Lunar Flashlight Mission Overview

Philippe Adell, PhD.

On behalf of LF Team

Wednesday, July 10, 2024

S3VI Community of Practice Webinar Series

Jet Propulsion Laboratory
California Institute of Technology

Georgia Tech

Outline

- Why are we using Small Spacecraft Technologies
- Past and future deep space mission using Small Spacecraft
- Lunar Flashlight mission overview
  - History and Background
  - Mission objectives and Radiation Hardness Assurance
  - Spacecraft overview and I&T activities
  - New technologies demonstrated
  - Operation activities and in-flight technology demonstrations
  - Propulsion anomaly
  - Conclusion

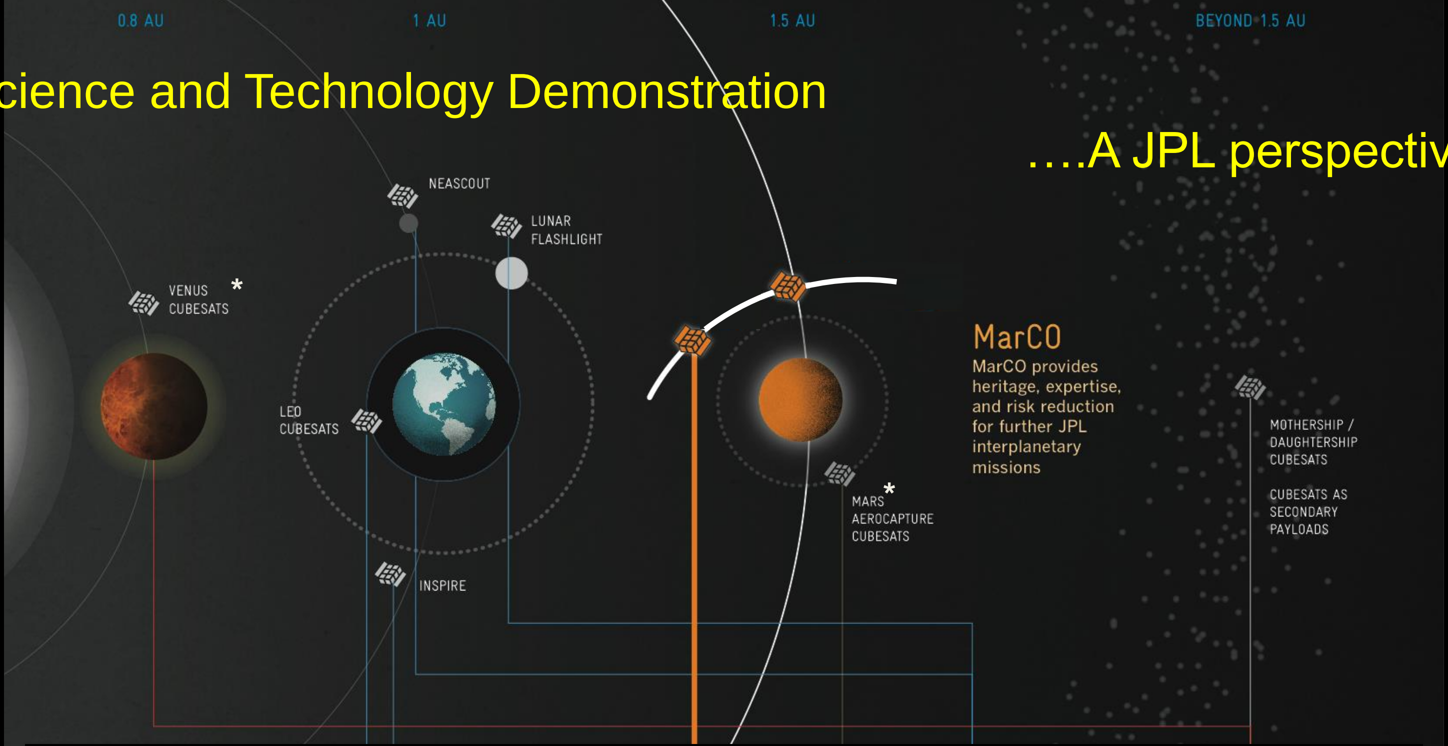
Small Spacecraft Technology: WHY?

- For technology demonstrations in relevant environments
- A low cost approach for focused science objectives and enable new science via novel architectures
- Solidify the partnership between space, academia and industry to maximize innovation
- For low cost constellation and global activities monitoring (imaging and communication)
- For hands-on training opportunities for young professionals

Vision is to develop, low-cost missions on a broad range of science and commercial applications

For Science and Technology Demonstration

….A JPL perspective



Known Challenges

- Propulsion, Communications
- Environments, Power, ADCS
- Thermal, Energy storage
- Proximity operations and autonomy

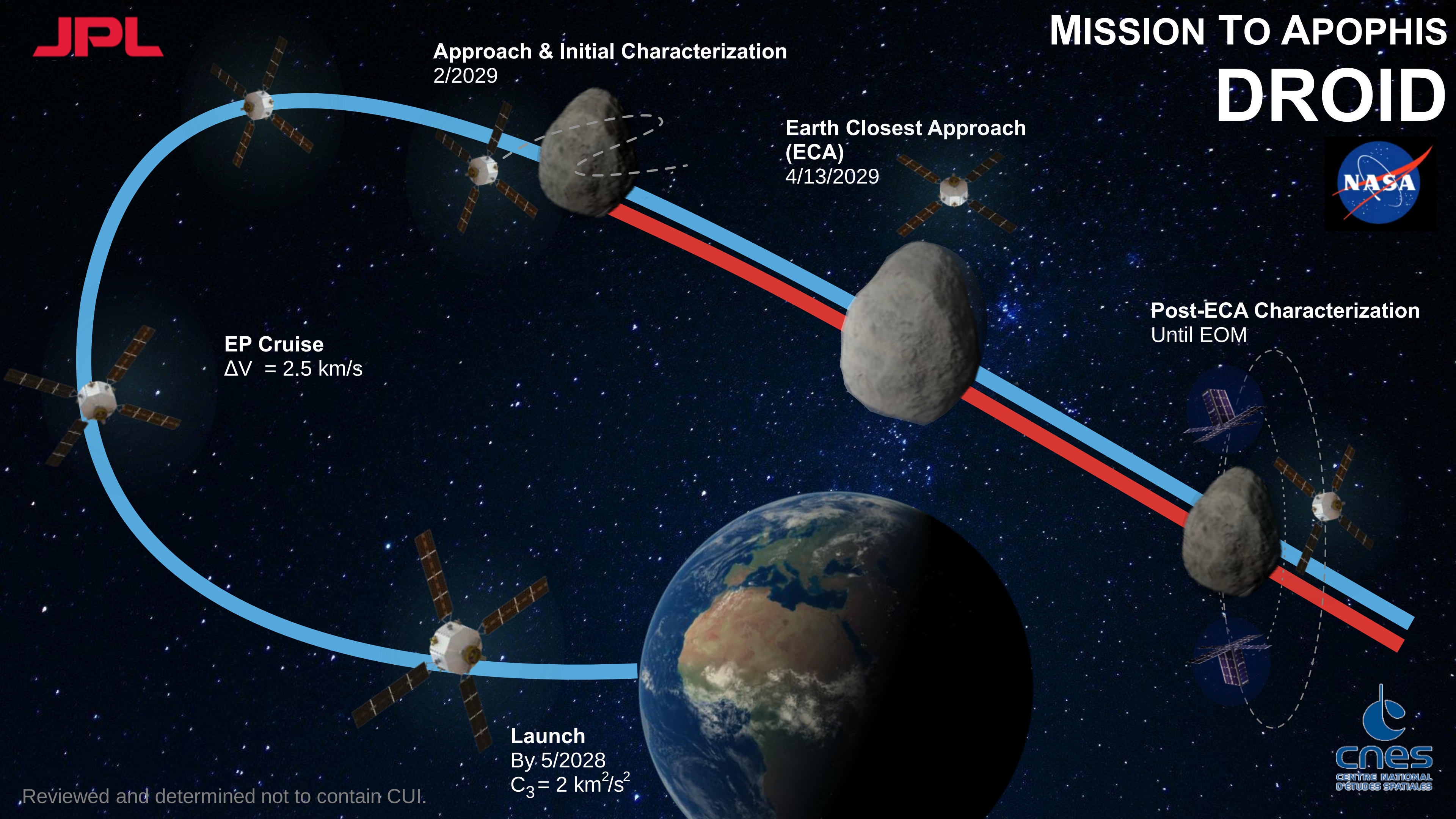
Less Obvious Challenges

- Mission assurance and reliability
- Multi-mission ground operation systems
- Planetary protection, Hazard avoidance
- Flight software standards

*Proposed Mission - Pre-Decisional – for Planning and Discussion Purposes Only


MARS PHOTO FROM MARCO
$40 COTS CAMERA

Reviewed and determined not to contain CUI.


JPL
MISSION TO APOPHIS
DROID
NASA
Approach & Initial Characterization
2/2029
Earth Closest Approach
(ECA)
4/13/2029
Post-ECA Characterization
Until EOM
EP Cruise
ΔV = 2.5 km/s
Launch
By 5/2028
$C_3 = 2\ km^2/s^2$
cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES
Reviewed and determined not to contain CUI.

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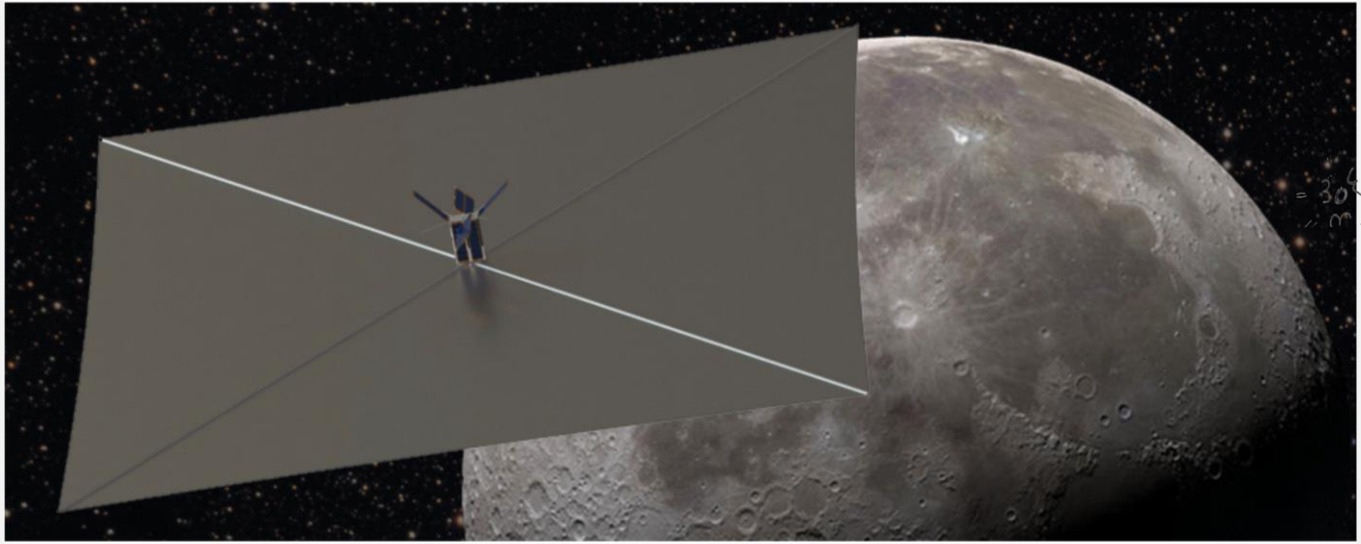
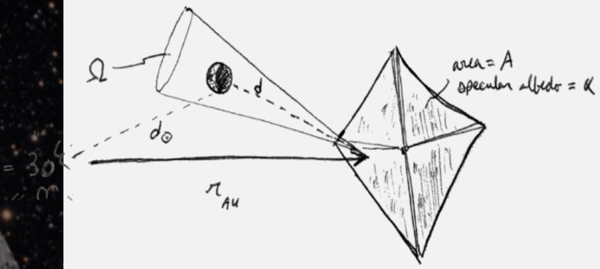
Lunar Flashlight History





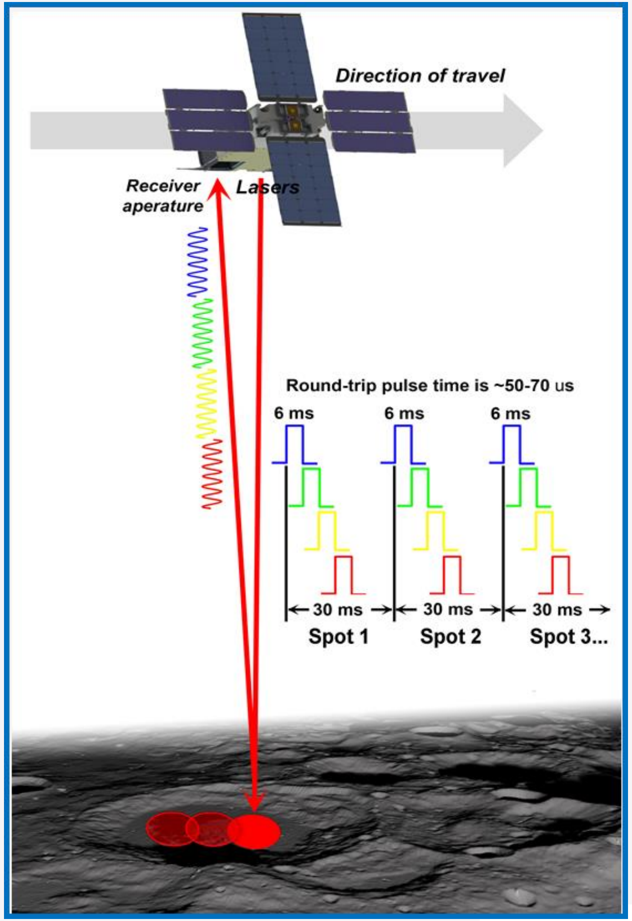
Sketch by P. Hayne (c. 2014) of the solar sail-based concept for Lunar Flashlight.

