Cislunar Explorers: Lessons Learned from the Development of an Interplanetary CubeSat

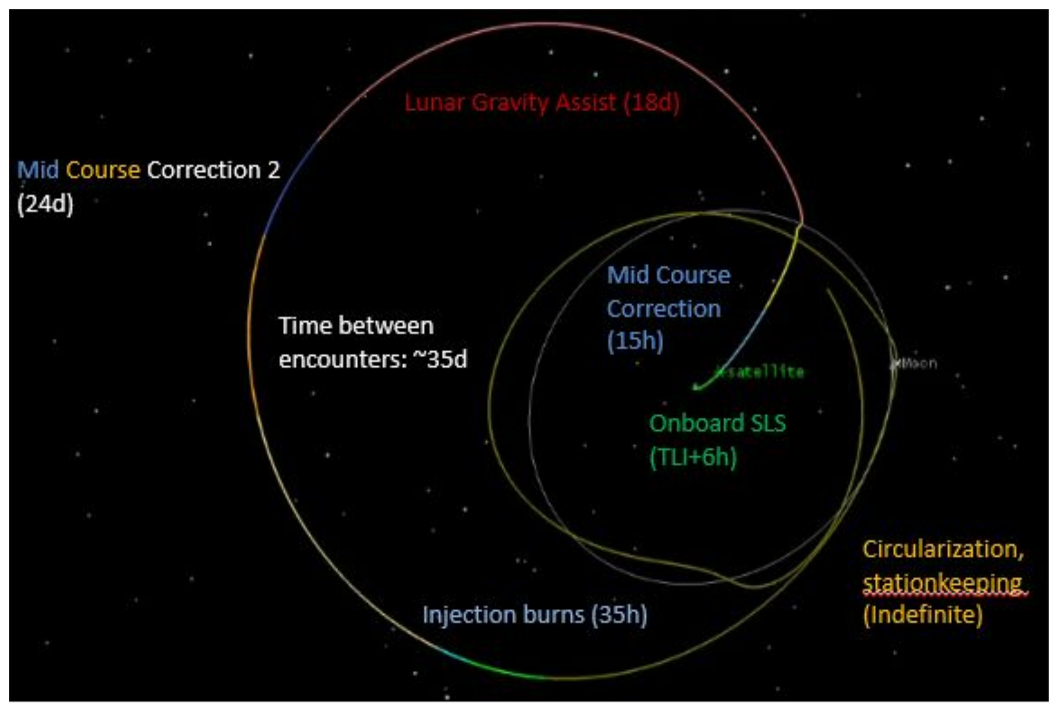
The Cislunar Explorers mission is a pair of ~3U nanosatellites (named Hydrogen and Oxygen) launching as a single 6U CubeSat as part of NASA's Artemis-1 mission on the Space Launch System (SLS). The two spacecraft will demonstrate technologies increasing the reach, flexibility, and cost-effectiveness of interplanetary smallsats. These innovations include water electrolysis propulsion, multi-body optical navigation, and passive spin-stabilization. Cislunar Explorers also serves as a pathfinder for demonstrating the utility and versatility of water for future In Situ Resource Utilization (ISRU) on space missions. Critical subsystems complement each other to reduce the cost and complexity, such as the water propellant acting as a radiation shield, electronics heat sink, and nutation damper. By leveraging the lessons learned from the development of the Cislunar Explorers mission, future interplanetary missions can utilize its technology to reduce cost, risk, and complexity.

Zoom Link: https://cornell.zoom.us/j/98803218007?pwd=dS9Vc3NQZFI3aEE3cGlMczFaSXpTQT09

Initialization (T+0)	Lunar Swingby (T+6.5D)		Ballistic Lunar Trajectory	Lunar Capture (T+~1M)		Station-keeping	End of Life (T+1Y)

