Lunar Flashlight: Assessing Eco-Friendly Propellants and Leveraging SmallSat Technology for Lunar Observations

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Artemis: Landing Humans On the Moon

- Artemis I: First human spacecraft to the Moon in the 21st century
- Artemis II: First humans to orbit the Moon and rendezvous in deep space in the 21st century
- Gateway begins science operations with launch of Power and Propulsion Element and Habitation and Logistics Outpost
- Artemis III-V: Deep space crew missions; cislunar buildup and initial crew demonstration landing with Human Landing System

LUNAR SOUTH POLE TARGET SITE

Early South Pole Robotic Landings
Science and technology payloads delivered by Commercial Lunar Payload Services providers

Volatiles Investigating Polar Exploration Rover
First mobility-enhanced lunar volatiles survey

Humans on the Moon - 21st Century
First crew expedition to the lunar surface
The lunar poles are a special place

VALUABLE LUNAR SCIENCE

- Study of Planetary Processes
- Understanding Volatile Cycles
- Impact History of Earth-Moon System
- Record of the Ancient Sun
- Fundamental Lunar Science
- Platform to Study the Universe
Lunar Flashlight Mission

• Lunar Flashlight is a 14 kg 6U CubeSat
• Launch: SpaceX Falcon 9 secondary
• Team:
  - Engineering: JPL, MSFC (Propulsion)
  - Mission Design/Navigation: JPL
  - Mission Operations: GT
  - Science PI/Co-I: GSFC, JHU APL, UC Boulder
  - Science Operations: UCLA
  - External Entities: SpaceX, DSN, PDS

• Demonstrate several technologies:
  planetary CubeSat mission using green propulsion, active laser spectroscopy

Lunar Flashlight Goals

Measurement goal
• Lunar Flashlight will illuminate permanently-shadowed and detect water ice absorption bands in the near-infrared

Mapping goal
• By repeating this measurement over multiple points, Lunar Flashlight will create a map of surficial ice concentration that can be correlated to previous mission data and used to guide future missions
Lunar Flashlight Measurement

Lasers in 4 different near-IR bands illuminate the lunar surface in a 1 km spot
• Light reflected off the lunar surface enters the spectrometer to distinguish water ice from regolith

Lunar Flashlight Mapping

- The surface area occupied by water ice cold traps on the Moon is ~10^5 km², predominantly poleward of ~80°S, more-or-less evenly distributed in longitude
- Lunar Flashlight should resolve (>2 measurement across) the largest PSRs along its orbit track; this translates to a spatial resolution of <10 km for the largest (~20km) PSRs
- Enables prediction of other ice deposits by correlating data with other mapped geologic characteristics, including latitude, temperature, topography, lighting, proximity to young fresh craters, etc.
Lunar Flashlight ConOps

- Deployment and initial bootup
- Detumble and solar panel deployment
- Initial contact
- Desat burns
- System checkout

- Thruster calibration
- Receiver calibration
- Instrument system tests

L2 NRHO, perilune altitude = 15 km
Period = 5 - 7 days
Direction of motion: CW from Earth

TCM 1, 2, 3

Deployment and initial bootup
Detumble and solar panel deployment
Initial contact
Desat burns
System checkout

Thruster calibration
Receiver calibration
Instrument system tests

Additional TCMs

TCM 4

L+10 days
L+135 days
L+180 days

LEOP

Cruise (4 months)
Approach
Science (60 days)
Deorbit

Preliminary
10 Science Orbits (~60 Days)

Disposal at Lunar South Pole

Low energy transfer to polar lunar orbit insertion point

June 8, 2023
Cohen: Lunar Flashlight for SmallSat & Space Access Summit

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Lunar Flashlight Spacecraft

Flight System Overview

| Payload          | • 4-band Laser Projector  
|                  | • Lunar Reflectometer Receiver  
|                  | • Battery - 3x1p Sony 18650 Li-ion Cells  
| Mechanical & Structure | • 6U CubeSat form factor  
|                  | • ≤14 kg total launch mass  
| Propulsion       | • ~250 m/s of delta-v capability  
|                  | • 4x100 mN thrusters  
|                  | • Utilizes AFM 315E “green” propellant  
| Avionics         | • Radiation tolerant architecture  
| Electrical Power System | • Flat-panel and tri-fold deployable solar arrays with ZT/JXTJ Prime cells  
|                  | • 3x2p 18650 Li-ion battery cells  
|                  | • 3.123 V unregulated, 5 V  
| Telecom          | • JPL Iris 2.1 X-Band Transponder; supports doppler, ranging, and D-DOR  
|                  | • INSPR heritage low gain antennas (RX/tx)  
| Attitude Control System | • 50 mNm-s (x3) RWAs  
|                  | • Nano Star Tracker, Coarse Sun Sensors & MEMS IMU for attitude determination  