Because so few solar photons are reflected in PSRs, the mission could not rely on passive spectroscopy by solar illumination.
Maneuvering into and maintaining lunar orbit using a solar sail was almost impossible. LF project changed its technical approach, moving to a chemical propellant and to an active illumination source for measurement.

Lunar Flashlight Mission Objectives

- Demonstrate new technologies with a stretch goal of detecting surface ice deposits in the south pole lunar cold traps
- Demonstrated the following technologies:
  - Green monopropellant miniaturized propulsion system
  - First ~2U miniaturized 4 IR laser reflectometer
  - New C&DH sub-system: Sphinx computer board / interface board– now commercially available
  - IRIS deep space radio new generation with new firmware – now commercially available

Key Parameters				
Form Factor	**# Spacecrafts**	**Orbit**	**Altitude (perigee/apogee)**	**Launch Date**
6U	1	Lunar Orbit	10-20km Perilune ~65km Apolune	12/11/2022
Mass	**Dispenser or Interface**	**Mission Duration**	**Comm Licensing Status**	**Current Phase/Activity**
13.3 kg	6U dispenser	~1 year	Complete	Finished



Team Composition

Management	Principal Investigator	Project Manager	Mission Systems Engineer
Team Member Name	B. Cohen	J. Baker/P. Adell	A. Shao/C. Kneis
Organization	NASA-GSFC	NASA-JPL	NASA-JPL

Payload & Bus	Instrument #1	Tech Demo	Tech Demo	Spacecraft Bus
Title/Acronym	4 IR Laser Reflectometer	IRIS radio / C&DH	Green Prop System	Avionics
Organization	JPL	JPL	MSFC-GT	JPL

Data Systems	Mission Operations Center	Science Operations Center	Ground Station/Network	Data Repository
Title/Acronym	MOC	GDS	DSN	Science Data
Organization	GT	UCLA	JPL	GSFC

Lunar Flashlight Risks and Mitigations

Top 3 Risks….

	Risk Description	Mitigation Approach
1	Non-Flight Payload End-to-End Verification test	Extensive testing on the ground for instrument calibration
2	Non-Flight Propulsion End-to-End test (only one tank and once fueled no turning back)	Performance was verified using system-level flat-sat - Used spare controller, pump, valves, thruster - Used stand-in parts for manifold/tank - Verified all components worked as expected - Hot-fire testing verified that the system meets performance requirements
3	First time Georgia Tech operated a spacecraft	Extensive training by JPLers JPL shadowed GT during the entire mission operation

We carried about 58 Risks throughout the project

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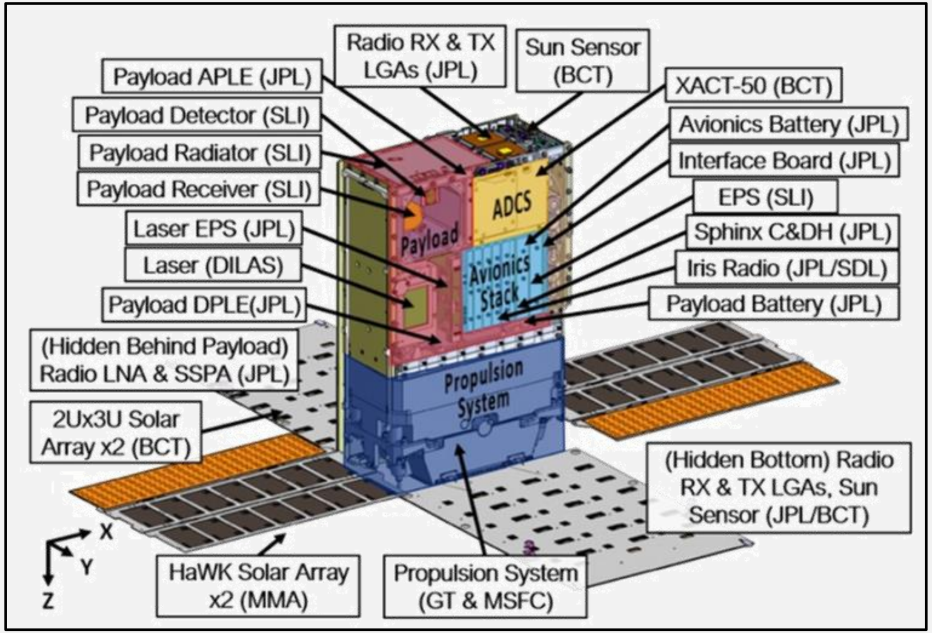
Mission Technology Objectives

L1 Technology Objectives	Technology Demonstration in Flight	
Lunar Flashlight size: LF shall be a 6U CubeSat form factor compatible with a NASA provided CubeSat deployer	This L1 requirement was met	✓
Weight less than 14 kg	Spacecraft measured mass: 13.29 kg	✓
Do not harm primary payload (succesful after launch)	Post-launch payload checkout was successful	✓
Test green propulsion (AF-M315E) technology at the CubeSat Scale (successful after first firing)	Fired the thrusters over 70 times	✓
Test Sphinx Flight Computer (successful upon boot up)	Flight computer successfully booted up and ran the SMS after launch	✓
Test C&DH interface board (successful post boot-up to assess other sub-systems)	All sub-systems interfaced with in flight	✓
Test in flight compact high power lasers at the CubeSat scale	Successfully fired during payload checkout activities and fired at 10, 30 and 90 seconds with a total of 14 firings	✓
Test IRIS radio with new performance upgrades	400+ successful contacts with the DSN (60-150 min) - in flight analysis allowed 2.5 hours in full duplex with ~30-60 min before next contact	✓

LF was a NASA funded technology demonstration mission with a secondary science goal of detecting water ice at the Moon PSR

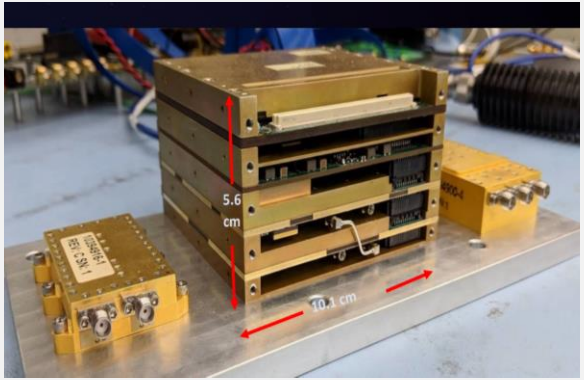
The Lunar Flashlight Spacecraft



Major Spacecraft subsystems and components (left) and the spacecraft photo during final I&T at Georgia Tech (right)

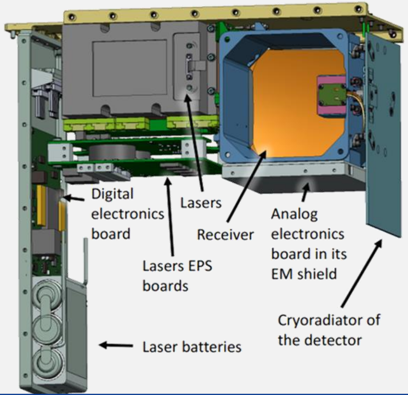
Four New Technologies successfully demonstrated

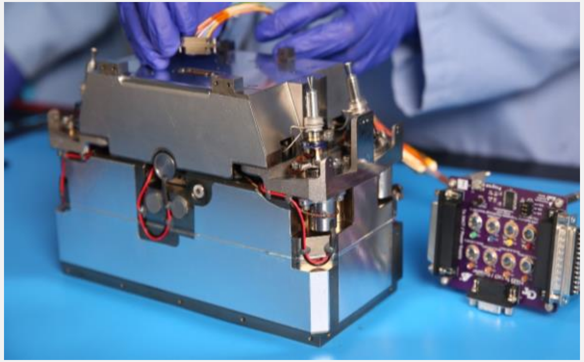
New C&DH sub-system: Sphinx new computer board with new interface board – Commercially available



IRIS deep space radio new generation with new firmware - Commercially available

First ~2U miniaturized 4 IR laser reflectometer to detect surface water ice





New Green propellant miniaturized propulsion system - Commercially available

FSW F-Prime, open source flight system product line for embedded systems

Key Sub-system Components

Subsystem	Description	Vendor	Subsystem	Description	Vendor
Instrument #1	4 IR Laser Reflectometer	JPL/SLI/DILAS	Sun sensors	4x with 0.05 deg accuracy	JPL
Bus C&DH	Sphinx	JPL/Cobham	**Bus Power**	Solar/EPS/Batteries	-
Processor	GR712 LEON-3	Cobham	EPS	9-12.3 V unregulated / 5 and 3.3 V regulated Power board	JPL/SLI
Data Storage	256 Mb – SDRAM 8G - NAND	3Dplus	Batteries	6.2 Ah, 3s2p Panasonic 18650 Li-ion Cells- 49 W/hr	Panasonic
Bus Comm	IRIS deep space radio	JPL/SDL	Solar Array	2Ux3U Solar Array x2 Hawk Solar Array x2 60W/hr	BCT MMA
Radio	IRIS X-Band transponder	JPL/SDL	**Propulsion**	AF-M315E pump fed miniaturized propulsion system	MSFC/GT
Antenna	Rx / Tx LGAs	JPL	Thrusters	4x100mN	Rubicon
Bus GNC	GNC Module	BCT	Propellant	AF-M315	AFRL
XACT-50	GNC module (RW 3x50 mNms, Star tracker ~0.01^0, IMU 3 deg/h bias)	BCT	Tank	AM Ti-6-4 manifold	GT/MSFC

FSW F-Prime, open source flight system product line for embedded systems

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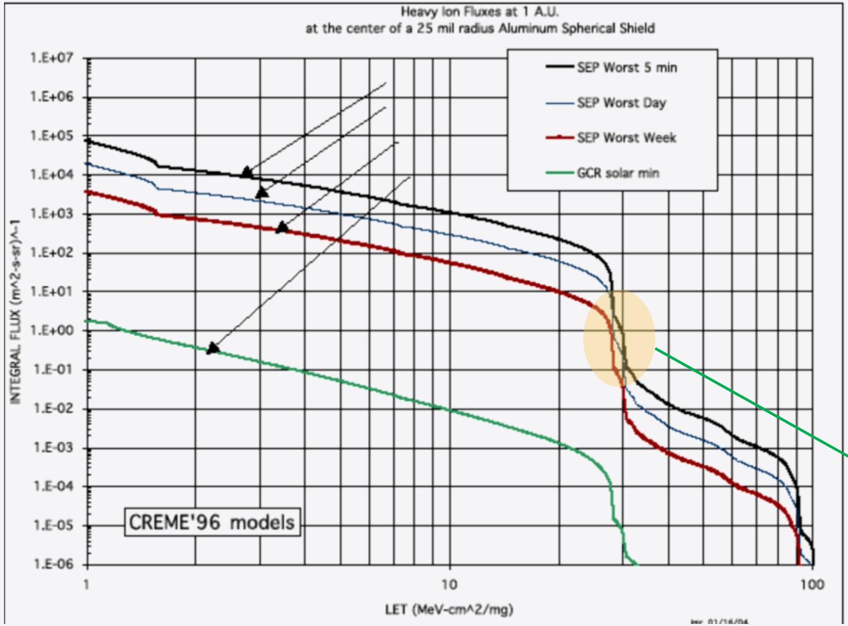
Lunar Flashlight Radiation Requirements



SEP and GCR Heavy Ion Fluxes behind 25 Mils Aluminum shielding (CRÈME96 Model)

TID level was 10 Krad (Si) at 100 Mil of Aluminum shielding

No Critical Event at an LET of 37 MeV.cm^2/mg is typical for low cost mission
Followed JPL standard for Type II/Tech demo

Radiation Hardness Assurance (RHA) - LF

- Lunar Flashlight TID assessment relied on a good part review process
  - Because of TID requirement is not benign, we relied on an hybrid architecture
  - Parts review focused only key radiation effects: destructive (SEE and SEL) and total dose with **RDF=1**
  - No **radiation lot acceptance testing (RLAT)** were performed
  - Relied on existing data of equivalent parts or technologies from reliable source
  - For key sub-system, relied on **some board level testing** (i.e. propulsion system)
  - For parts that did not meet the TID requirement, parametric or functional we used a **shielding analysis approach and accepted the risk**

We did not go fully COTS – we use an hybrid approach

Radiation Hardness Assurance (RHA) - LF

PARS Parts Acquisition and Review System

PARS Overview PARS Help

Home | Parts Search | Philippe C Adell [LogOut] | Logged In as: JPLe

Public View | My Dashboard | Report

Project: Show All ☐ Include Archive

Report

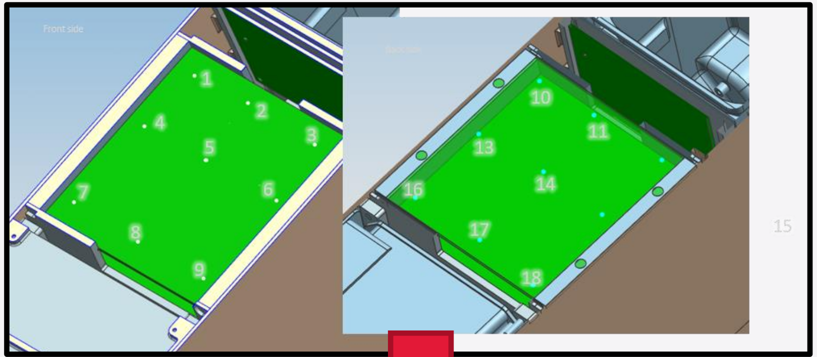
Parts Manager Module (CogE-View)