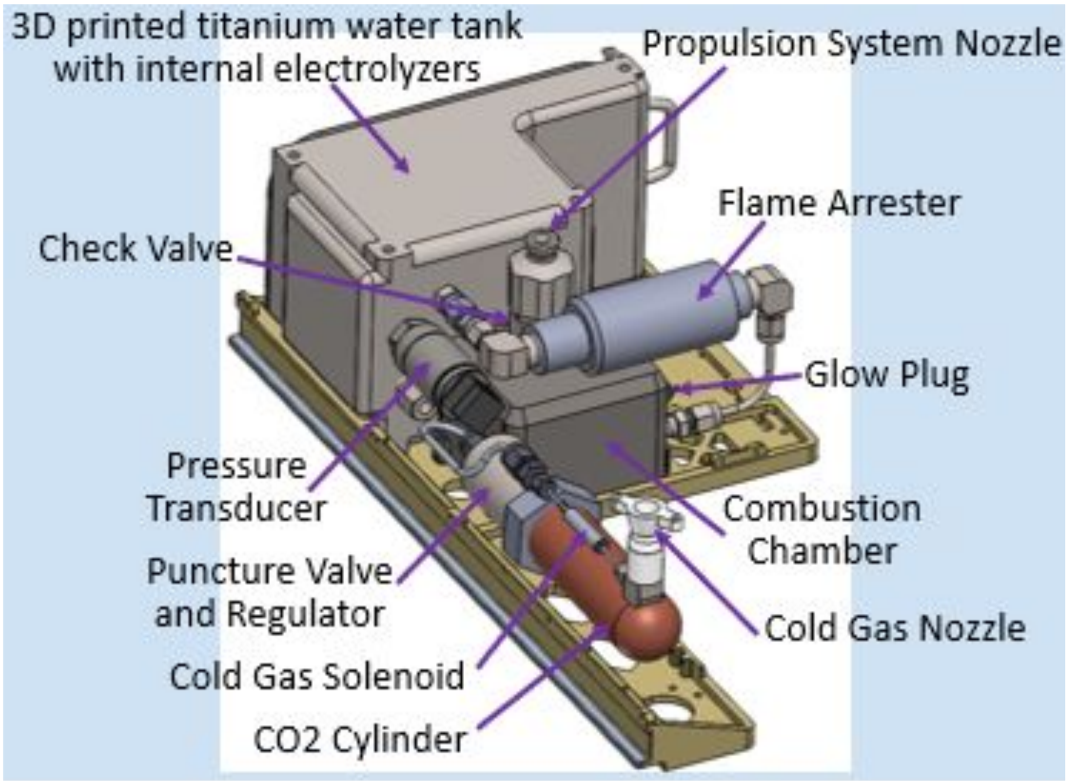
Initialization

CubeSat Deployment (T+0) → Establish Comms (T+5m) → 6U Spin-Up (T+1H) → 3U Separation (T+2H)



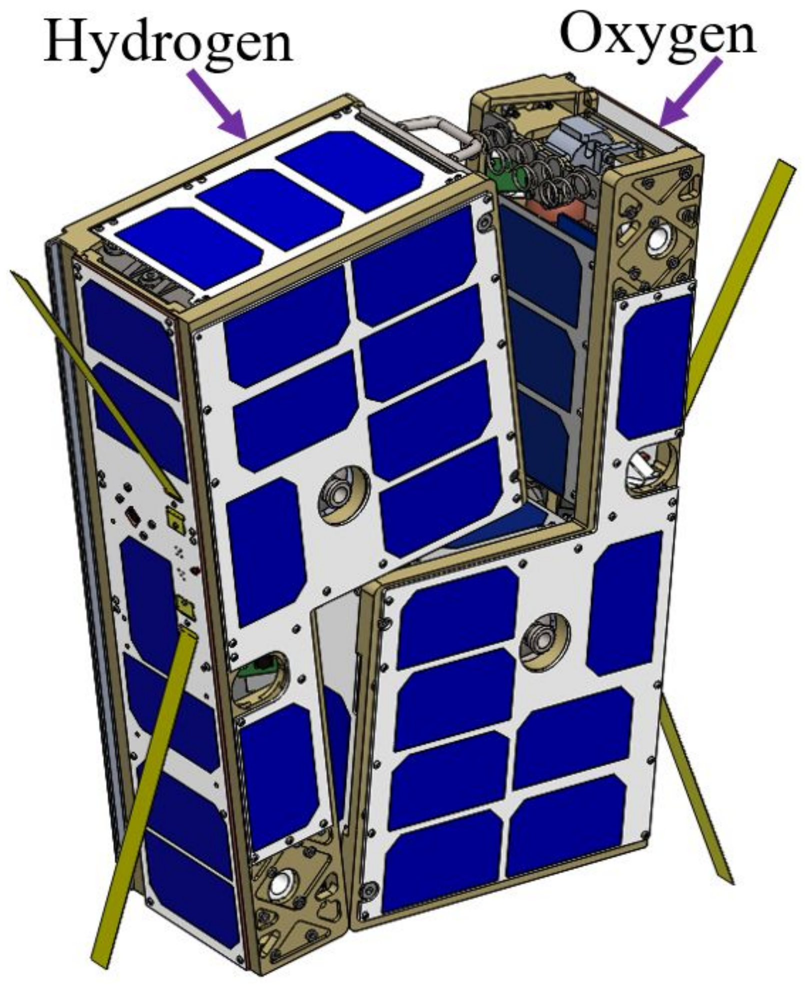
Lunar Orbit

- Apoapsis <10,000 km
- Periapsis >300 km altitude
- Maintain until end-of-life propellant threshold is reached
- Lunar impact disposal with remaining propellant



