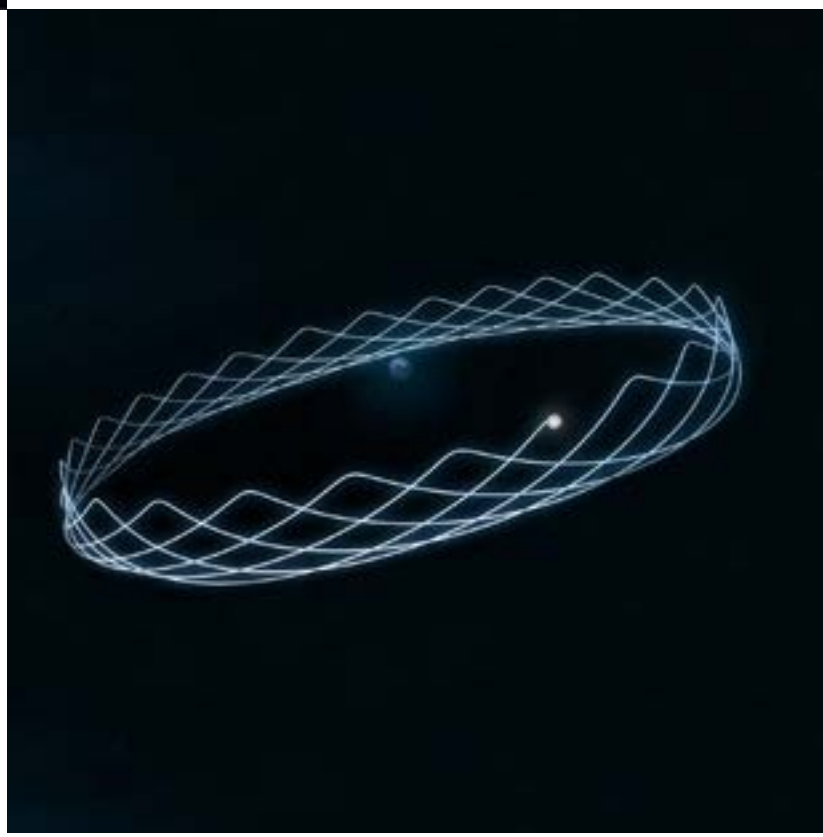
Entering into this NRHO orbit will require a critical maneuver by the CAPSTONE spacecraft. Astrodynamacists and navigation engineers at Advanced Space will operate critical maneuvers to orbit the Moon and there is very little margin for error. This unique orbit has many beneficial attributes to support sustainable architectures for exploring, developing, and settling the Moon. NRHOs are only marginally stable, so CAPSTONE will perform a small station-keeping maneuver about once a week. While in this orbit, the CAPSTONE spacecraft and the team at Advanced Space will demonstrate operational performance and confirm simulations to support planning for future NASA missions.