Part Lists (CogE)

Project	Part List Name	#Parts Changed	#Parts Require Attention	Recently Submitted	#Active Parts	#Total Parts	Last Modified
Lunar Flashlight	EPS (**EPS**) (Review) (Edit)		0	54	54	75	
Lunar Flashlight	Interface Board (**Interface Board**) (Review) (Edit)		0	56	57	62	
Lunar Flashlight	Driver Connect Board (**LFPS Driver Connect**) (Review) (Edit)		0	8	8	8	
Lunar Flashlight	Main Controller Board (**LFPS Main Controller**) (Review) (Edit)		0	59	59	59	
Lunar Flashlight	Sensor Board (**LFPS Sensor**) (Review) (Edit)		0	15	15	15	
Lunar Flashlight	Analog Electronics (**Payload Analog**) (Review) (Edit)		0	9	9	9	
Lunar Flashlight	Digital Electronics (**Payload Digital**) (Review) (Edit)		0	64	64	64	
Lunar Flashlight	Power Payload (**Power Payload**) (Review) (Edit)		0	40	41	41	
Lunar Flashlight	Sphinx FM (**Sphinx FM**) (Review) (Edit)		0	66	66	74	
Lunar Flashlight	XACT (**XACT**) (Review) (Edit)		0	30	30	30	

About 500 active parts were used to build the spacecraft – 50% were COTS parts

Residual Parts not meeting LF TID level



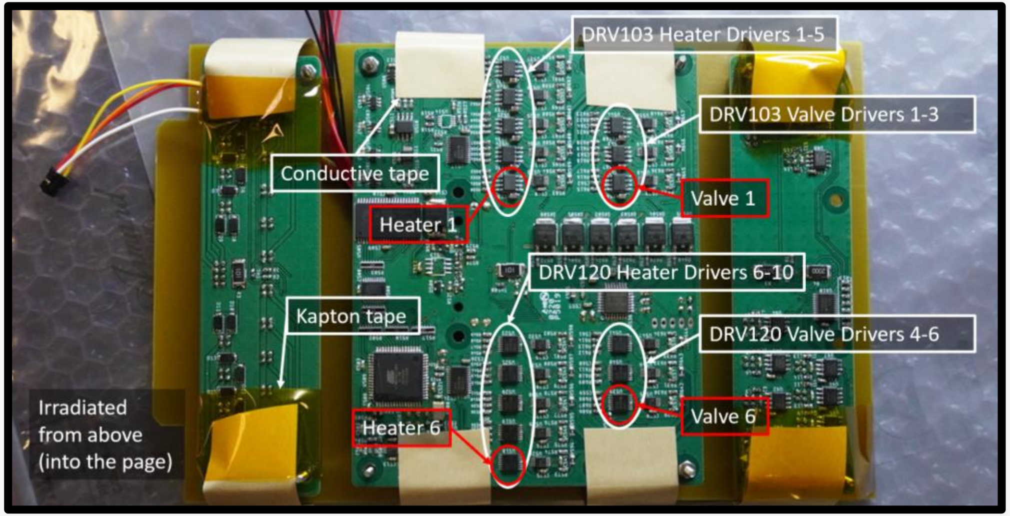
- About 10% of component were accepted after shielding analysis
- Relied on relevant parametric degradation without margin

Board	TID (rad, Si) RDF=1
Board 1	3.87E+02
Board 2	7.83E+02
Board 3	1.04E+03
Board 4	3.96E+03
Board 5	1.91E+03

We ran a COARSE shielding analysis to assess parts TID level within the S/C structure

Board Level TID Testing

Results on Prop system controller



DRV103 Valve 1 output voltage after 30krad showing proper operation (peak/hold PWM)

- For cost reason, board level testing was selected and give a more representative system response
- Test at High Dose Rate (10 rad/s) to 30 krad [0, 10, 20, 25 ,30]
- 12 parts show no measurable degradation when operating in the system
  - Only 2 parts showed parametric degradation and were accepted after refined shielding analysis

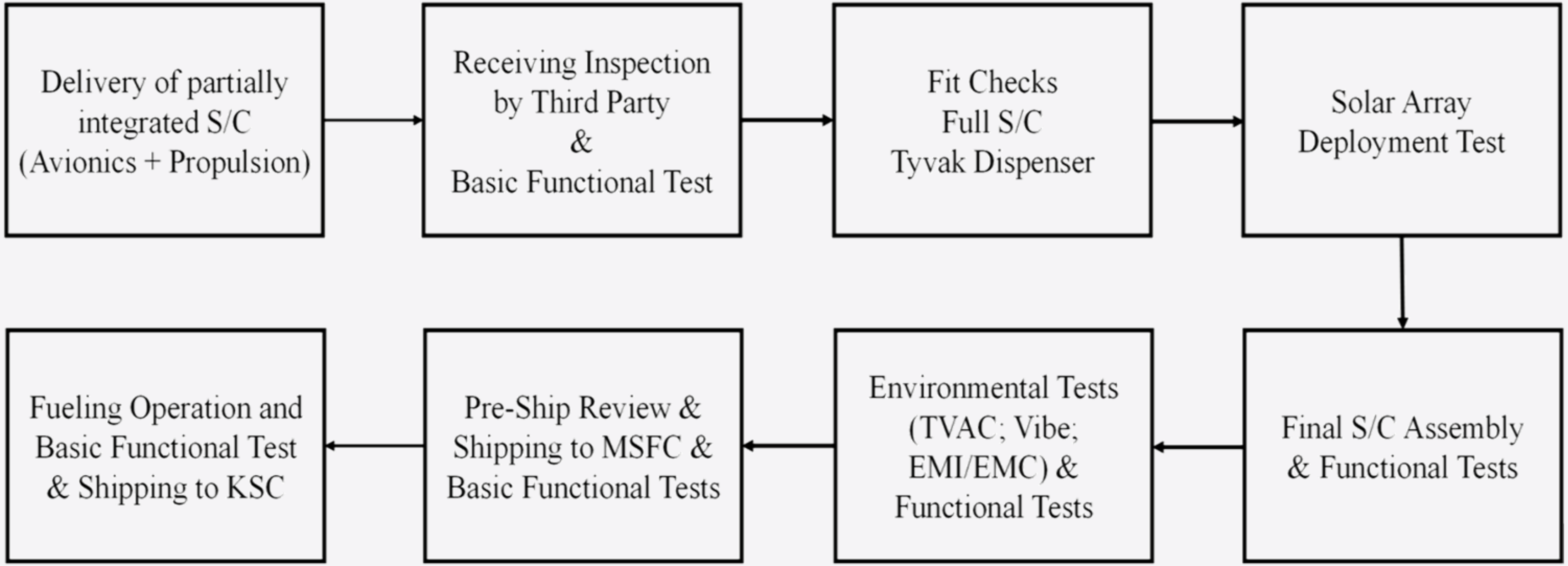
Board level testing showed as a promising cost-effective approach

RHA Summary

- **Define the environmental threats**
  - TID was a threat as well as Destructive SEEs (SEB, SEL and SEGR)
- **Set survivability requirements**
  - For TID we used 10 krad (Si) with an RDF of 1
  - For SEE we used type II SEE requirements; i.e. not even at LET of 37 MeV.cm^2/mg
- **Apply existing data and/or test sensitive components**
  - Use existing data obtained on other program from JPL database (reliable source)
  - Removed parts that failed functionally
  - Use board level testing when applicable
- **Explore mitigation solutions as required**
  - For parts that failed parametric; look at the design and assess impact
  - For parts of concerns; run a COARSE shielding analysis to assess "real" TID level
- **Use COTS parts where you can; otherwise use Rad-Hard parts**
  - For key sub-system we used an hybrid approach (combination of COTS and Radhard components)

Spacecraft Electronics performed very well during 12 months operation

Basic LF Spacecraft I&T Flow



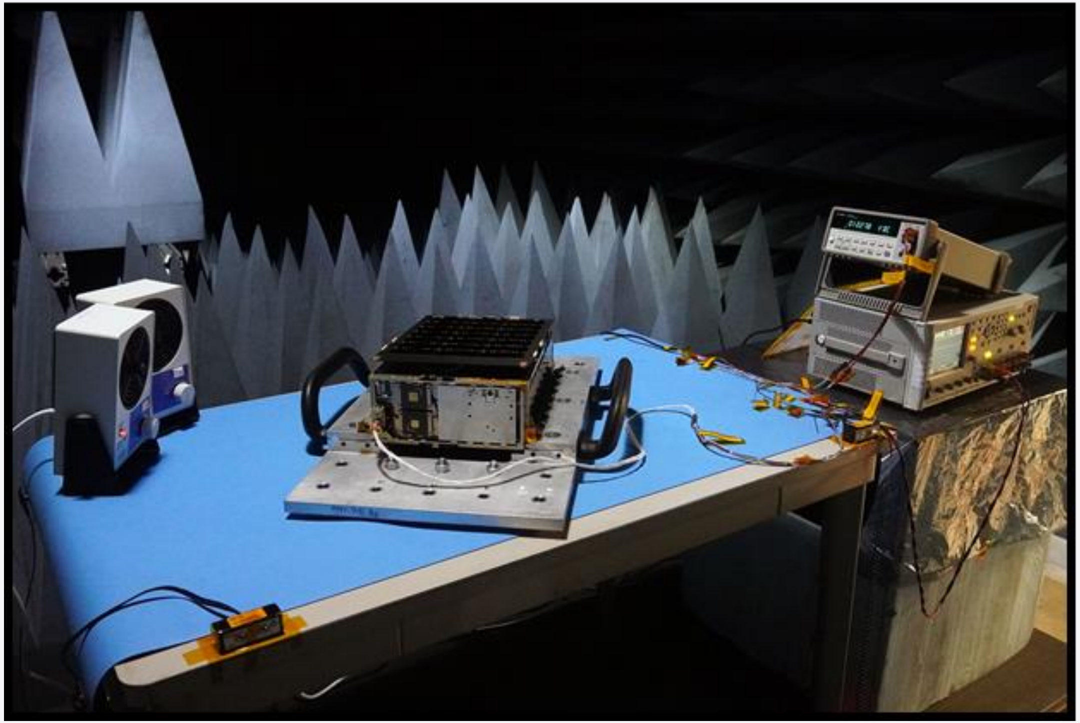
JPL provided integrated avionics + instrument + solar arrays
MSFC-GT provided propulsion system
Georgia Tech was third party integrator to S/C delivery

Vibe Test @GT

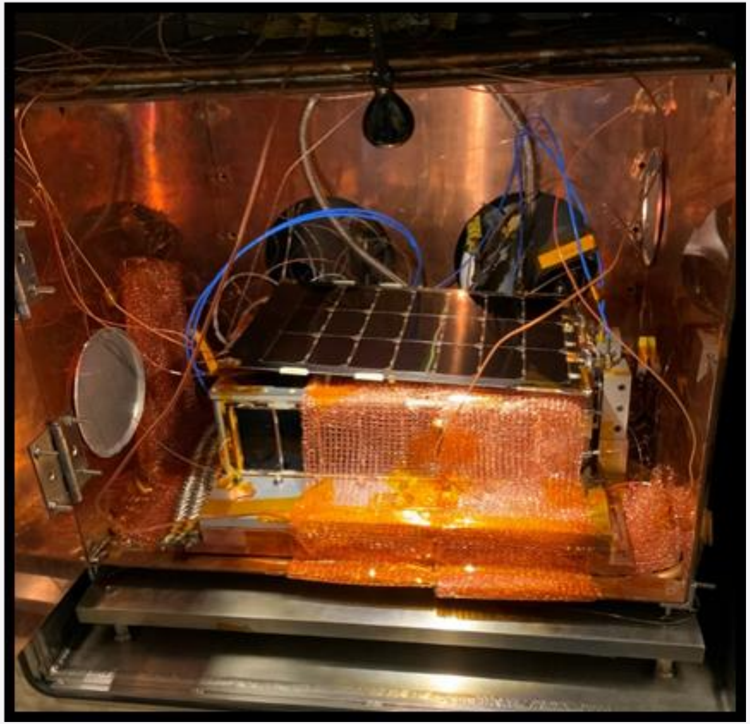

Ch 14, 15, 16
Ch 11, 12, 13
Ch 17, 18, 19
Ch 14, 15, 16
Ch 17, 18, 19
Ch 8 (not shown)
Ch 2
Ch 1
Ch 7 (not shown)
Ch 10 (not shown)
CH 20, 21, 22 (not shown)
CH 9 (not shown)

