Cislunar Explorers Mission Update
Enabling Low Cost Interplanetary SmallSat Missions

Presented By:
Aaron Zucherman
Cislunar Explorers Mission Manager
PhD Systems Engineering Student
apz24@cornell.edu
Cislunar Explorers Team Organization

• Cornell University’s Space Systems Design Studio (SSDS)
  • Principal Investigators: Prof. Mason Peck and Dr. Curran Muhlberger
  • Mission Manager: Aaron Zucherman, PhD Student
  • Other members: ~18 Cornell Students

• National Space Society
  • NSS Liaison: Dr. Dean Larson
Cislunar Explorers Mission Background

• NASA’s CubeQuest Challenge
  • 3rd place at Ground Tournament (GT) 1 in 2015
  • 1st place at GT2 in 2016
  • 2nd place at GT3 in 2016
  • 1st place at final GT in 2019

• CubeQuest Lunar Derby
  • Achieve Lunar Orbit Prize
  • Spacecraft Longevity Prize

• 1 of 13 6U CubeSats on Artemis-1
  • Formally EM-1
  • First Lunch of NASA’s SLS rocket

Images Curtesy of NASA
Cislunar Explorers Design Overview

- **Technology Demonstrator**
  - No science payload
  - Redundant spacecraft

- **Spin-Stabilized Attitude Control System**

- **Water Electrolysis Propulsion System**
  - Demonstrate potential In Situ Resource Utilization System

- **Optical Navigation System**
  - Low cost position and attitude determination
  - Triangulation using celestial bodies

- **ChipSat**
  - Rideshare on a rideshare
  - Self-contained Satellite
Cislunar Explorers Mission Goals

• Lower barriers to exploring cislunar and interplanetary space
  • Test technologies that can be leveraged by future missions
  • Commercial off-the-shelf (COTS) parts wherever possible
  • Open-source design

• Mission Objectives
  1. Electrolysis propulsion demo
  2. Optical navigation demo
  3. Reach Lunar Orbit
  4. Femtosatellite operations beyond LEO demo

Image Courtesy of NASA
Cislunar Explorers Deployment

- Spring-loaded separation releases both into opposite spins providing passive spin stabilization
- Redundant Spacecraft
  - Stowed: 6U CubeSat
  - Deployed: 2x 3U volume L-shaped NanoSats
  - Nearly identical
Cislunar Explorers Subsystems

• **Command and Data Handling (C&DH)**
  • Raspberry Pi Model A+

• **Electrical Power System (EPS)**
  • ZTJ Photovoltaic Cells
  • GomSpace Nanopower p31us
  • Integrated 18650 lithium-ion batteries

• **Communications**
  • RX/TX: Amateur radio UHF 70 cm band
  • Spring tape deployable antennas

• **Flight Software**
  • F-Prime open source software
  • Developed at JPL
• **Switch**: Jameco Subminiature E Series Switches

• **Pressure Sensor**: Cynergy3 IPSU Industrial Pressure Transducer

• **Inertial Measurement Unit**: Adafruit 9-DOF IMU BNO055 Breakout

• **Real Time Clock**: Adafruit DS3231 Precision RTC Breakout

• **Analog to Digital Converter**: Adafruit ADS1115

• **Voltage regulator**: U3V50AHV
Propulsion and Attitude Control

- **Electrolysis Propulsion System**
  - ~1 kg of water propellant
  - > 500 m/s of $\Delta V$

- **Passive Attitude Control**
  - Sloshing of water provides damping for spin-stabilization
  - Spinning separates water from electrolyzed gas

- **Single CO2 cold gas thruster**
  - “Active” attitude control system
  - Simple in-house design
Electrolysis Propulsion (1 of 2)

- Simple construction and operation
  - No pumps or actuated components
  - No cryogenic systems
  - Low power consumption (~6W)
  - Low pressure

- Water as a propellant
  - Non-toxic
  - Inert

- Subsystem Synergy
  - Damping for spin-stabilization
  - Propellant tank serves as heat sink
  - Tank is structural element of spacecraft
  - Water is a good radiation shield