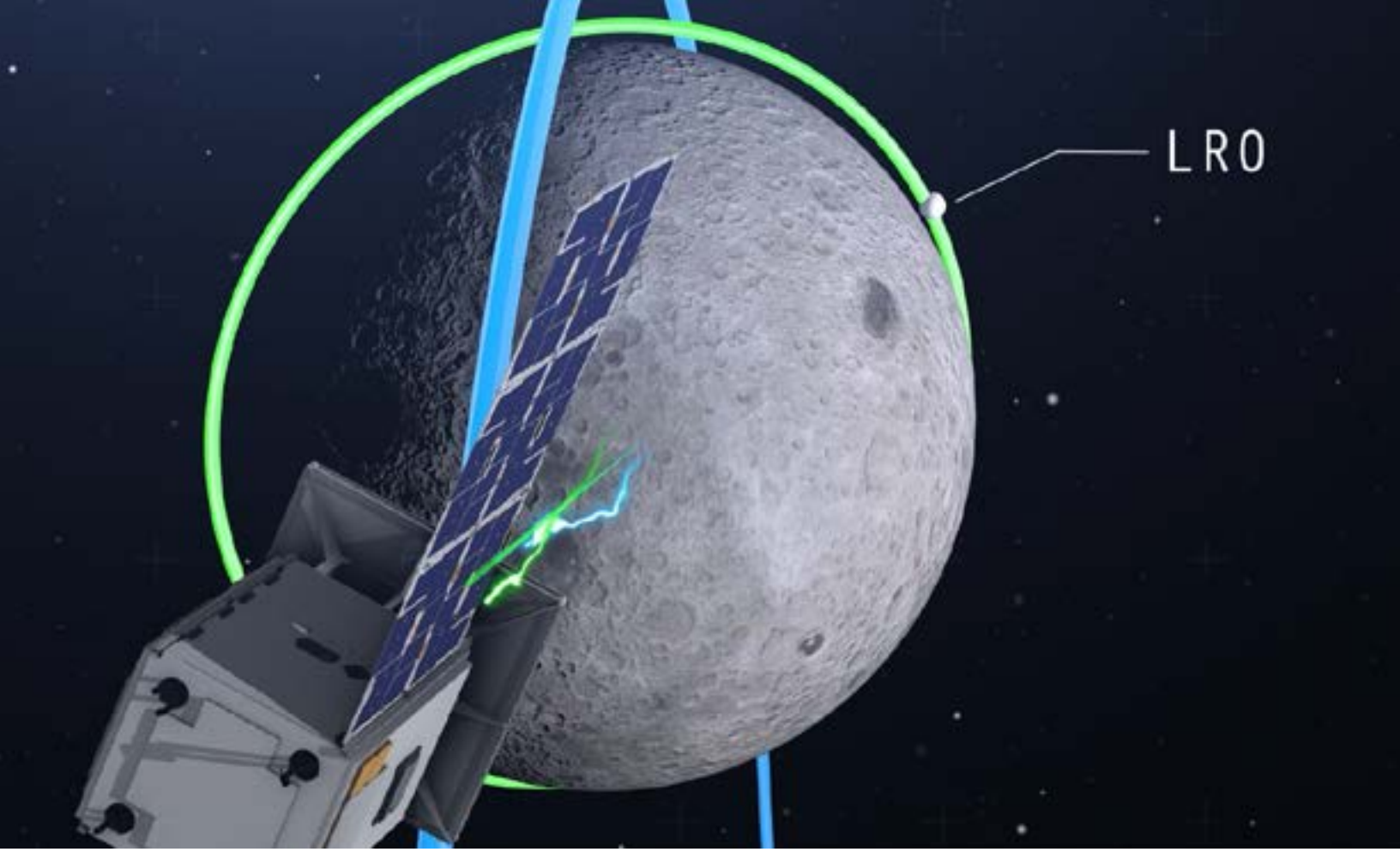
- CAPSTONE will arrive at the NRHO on the same day for each launch period, approximately 4 months after launch, depending on the launch period.
- Rocket Lab Electron will take the Photon spacecraft containing CAPSTONE to low-Earth orbit (LEO)
- Photon will perform a series of orbit-raising maneuvers to inject the CAPSTONE spacecraft into its transfer path to the Moon
- CAPSTONE will utilize a Low Energy (Ballistic) Lunar Transfer (BLT) to enter the NRHO.

Why An NRHO?

The NRHO is desired for NASA's Gateway, the Moon-orbiting outpost that is part of NASA's Artemis program

- This stable orbit minimizes the propellant required for orbit maintenance
- Offers a continuous view of Earth
- Avoids and/or minimizes eclipses to ensure continuous communication
- 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 – nine times around the Moon every two lunar synodic months or complete cycle of phases of the Moon as seen from Earth which is about 29 days





CAPS™

Demonstrating enabling technologies for future cislunar exploration and development is a top objective for the CAPSTONE mission. Throughout the mission, the spacecraft will be demonstrating foundational capabilities for new technologies. Specifically the mission will mature the flight software for the Cislunar Autonomous Positioning System (CAPS). The mission will also be working closely with NASA's Lunar Reconnaissance Orbiter (LRO) operations team to demonstrate a first-of-its-kind crosslink. This crosslink demonstration will see CAPSTONE send a ranging signal to LRO and for LRO to return it to CAPSTONE where it will be turned into a radiometric measurement and used in the CAPS software onboard to estimate the state of both spacecraft. This navigation approach will be the key to the future of cislunar operations where many more spacecraft will be operating at the Moon.