Plug Out Test and TVAC Test @GT

Plug out Test

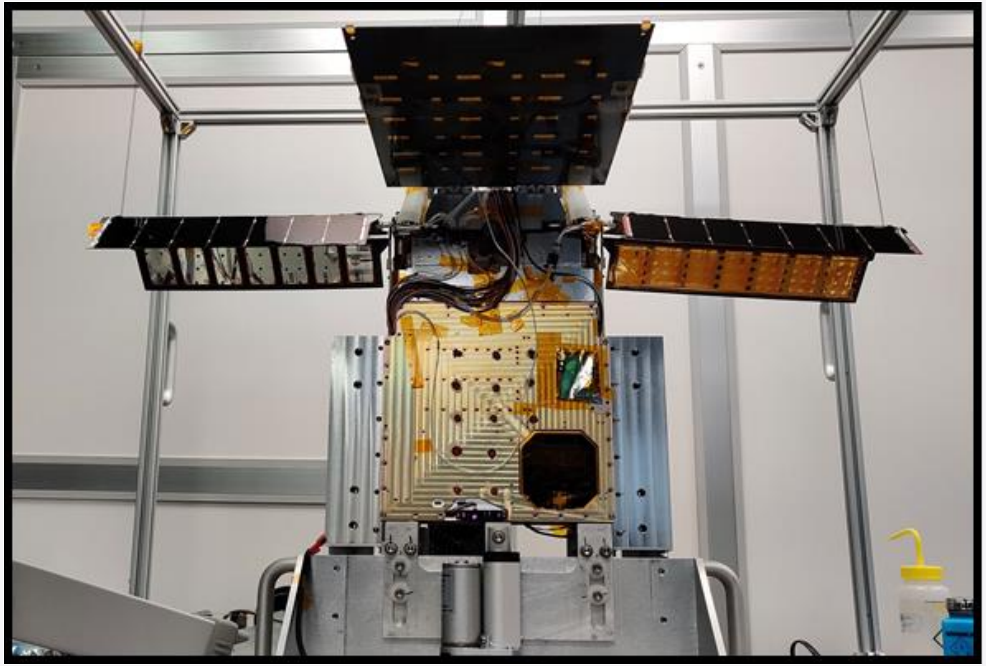


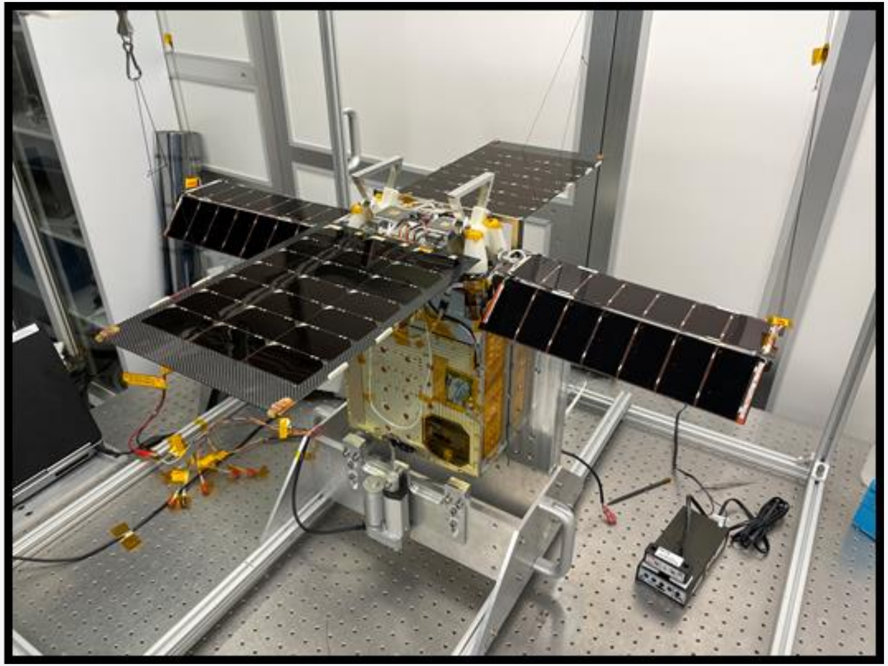
TVAC Test



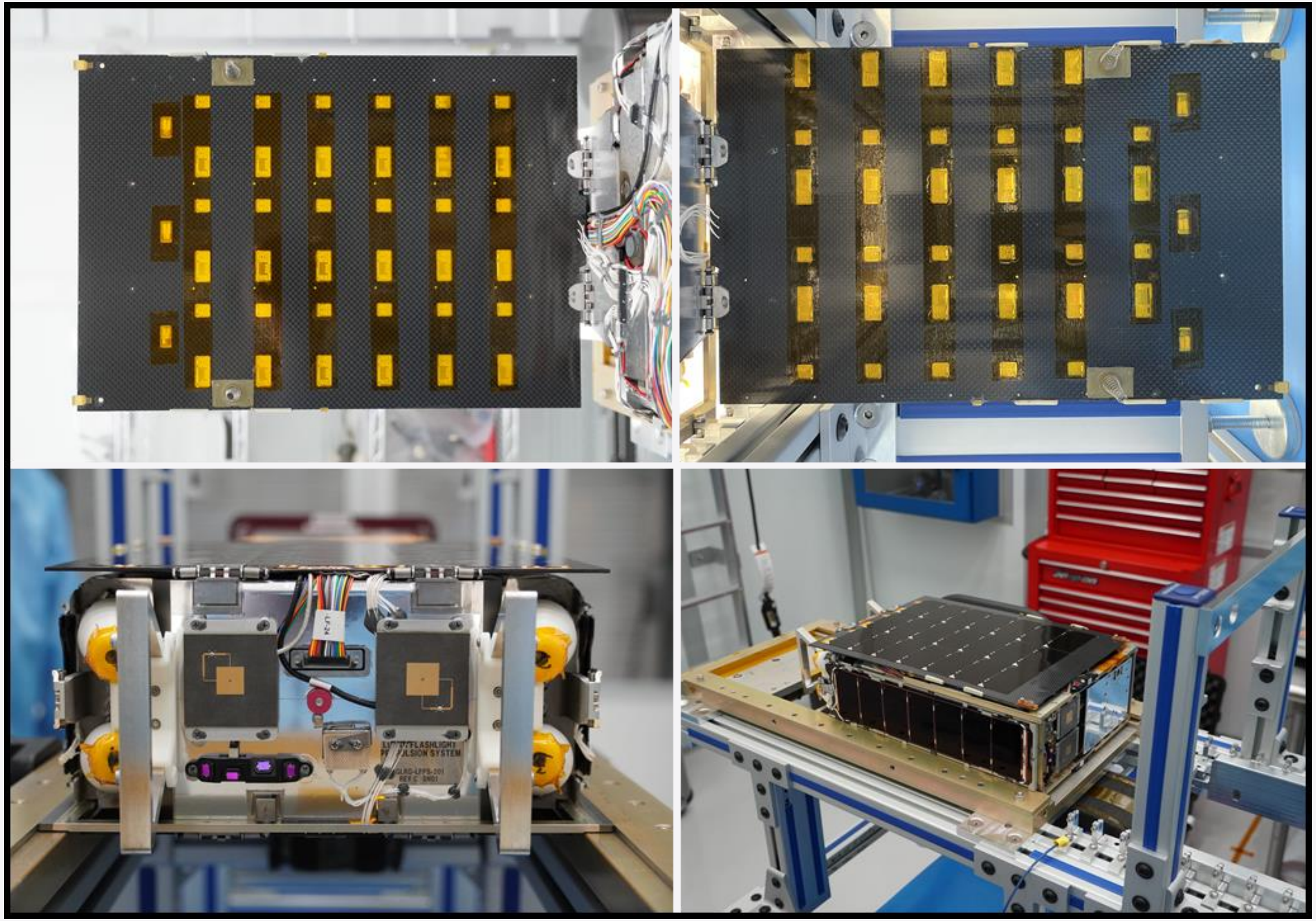
Reviewed and determined not to contain CUI.

Solar Array Deployment Test





LF photos prior to packing…



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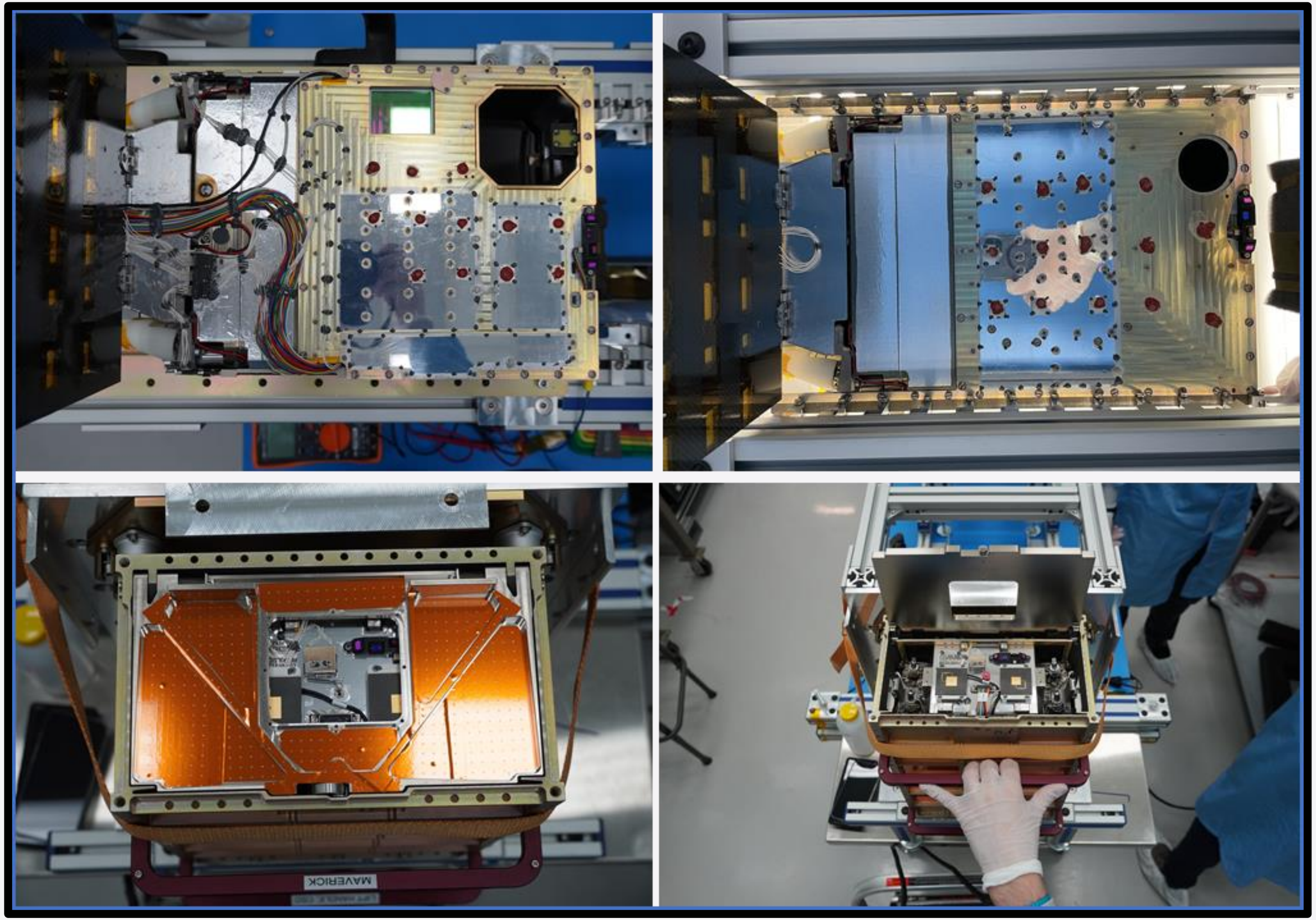
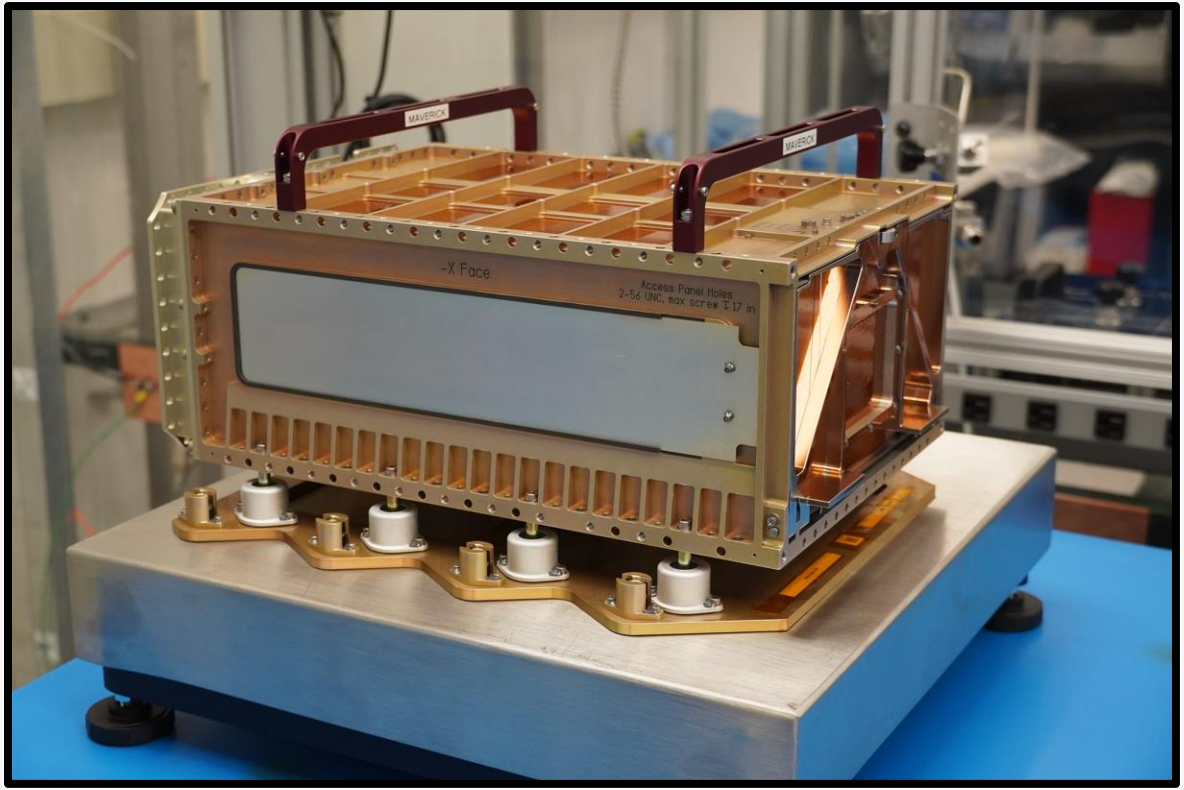