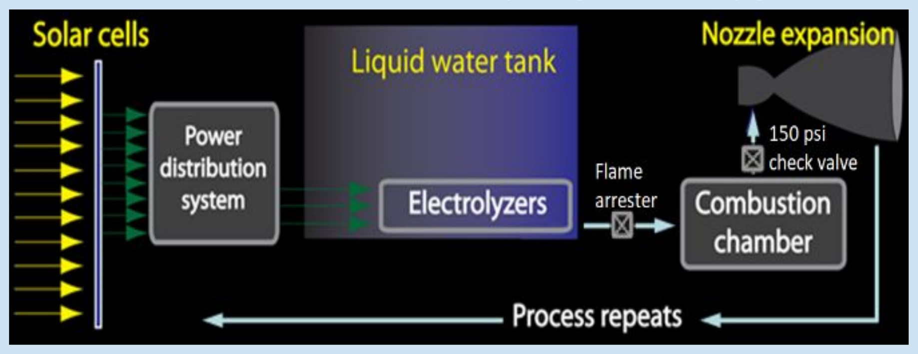
Commercial-Off-The-Shelf Subsystems

- **Command and Data Handling**
  - Raspberry Pi Model A+
- **Electrical Power System**
  - ZTJ Photovoltaic Cells
  - GomSpace Nanopower p31us
  - 18650 lithium-ion batteries
- **Communications**
  - RX/TX: Amateur UHF 70cm band
  - Spring tape deployable antennas
- **Sensors**
  - 3x Raspberry Pi Cameras v2
  - Pressure Transducer: Cynergy IPSU-GP300-6
  - Inertial Measurement Unit: Adafruit NXP Precision 9-DOF
  - Real Time Clock: Adafruit DS3231



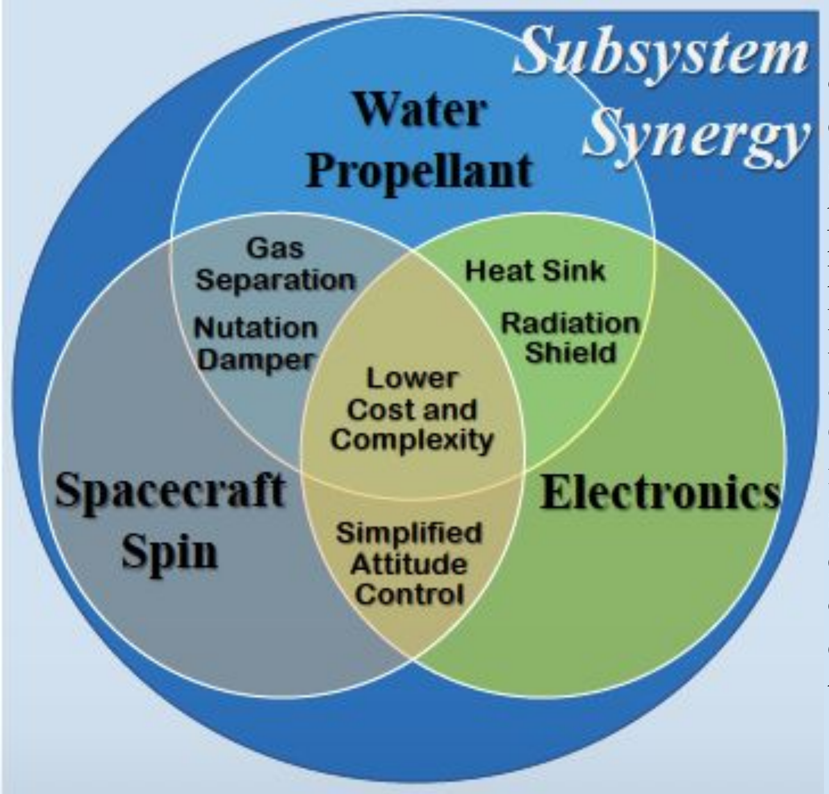
Water Electrolysis Propulsion Operation

Two electrolyzers, located in the water propellant tank, produce gaseous hydrogen-oxygen mixture from the water which is directed through the flame arrestor into the combustion chamber. When the system reaches its critical pressure, a glow plug is activated, which ignites the gaseous mixture. This is ejected through a nozzle, producing thrust. This process can repeat for as long as there is sufficient water for the electrolyzers to produce gas. One of the main advantages of this system is that it only utilizes passive pressure bearing components. The flame arrestor and check valve are pressure-driven, unactuated devices that inhibit the flow of hydrogen and oxygen from the combustion chamber before performing a burn. The propulsion system consists of a series of terrestrial vacuum-sealed components to carry the gaseous products of the electrolysis process.