- CAPS starts with the algorithms and logic of automated navigation layered on top of an innovative approach to absolute orbit determination.
- To demonstrate and accelerate the infusion of CAPS, CAPSTONE will perform several crosslinks with the Lunar Reconnaissance Orbiter (LRO). These tracking passes will provide two-way, coherent range and Doppler measurements.
- The cross-link experiment between CAPSTONE and the LRO spacecraft will evaluate ranging capability.
- CAPS will be demonstrated for lunar missions to utilize automated navigation solutions to reduce ground segment burden and enhance future mission operations.
- CAPS will perform peer-to-peer measurements between CAPSTONE and the LRO spacecraft to generate absolute estimates of spacecraft position and velocity.

A Story in a Patch

The mission patch is a snapshot of CAPSTONE's daily life at the Moon with details that thread its story through past, present, and future.

- **The Past:** Nodding to the Apollo patches of the past, the stars honor those in the program who were lost but not forgotten. Our stars represent the late Dr. George Born and Darrell D. Cain, both of whom were foundational to Advanced Space's technical expertise and core beliefs.
- **The Present:** The orbit that CAPSTONE will be traversing is integral to the Artemis program. By being the first craft to navigate this NRHO, CAPSTONE will provide pathfinding data and experience to go beyond. The extension of the orbit beyond the confines of the patch represents the pathfinder nature of the mission. The location markers on the spacecraft and above the Moon represent the technology demonstration of CAPS.
- **The Future:** We see a future at Mars enabled by the technology demonstrated during the CAPSTONE mission. And so, we put Mars on the horizon for the next giant leap, as seen in the red point among the stars.

A Collaborative Effort

With this mission being a coordinated effort between commercial and public interests, we wanted a representation of that collaboration through the logo. The result is a harmonious joining of two brands into a singular idea.

The Details

- The central A is the Artemis arrow tip
- The orbit is from the Advanced Space logo
- The inner red path points the future journey to Mars
- The Moon element is central to CAPSTONE and Artemis.

Meet The CAPSTONE Team

Bradley Cheetham, *CEO, Principal Investigator of CAPSTONE Mission*

Bradley Cheetham is the CEO and PI of Advanced Space. He is an engineer, 3x entrepreneur and lifelong commercial space advocate. He is best known as the co-founder and CEO of Advanced Space where he leads company operations and strategy to deliver flight dynamics and operations solutions to clients across the space industry. As an advocate for the space industry, he serves as the Chair on the Board of Directors for the Future Space Leaders Foundation, is a member of the Entrepreneurship and Investment Committee of the International Astronautical Federation and serves on the Board of Advisors and the Board of Trustees of Students for the Exploration and Development of Space (SEDS).

Tom Gardner, *Director of Engineering, Program Manager for CAPSTONE*

Tom Gardner is the Director of Engineering of Advanced Space. He has over 40 years of aerospace experience. As the Program Manager for CAPSTONE, he has great detailed insight of the CAPSTONE mission from top level objectives down to specific issues related the design, implementation, and execution of the project. Gardner is an expert in lunar mission systems design for both orbiters and landers across the spectrum of NASA and commercial customers.

Dr. Jeffrey Parker, *Chief Technology Officer of Advanced Space*

Dr. Jeffrey Parker is the co-founder of Advanced Space, Chief Technology Officer, and author of the book Low-Energy Lunar Trajectory Design, the transfer method being used by the CAPSTONE mission. Dr. Jeffrey Parker is a preeminent expert on all matters pertaining to the mission design and navigation of spacecraft in cislunar space.