XACT-55 (JPL)  
Lithium battery (Panasonic)  
IRIS V2.1 Prototype (JPL)  
Sphinx CADH (rad hard Looor 3 FT - JPL)  
LGA (JPL)  
Coarse sun sensors (JPL)  
Laser EPS (JPL)  
Laser array (ILAS)  
Trifold solar panels x2 (JPL)  
4 x 100 mN thrusters (JPL)  
Flight system LED (JPL)  
Solar panel x2 (JPL)
Spacecraft I&T

Payload and avionics module during final assembly and without the cover. Slices are avionics (flight computer, Iris radio, EPS, interface board), silver box is our XACT-50 (ADCS), the payload is on the right. Receiver on the right and 4 laser pack above it. The open gap on the left is for the spacecraft batteries which get integrated last. You are seeing the top of the spacecraft, the prop module mates with the bottom.

Mission Operations

• Mission Operations student-led and executed by Georgia Tech
Launch!

- Lunar Flashlight was launched as a SpaceX Falcon 9 rideshare on December 11th, 2022.
- Following deployment on a translunar trajectory, the spacecraft’s autonomous subsystems activated.
- Contact with the Deep Space Network successfully occurred soon after the spacecraft achieved stable sun-pointed control.
- All LF Level 1 requirements were achieved! Including laser firing, successful demonstration of IRIS and SPHINX, and excellent performance of the GT operations team.
- However, we did not make it to the Moon…

LF Propulsion System

- ASCENT (Advanced Spacecraft Energetic Non-Toxic) propellant, formerly known as AF-M315E, is an advanced monopropellant formulation developed by the Air Force Research Laboratory (AFRL).
- Previously used in LEO during GPIM (Green Propellant Infusion Mission).
- 4x 100mN thrusters from Plasma Processes (Rubicon).
**LF Propulsion System**

- Electric gear pressurant pump from FlightWorks
- Iso valve and 4x thruster valves from NASA MSFC
- 3D-printed titanium manifold designed and manufactured by MSFC and Georgia Institute of Technology - provides propellant routing between tank, pump, recirc block, valves, and thrusters

After the prop subsystem was assembled, it underwent a short test campaign:
- Flow testing with He (no hot fire test) - all four thrusters had flow rate within acceptance range
- Leak test in vacuum by pressurizing tank with He with all valves closed, no leakage detected

The LFPS was integrated into the spacecraft and went through the integrated environmental test campaign (EMI/EMC, random vibration and thermal vacuum testing), including functional testing to confirm communication with the prop system through the flight computer and XACT, verify temperature and pressure sensor feedback, exercise all heater channels at safe benchtop temperatures, and exercise the valves.

After launch, the propulsion system was activated during the first contacts, but experienced anomalous thrust levels during the first programmed momentum desaturation.

During the next five months, troubleshooting, testing, and recovery activities were performed with the goal of completing the trajectory maneuvers and the lunar orbit insertion burn.
LF Propulsion System Troubleshooting

- Troubleshooting was a slow process - Ground software and staffing not prepared for continuous troubleshooting
- Limited DSN contact time and team time to develop and V&V sequences
- Momentum constraints and limitations of BCT software automating desaturation maneuvers
- Lining up doppler/momentum/thermal response using ACS telemetry and Doppler to look at change in momentum and calculate thrust generated

- In-flight test campaign was comprehensive including heating, duty cycle, pressure, valve actuation, etc.
- Results helped narrow down the fault tree
- Overall performance degraded over time though

- Rapidly developed many alternative TCM solutions for the mission
- Using just 2 thrusters, then with just 1 thruster, using rotating TCM’s to keep thrust in line
- Lunar flyby rather than lunar orbit
- Decreasing amounts of delta-V needed, creative capture timelines