LF Prior to shipping



Lunar Flashlight captured in Dispenser
Shipping from MSFC to KSC on **November 9th 2022**

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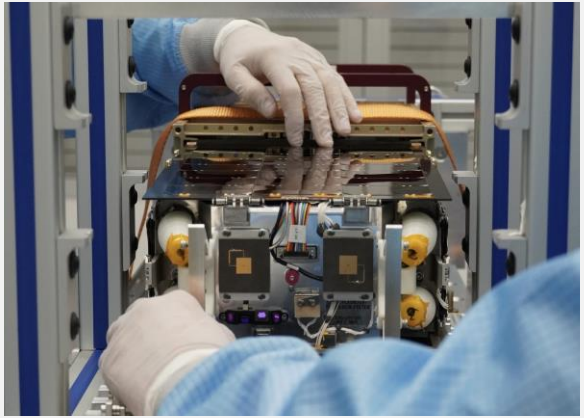
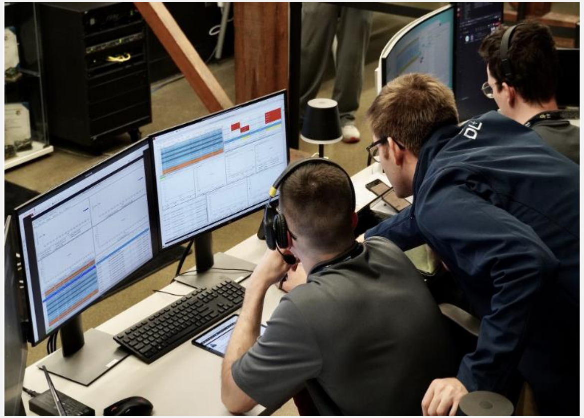
Successful Launch – December 11, 2022



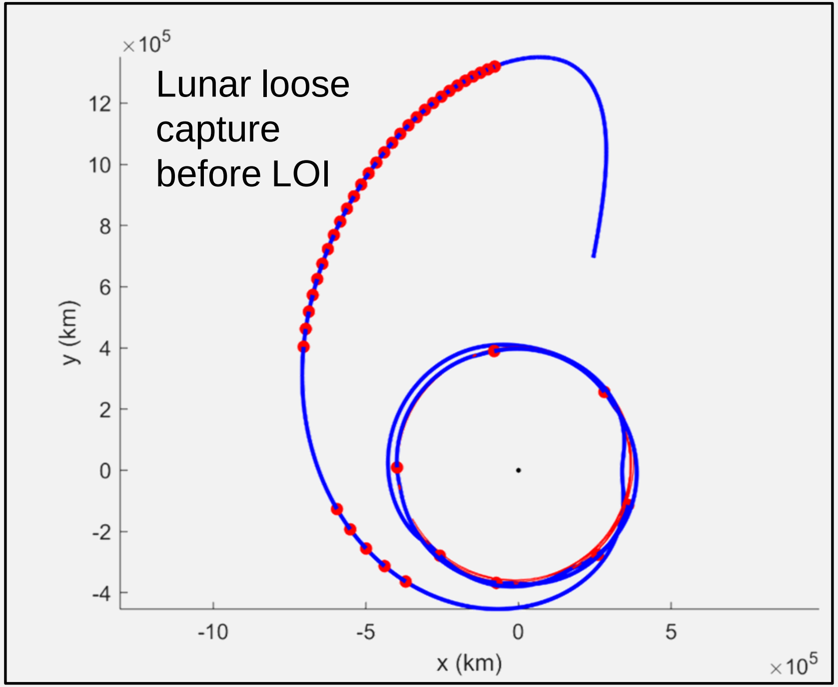


LUNAR FLASHLIGHT ANIMATIONS

11/14/2022

Early Operations
…quickly into an anomaly mode

- **Immediate thruster problems**
  - First de-sat increased spacecraft momentum state
  - Severe Thruster 1 underperformance
  - Initial testing showed Thruster 3 low performance
  - During further testing, Thruster 2 went to zero
- **Resulting priorities for LF team**
  - Update FSW and ACS params to operate safely during thruster testing
  - Figure out how to do TCMs
  - Find a trajectory with delayed TCMs
  - Figure out smaller LOI
  - Try to recover thruster performance
  - **Implement rotating TCMs**



After a few months of operation, we tried many TCM scenarios but propulsion system could not give us expected performance

Mission Science Objectives

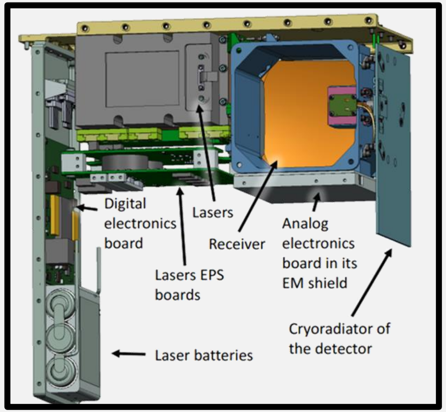
[Old L1 Mission Objective] L1-01: Address SKG - Lunar Flashlight shall have the capability to address a key strategic knowledge gap at the moon. Full Success Criteria: Detect and map surface water ice on the moon with a spatial resolution of 1 km over 10% of the permanently shadowed and occasionally sunlit regions poleward of 80 deg S latitude. Minimum Success Criteria: Demonstrate the ability to detect surface water ice content with a spatial resolution of 10 km or better with multiple measurements in permanently shadowed and occasionally sunlit regions poleward of 80 deg S latitude.	This L1 requirement was deprecated after the propulsion system anomaly was discovered and assessed, but the flight data from the successful payload firings and payload dither activity indicate that the payload worked as expected, and that theoretically the laser technology would allow us to detect surface water ice content in permanently shadowed and occasionally sunlit regions of the moon. Though we were unable to make it close enough to the moon to demonstrate this, the data indicates that the payload would have operated as intended at the moon.

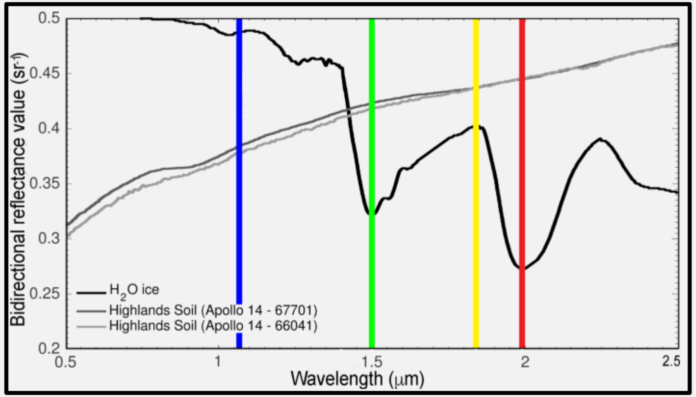
Due to the propulsion system anomaly, LF could not reach the moon; impacting L1 science requirement even we proved the instrument could have detect surface water ice based on flight date

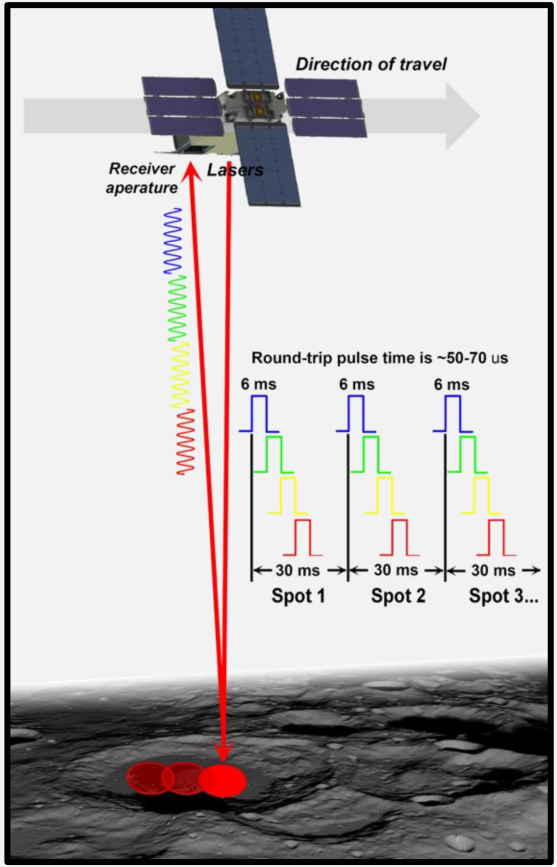
Key results 1 – LF instrument operation – Now TRL 9

4-Laser IR reflectometer: concept of operation

- Lasers in 4 different near-IR bands illuminate the lunar surface in a spot ~15-20 m in diameter
- Light reflected off the lunar surface enters the spectrometer to distinguish water ice from regolith
  - Band depths to absolute reflectance values
  - Correlated bands to disambiguate water ice from CO_2

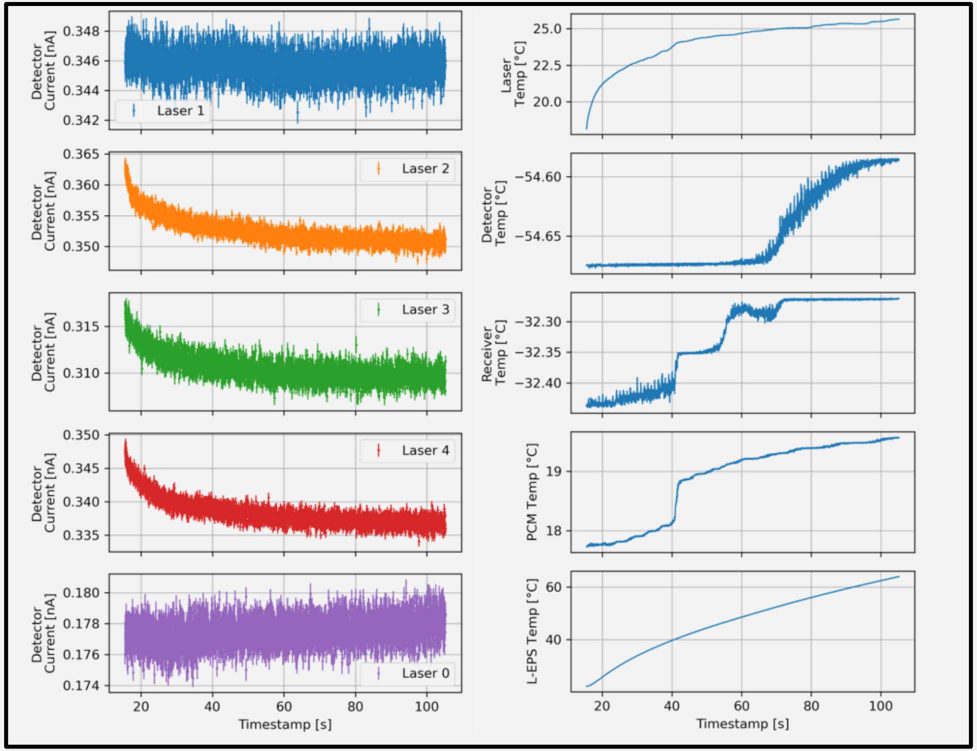






Key results 1 – LF instrument operation – Now TRL 9

Successful flight demonstration – many successful laser firing sequences



Sensor	C207 (T)	ETE-4 (T)
Laser	18.1 – 25.6	19 – 26
Detector	-54.63	-61
Receiver	-32.35	-37
PCM	17.7 – 19.6	17 – 19
L-EPS	22.2 – 64.0	30 – 70

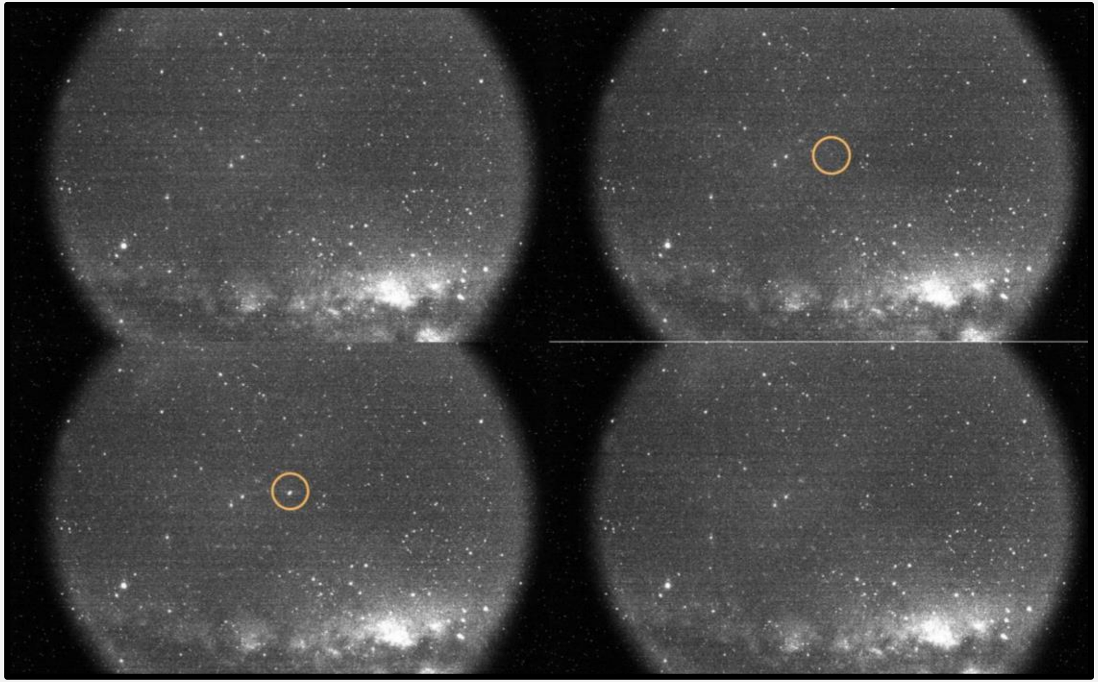
Detector rms noise performance in flight with 5.9 pA rms (better than ground data)