Alec Forsman
Mission Lead Systems Engineer

Astrodynamics Engineer who serves as the subject matter expert for the onboard payload, CAPS, which will demonstrate autonomous cislunar navigation.

Ethan Kayser
Mission Design Lead

Astrodynamics Engineer who is responsible for designing the trajectory and all maneuvers for CAPSTONE.

Jaquelyn Romano
Mission Operations Planning

Astrodynamics Engineer who interfaces control and documentation between CAPSTONE partners (data file exchanges, network interface).

Michael Thompson
Orbit Determination Lead

Astrodynamics & Navigation Engineer who leads both operational activies and conceptual studies in xGEO domain awareness.

Catch-Up on Capstone

Want to follow CAPSTONE'S journey live?

NASA invites people to see CAPSTONE in real-time using NASA Eyes on the Solar System interactive real-time 3D data visualization. Starting about one week after launch and during CAPSTONE's mission, you can virtually explore current or preview its path with NASA's Eyes.

The simulated view of our solar system runs uses real trajectory data in the app. The positions of solar systems objects – planets, moons and spacecraft – are shown where they are right now. This visualization is a mobile-friendly version of NASA Eyes software that runs directly through a web browser. Check it out at eyes.nasa.gov

Learn more about CAPSTONE;

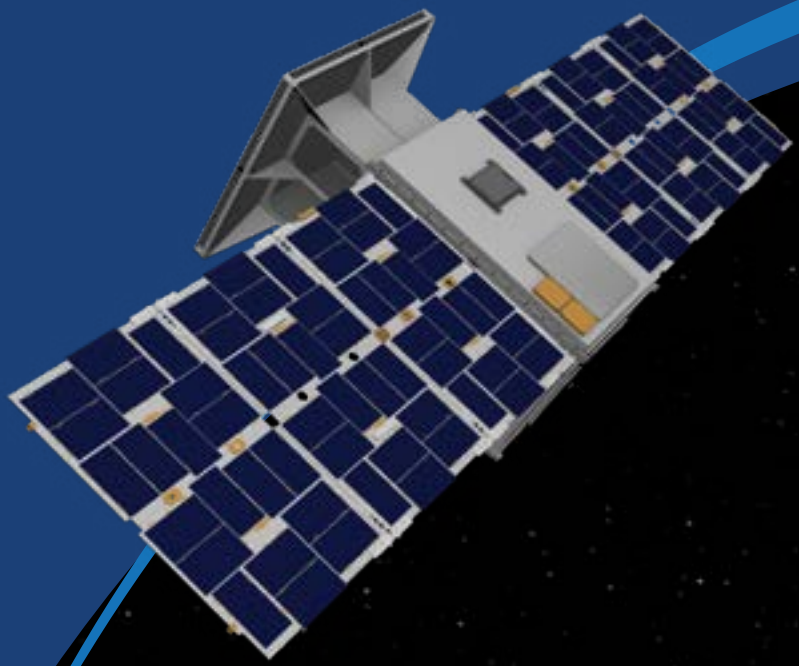
- advancedspace.com/missions/capstone
- nasa.gov/capstone
- nasa.gov/feature/ames/capstone-charts-a-new-path-for-nasas-moon-orbiting-space-station
- nasa.tumblr.com/capstone-testing-a-path-to-the-moon

Additional Resources

- CAPSTONE FAQs
- Fun Facts Sheet

Advanced Space, a leading high-tech space solutions company, supports the exploration, development, and settlement of space through software and services that leverage unique subject matter expertise to improve the fundamentals of spaceflight. Advanced Space is dedicated to improving flight dynamics technology development and expedited turn-key missions to the Moon, Mars, and beyond.

#innovation2orbit #CAPSTONE



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