Images courtesy of NASA
Electrolysis Propulsion (2 of 2)

- Highly Scalable
- High thrust-per-unit-power

**In Situ Resource Utilization (ISRU):** using available materials to replenish supplies
  - Water is relatively abundant in the solar system
  - Targets with water have scientific/commercial value
  - Additional use for a resource necessary for human activity
  - Greater efficiency and lower infostructure requirements for using water as fuel than liquid oxygen and hydrogen systems
  - Could turn delta-v limits into delta-v increments

Images Curtesy of NASA
Optical Navigation (1 of 2)

• Autonomous position and attitude determination
• Triangulation using celestial bodies
  • Captures images of the Sun, Earth, and Moon
  • Compares apparent size and angular separation with a table of ephemerides
• Apply estimation methods overtime for accuracy
  • Kalman filter, ext.
  • < 100km expected error by end of mission
• Applicable to other environments
  • Gas giant moon systems
• Robust navigation within planetary systems
  • Utilize low-cost optics
  • Little to no impact on mission operations

### Apparent Size of Earth Chart

<table>
<thead>
<tr>
<th>Distance to Earth at Burn</th>
<th>Apparent Diameter of Earth</th>
<th>Computed Diameter of Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,100,017 km</td>
<td>30 pixels</td>
<td>30 pixels</td>
</tr>
<tr>
<td>594,600 km</td>
<td>55 pixels</td>
<td>54 pixels</td>
</tr>
<tr>
<td>368,982 km</td>
<td>88 pixels</td>
<td>86 pixels</td>
</tr>
<tr>
<td>28,034 km</td>
<td>1161 pixels</td>
<td>1158 pixels</td>
</tr>
</tbody>
</table>
Optical Navigation (2 of 2)

- Position and attitude from the same sensors
- Use of only hobbyist electronics
  - 3x Raspberry Pi Camera v2 (8 megapixels)
  - Raspberry Pi Camera Multiplexer
  - Real Time Clock
  - Inertial Measurement Unit
- Does not require constant comms link for tracking
  - Spacecraft can check in with position
  - Saves power, useful for SmallSats
  - Ground tracking may be impractical for deep space SmallSats
- Final lunar orbit verified by doppler tracking from multiple ground stations
ChipSats

• **ChipSats:**
  • Femtosatellites developed at Cornell University’s Space Systems Design Studio
  • Includes power, C&DH, sensors, and comms systems on a printed circuit board
  • 22mm x 50.5mm x 1mm
  • Flight heritage on ISS and on KickSat 1 and 2
  • Future Beyond LEO missions:
    • Interplanetary Exploration (see CAESAR)
    • Interstellar Exploration (see Breakthrough Starshot)

• **Secondary Payload on a Secondary Payload**
  • Fastened to outer surface of each spacecraft
  • “Monarch” - latest iteration of ChipSat design
  • Electrical connections to spacecraft for radio activation and shut-off.
  • Flexible printed circuit board (Kapton)
Mission Operations (1 of 3)

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

**Primary Mission**
- Optical Navigation
- Electrolysis Propulsion
- 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

**Timeline**
- Initialization (T+0)
- Lunar Swingby (T+6.5D)
- Ballistic Lunar Trajectory
- Lunar Capture (T+~1M)
- Station-keeping
- End of Life (T+1Y)
Mission Operations (2 of 3)

- Mid Course Correction 2 (24d)
- Time between encounters: ~35d
- Lunar Gravity Assist (18d)
- Mid Course Correction (15h)
- Onboard SLS (TLI+6h)
- Injection burns (35h)
- Circularization, stationkeeping (Indefinite)
• Thanks to the National Space Society for their guidance and support.

• NASA’s Space Technology Mission Directorate for selecting this project for a launch opportunity via their Centennial Challenges CubeQuest program.

• Kyle Doyle for his great contributions to the Cislunar Exporters

• The entire Cornell University student team
Questions?

Contact Aaron Zucherman at apz24@cornell.edu