In Flight Data ~90s experiment – detect surface ice at the Moon feasible

Key results 1 – LF instrument operation – Now TRL 9

Panopticon (P007) – Antofagasta, Chile 05/17/23

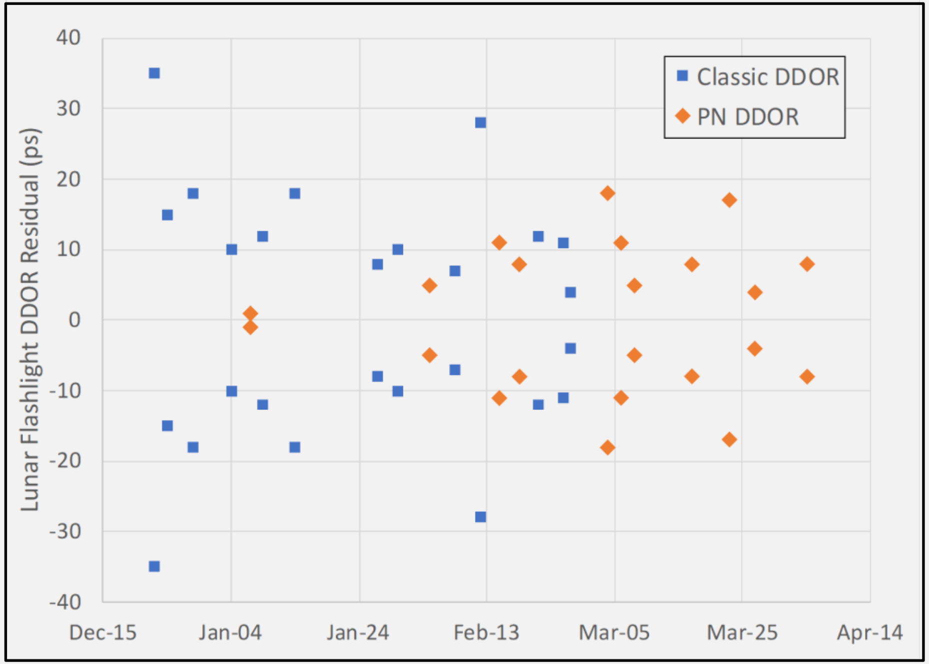
Detected 09:10:34 UTC. Scheduled 09:00:00-09:14:06 UTC



Passing by Earth was an opportunity to fire payload laser at couple of observatory

Key results 2 – PN DDOR

Pseudorandom-Noise (PN) Delta Differential One way Ranging (DDOR) with DSN

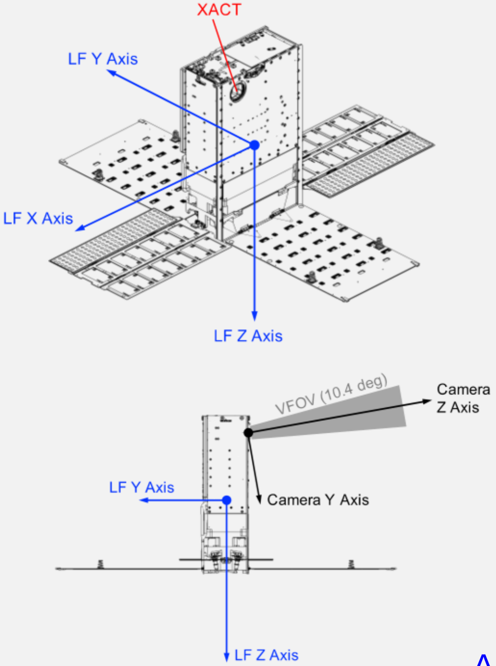


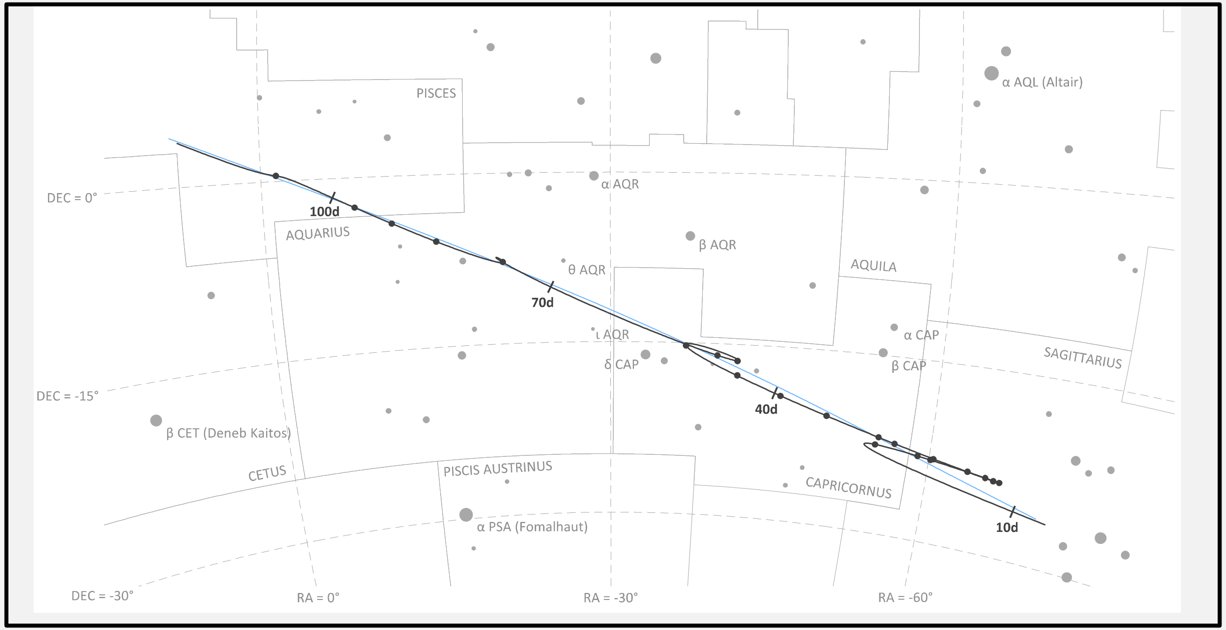
- DDOR provides critical navigation data with less spacecraft transmission than ranging/doppler and less antenna contention on busy launches
- PN DDOR enhances Classic DDOR with improved ambiguity resolution and performance
- The Iris radio has successfully demonstrated PN DDOR in-flight on Lunar Flashlight

Residuals showed consistency between classic and PN DDOR
1st LF PN DDOR benefited from improved ambiguity resolution

Key results 3 – OPNAV (1/2) – Extended Mission

The Lunar Flashlight Optical Navigation Experiment with a Star tracker





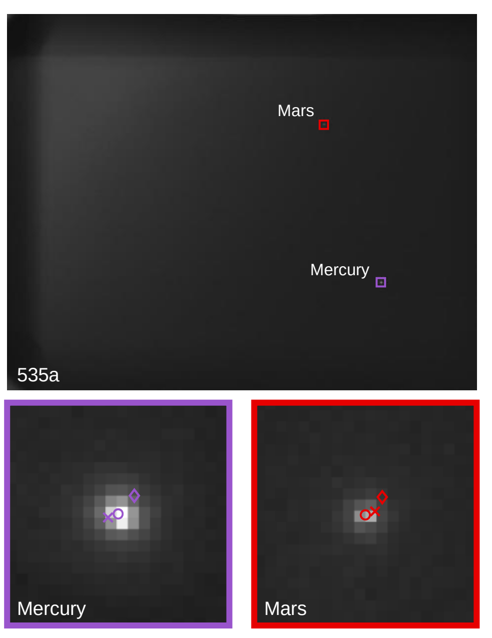
Apparent path of Moon (black) and Earth (blue) as seen by LF against the celestial sphere during the LONEStar OPNAV campaign. Black dots are Moon line-of-sight measurements.

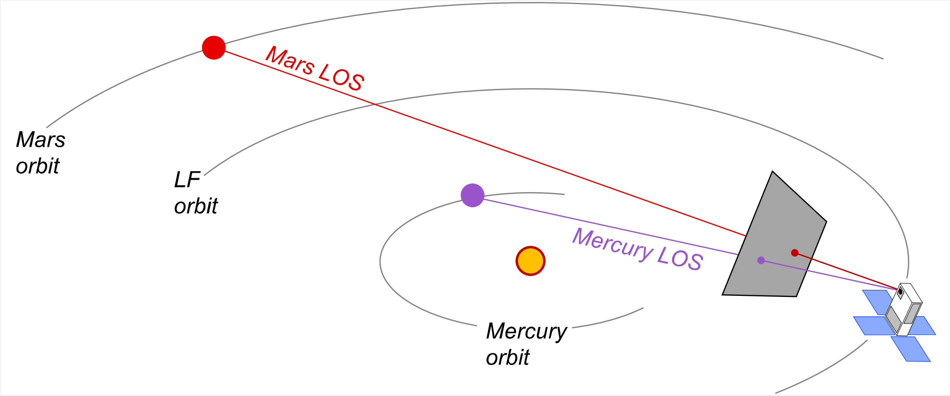
(LONEStar) demonstrated new celestial triangulation algorithms in heliocentric space using nearly 400 images of stars, distant planets, and the Earth and Moon

Key results 3 – OPNAV (2/2) – Extended mission

Simultaneous imaging of Mercury + Mars permitted instantaneous localization of the LF spacecraft using the new LOST algorithm

Short exposure OPNAV images





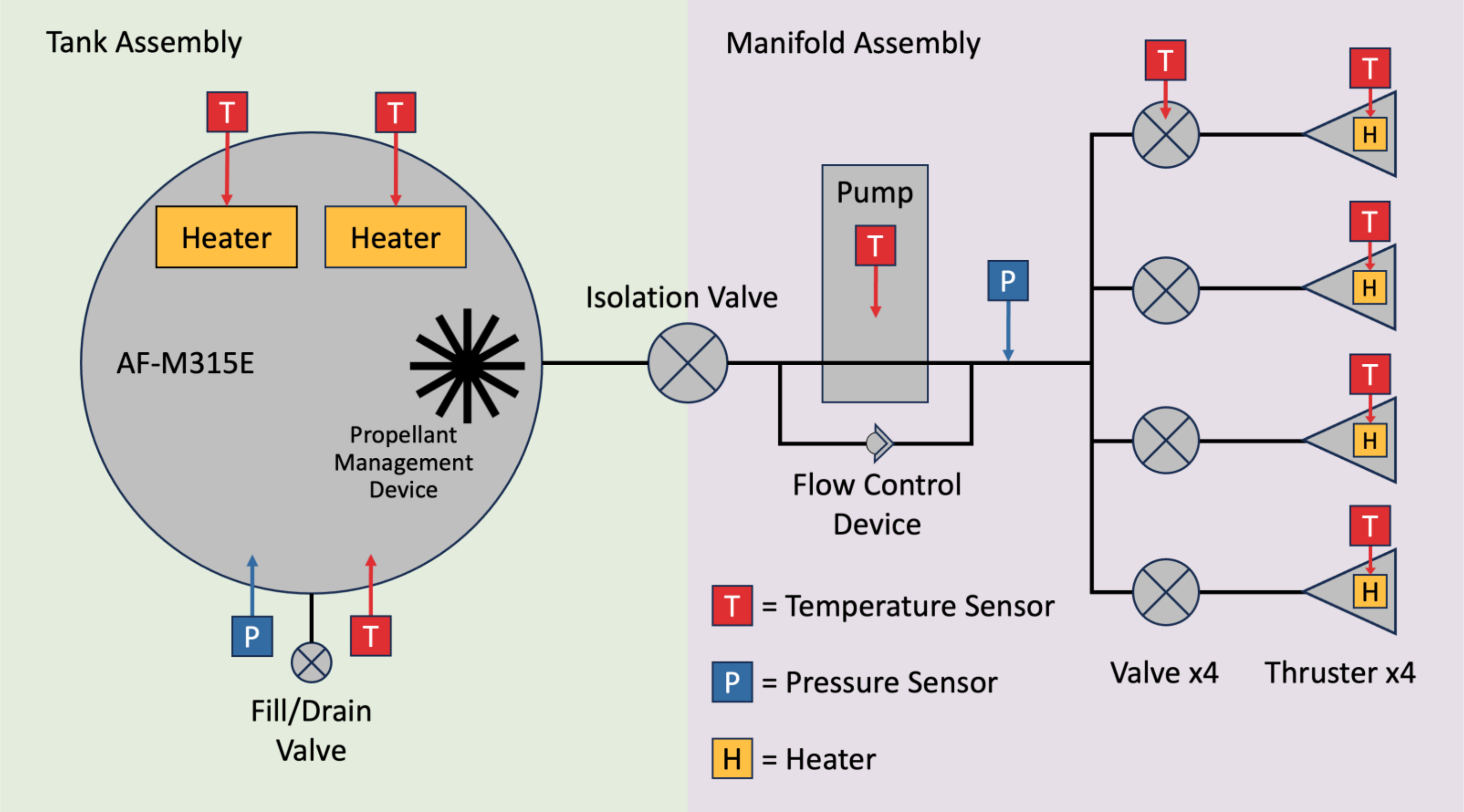
Long-exposure star images (inside Sun KOZ)

The entire Mercury + Mars imaging campaign was conducted within the camera's recommended Sun Keep-Out-Zone (KOZ).