- Eventually, level of risk acceptance was greatly increased, enabling more aggressive troubleshooting, including running the pump backwards to generate suction or slosh
- Thruster 2 showed signs of life but its performance was too variable to rely on for the required TCM
- Mission ran out of time to perform TCM to stay in the Earth-Moon system

- Lunar Flashlight is now in a heliocentric orbit
  - Passed by Earth and Moon on May 17 (UTC)
  - Next Earth flyby in 2037

LF Propulsion System Fault Tree

- Debris issues
  - Debris in feed line
  - Debris in valve seat would keep valve from opening
  - Debris between valve and thruster feed tube
  - Debris here would result in decreased flow rate

- Valve issues
  - No indication of valve seat
  - Valve still operating (false thrust)
  - Valve in part open state, but not closed

- Excluded
  - No indication of valve leak
  - Valves still operating (little thrust)
  - Unlikely to partially open, but possible

- Electronics issues
  - Thrust still operating as expected
  - Thruster, valve, and pump telemetry match expectations
  - Pump controller driver failure
    - Thruster, valves, and pump still operating
    - Can still valves are opening due to thrust

- Other HW issues
  - Increased fuel, temperature, or flow rate
  - Higher thrust levels
  - No indication of feed line issues
  - Would see different thrust vector

- Other HW issues
  - Increased flow rate
  - Excess propellant remains
  - Different thrust vector

- Excluded
  - No indication of valve leak
  - Valves still operating (little thrust)
  - Unlikely to partially open, but possible
LF Propulsion System

- Most likely cause: FOD from 3D printed titanium manifold
  - Between valve and thruster feed tube
  - In valve after seat

- During flatsat stand preparation, an isolation valve* was found to be performing at a much lower flow rate than expected
- Upon inspection of the valve, it was found a piece of FOD had lodged itself into the valve limiting the exit flow area
- Flow rate (He) without FOD: 58.3 mL/s (thus passing the ATP)
- Flow rate (He) with FOD: 4.5 mL/s and 5.1 mL/s
- With the FOD, the flow rate was on average 8% that of without FOD
- This reduction is similar to the flight performance of LF system

*NOTE: The only difference between an isolation valve and thruster valve is the orifice size of the two configurations

Looking up into valve from thrust plate via microscope, can see FOD in center of valve outlet
Lunar Flashlight Outcomes

- Lunar Flashlight successfully met all Level 1 Mission goals
  - Newly developed propulsion system components exceeded performance expectations, tested under unusual and extenuating circumstances
  - Sphinx flight computer successfully performed in deep space radiation environment
  - Iris radio updated to include a new precision navigation capability, can be used by future small spacecraft to rendezvous and land on solar system bodies
  - Active laser reflectometer – both lasers and detector functioned as expected and matched ground test data

- ASCENT propellant worked well
  - We have ~90 minutes of nominal thrust data from Thruster 4
  - Preliminary ISP calculations show that ASCENT provided expected performance
  - Calculation ongoing to compare with GPIM
  - No reason to think that the fuel was contaminated or unsuitable

- Most likely cause of LF prop system failure: FOD from 3D printed titanium tank/manifold
  - Despite extensive cleaning during manufacturing and assembly
  - The 3D printing process needs to be better understood and characterized
Summary

- Current orbital maps of "volatiles" are not mutually consistent, cannot establish resource potential
- Lunar Flashlight met all Level 1 Technology Demonstration goals! But stretch goal to provide unambiguous measurements of lunar surface ice in south polar PSRs was not successful 😞
- Additional new data will be gained through upcoming missions
  - Artemis-1 carried 10 cubesats, several to the Moon – note were successful. There are lessons to be learned about size, reliability, and risk for beyond-earth spacecraft here!
  - CLPS missions in 2022 and beyond will deliver a multitude of payloads to the lunar surface – keep your fingers crossed!
  - Even more lunar robotic missions (TrailBlazer, VIPER) will be helping investigate lunar polar volatiles
- Correlating datasets of mapped geologic characteristics enables prediction of ice deposits, informs which ISRU recovery/processing path to follow, constrains what is “economical”