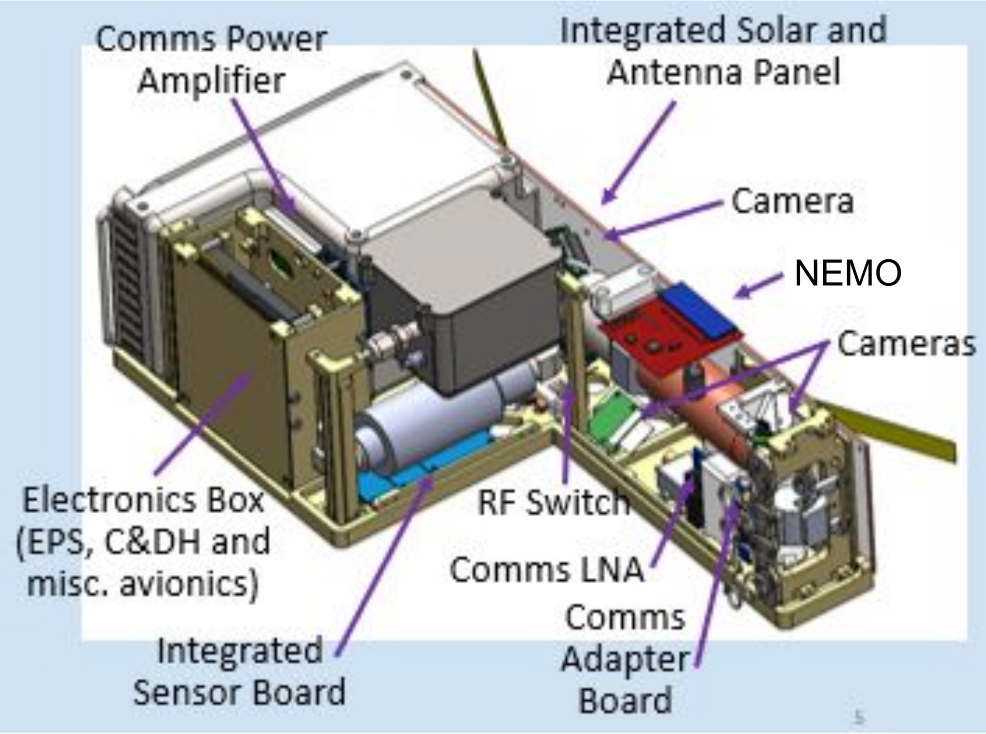


Optical Navigation Operation

The Op-Nav System provides autonomous position and attitude determination using low cost optics and minimal computing power. The spacecraft relies on three onboard cameras to obtain images of the Sun, Moon, and Earth. The software analyzes these images to determine the apparent diameter and body center. These measurements are compared with a table of ephemerides and unit vectors to each celestial body in the spacecraft body frame are generated. These measurements are used to create a transformation from the spacecraft body frame to an Earth-Centered Inertial frame. Position, velocity, and attitude determination are performed by a pair of Unscented Kalman Filters. A three-axis gyroscope provides spin measurements for attitude propagation. These quantities are telemetered to the ground station for planning open-loop reorientation maneuvers to align the main thrusters in the direction required by burns during the mission. There is less than 100 km expected error by end of mission.



Subsystems complement each other to reduce the cost and complexity. Water not only serves as the propellant for the propulsion system, but also as a radiation shield, electronics heat sink, and nutation damper. Each spacecraft's spin provides attitude stabilization, separates electrolyzed gas from the water in the propulsion tank, simplifies the active attitude control system, and enables the optical navigation system to cover a panoramic view around the spacecraft.



Challenges and Lessons Learned

Software:

- Increasing complexity due to pushing functionality to meet autonomous real-time mission operation requirements.
- Difficulty designing easily testable flight software
- Development complications were brought on by unnecessary features when implementing open source flight software frameworks

Hardware:

- Delays due to long turn around times for outsourced production of vacuum compatible plastic and metal 3D printed materials.
- Metal 3D printed parts while providing optimized designs and easer integration ended up proving to be a constant source of cost overruns and schedule delays due to excessive and specialized post machining due to:
  - Errors and tolerancing issues on compound and complex features were missed on delivery inspection.
  - Post machining on weld hardened material
  - Difficulty in sealing vacuum fittings that interfaced with the material

Programmatic

- Creating viable low energy trajectories was labor intensive, required significant time, and had to be redone with every launch delay.
- Getting earlier experience with chosen hardware would have reduced late-stage risk. Hardware "quirks" that required operational changes to work around manifested late in development.
- As observed with other academic programs, student turnover over such a long development period led to unnecessary repeated work and periods of uncertainty over past design, requirements, and trade outcomes. "Second system" decisions that broke continuity or complicated the onboarding process had long-lasting negative effects on productivity.

Conclusions

Interplanetary space exploration brings some of the most complex engineering requirements for smallsats to date. Technical and development problems were documented for the wider scientific and academic community to learn from. See the submitted paper for more in-depth information.

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