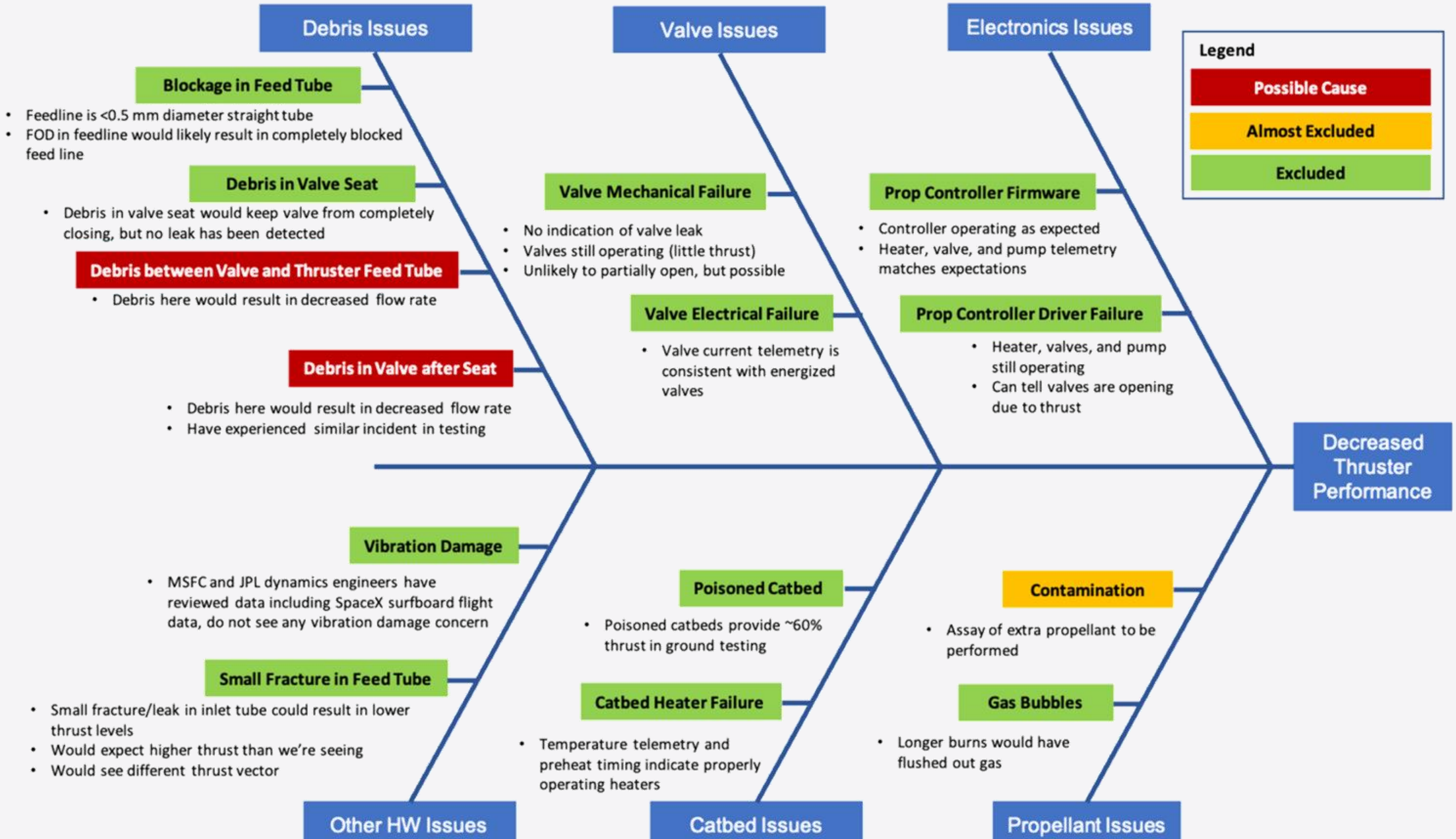
Outline

- Why are we using Small Spacecraft Technologies
- Past and future deep space mission using Small Spacecraft
- **Lunar Flashlight mission overview**
  - History and Background
  - Mission Technology objectives and Spacecraft Overview
  - Radiation Hardness Assurance and I&T activities
  - Operation activities and in-flight technology demonstrations
  - **Propulsion anomaly**
  - Conclusion and Lessons Learned

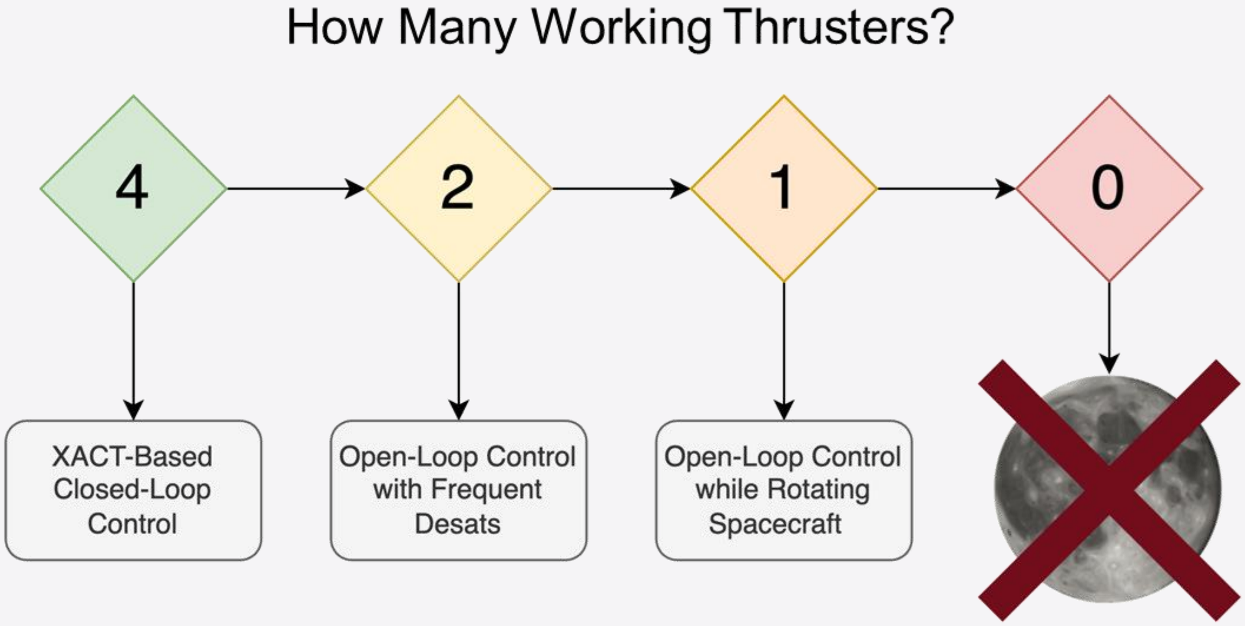
Lunar Flashlight Propulsion System (LFPS)



Final Fish Bone

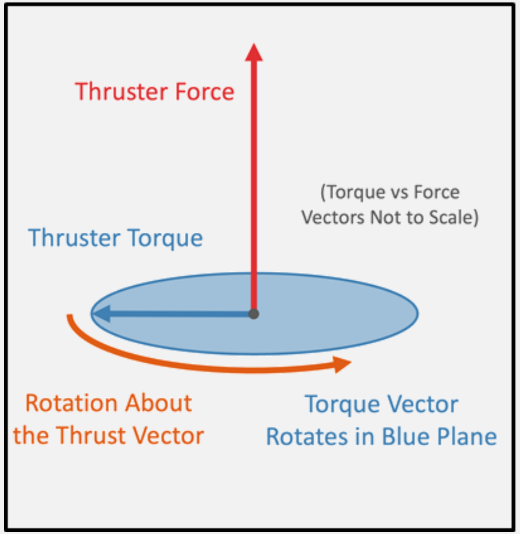


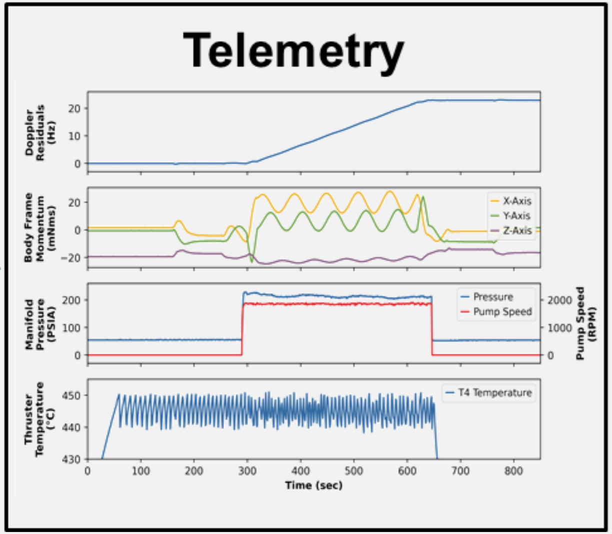
So, how do we get to the Moon?

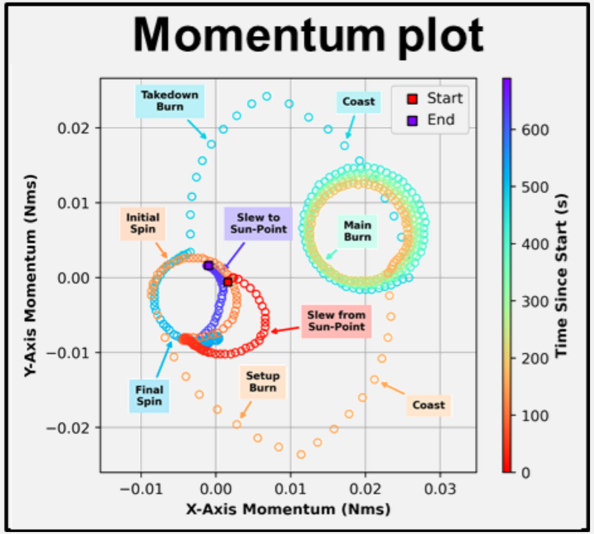


Key results 4 – Rotating TCM with single thruster

Rotating TCMs Worked!



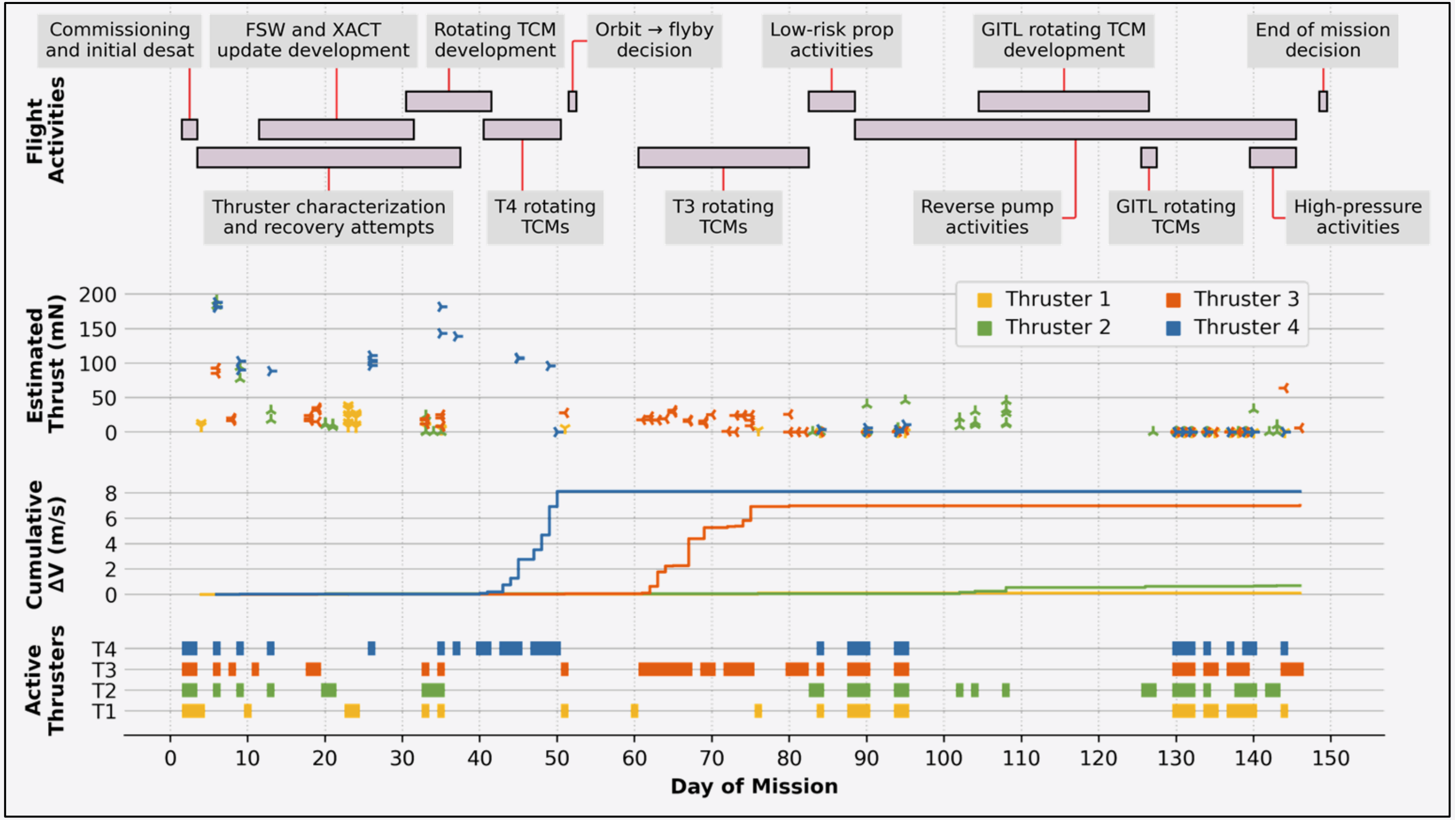




- Rotate the spacecraft about the force vector (using the reaction wheels) while firing a thruster to generate torque
- Over a complete rotation, the torque impulses cancel out
- Pick rotation rate and average torque level (thruster duty cycle) to keep momentum within reaction wheel capacity

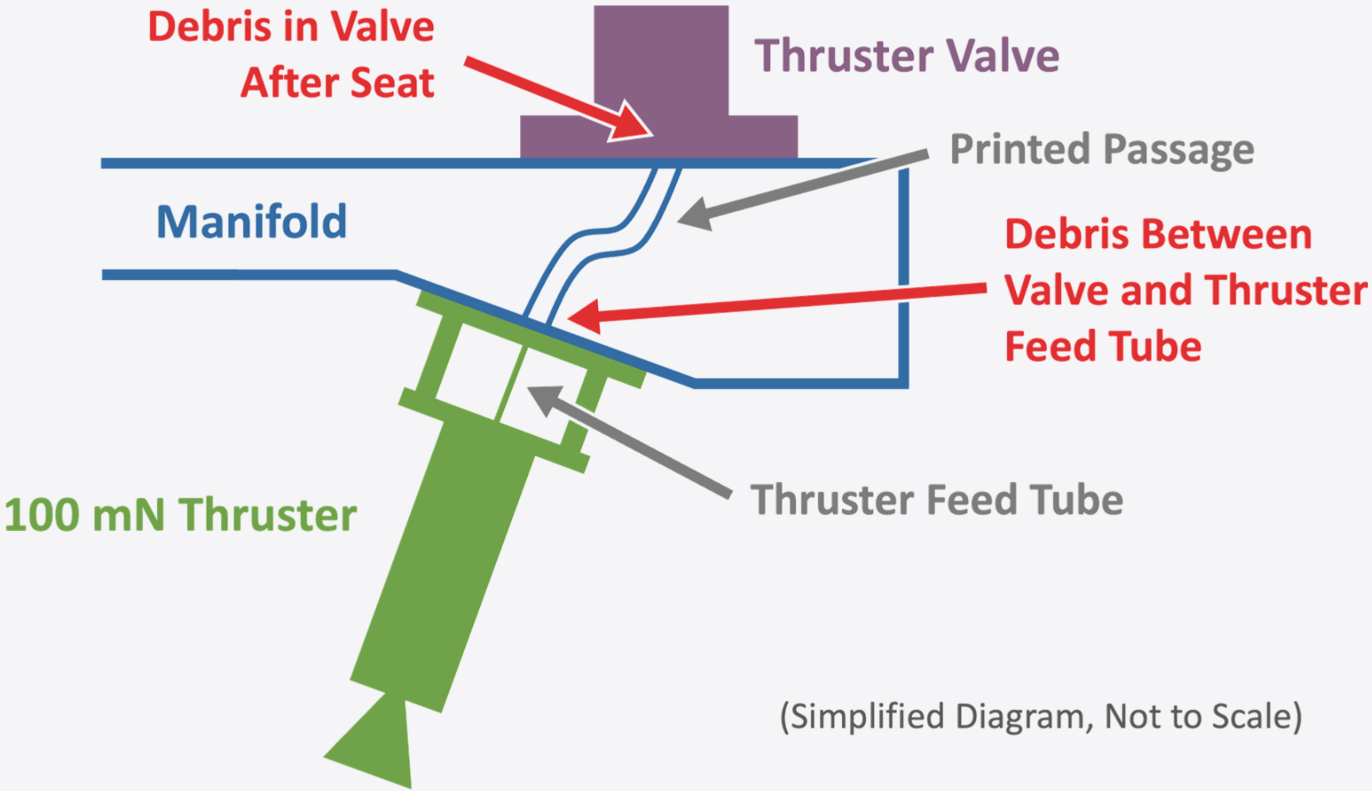
Due to propulsion anomaly, LF team had to be creative to develop TCMs

Lunar Flashlight Propulsion System Flight Activities and Performance



We got about 16.2 m/s out of the propulsion system; not enough to get to the moon!

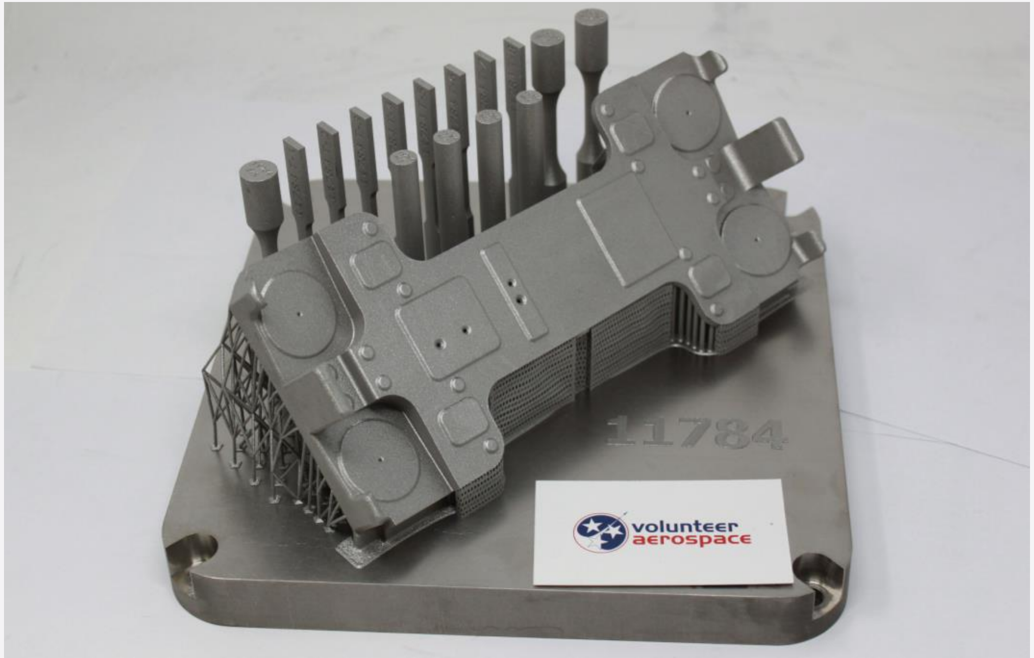
The Culprit



(Simplified Diagram, Not to Scale)

Lessons Learned and Recommendations: Design

- **Potential Sources of FOD**
  - Sintered particles or powder from the additive manufacturing process
  - Machining debris/burrs
  - Krytox lubricant
  - Methods of dislodging
    - Launch / prelaunch vibration loads
    - Cyclical pressurization and flow
- **Prevention**
  - Chemical etch surface finish
  - Abrasive cleaning
- **Mitigation**
  - Filters



Printed Manifold

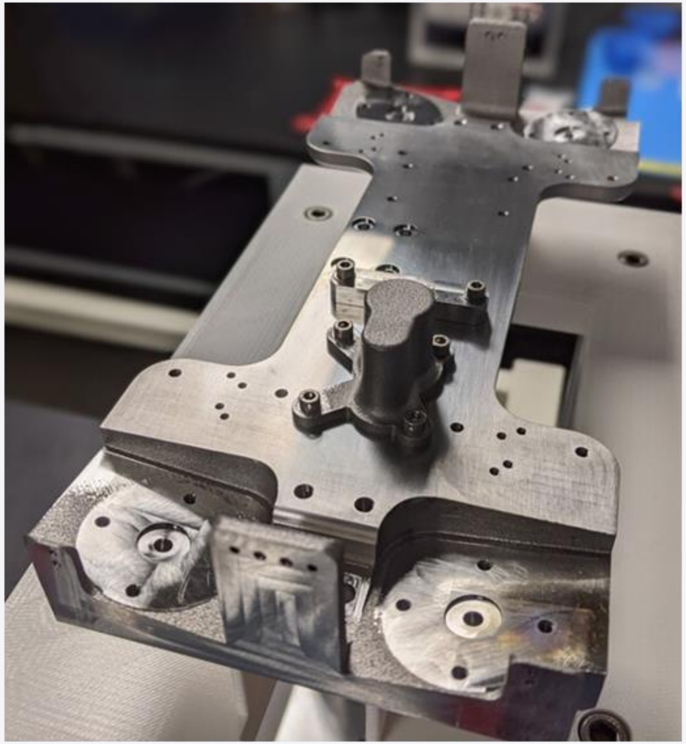
Lessons Learned and Recommendations: Testing

CT Scanning
- Might have spotted potential FOD

Flight-Like Hot-Fire Testing
- No flight-like tank/manifold

Liquid Flow Testing
- Only used helium

AM Parts Vibration Testing
- Only tested at system level



Printed Manifold after Machining

Conclusion

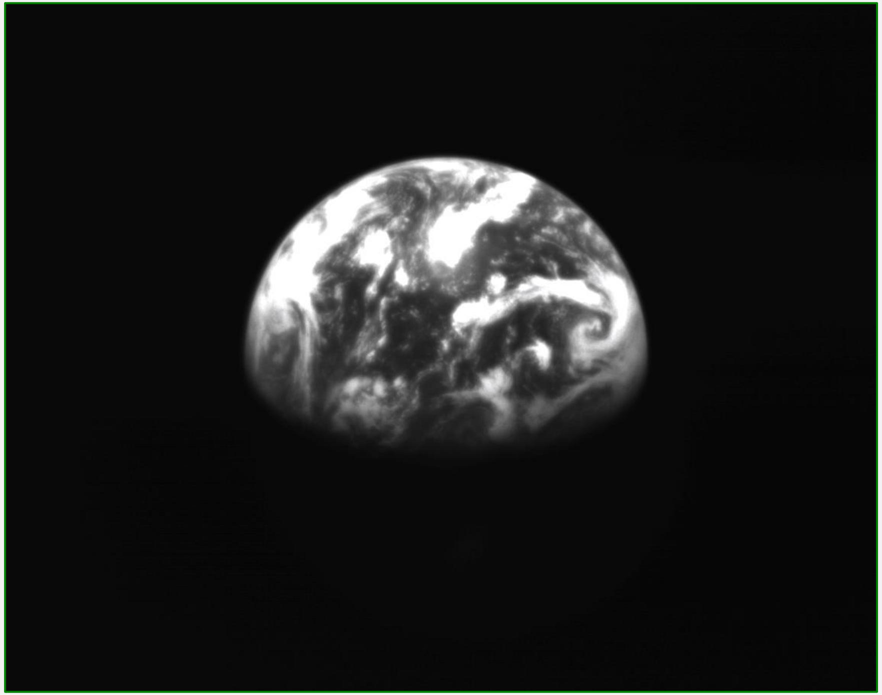


Image of Earth Captured by Lunar Flashlight
(2023-05-17 at 20:43 UTC)

- **Lunar Flashlight was a successful technology demonstration mission**
  - ASCENT propulsion system
    - 16.2 m/s ΔV imparted
    - Application: fuel efficient small satellite propulsion and planetary exploration
  - Infrared laser reflectometer instrument
    - Application: High-power laser for Optical comm
  - Sphinx C&DH with F Prime FSW
    - Application: Smart and energy efficient avionics
  - First flight demonstration of PN DDOR
    - Application: precision rendezvous on other planetary objects using PN DDOR
  - 1st LF OPNAV experiment successful
    - Application: AutoNav using OpNav capability
    - Reference: https://arxiv.org/abs/2401.12198

Top 3 Lesson Learned

	What Happened?	What did we learn from it?	Proposed Mitigation Strategies	Recommended Actions
1	Foreign Object Debris (FOD) in propulsion system	**Potential source:** Sintered particles or powder from additive manufacturing process Machining debris/burrs Lubricant **Methods of dislodging:** Launch prelaunch vibration loads, cyclical pressurization and flow	Chemical etch surface finish Abrasive cleaning Filter	CT scanning Flight like Hot fire testing Liquid flow testing AM parts vibration test
2	Spacecraft Operation by Georgia Tech	Universities can do spacecraft operation with proper training and guidance	Shadowing by Subject Matter Expert from JPL	Universities are a great resources for small size projects
3	Project implementation challenges	Keep same team over the project lifecycle Need combination of young engineer/experienced engineers Tailor large mission processes to make the workflow manageable	Maintained a small and dedicated team Good communication Tailor processes	Tailor processes that are used for large mission Standardize and simplify documentation Optimize your resources

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LUNAR FLASHLIGHT

NASA-STMD JPL

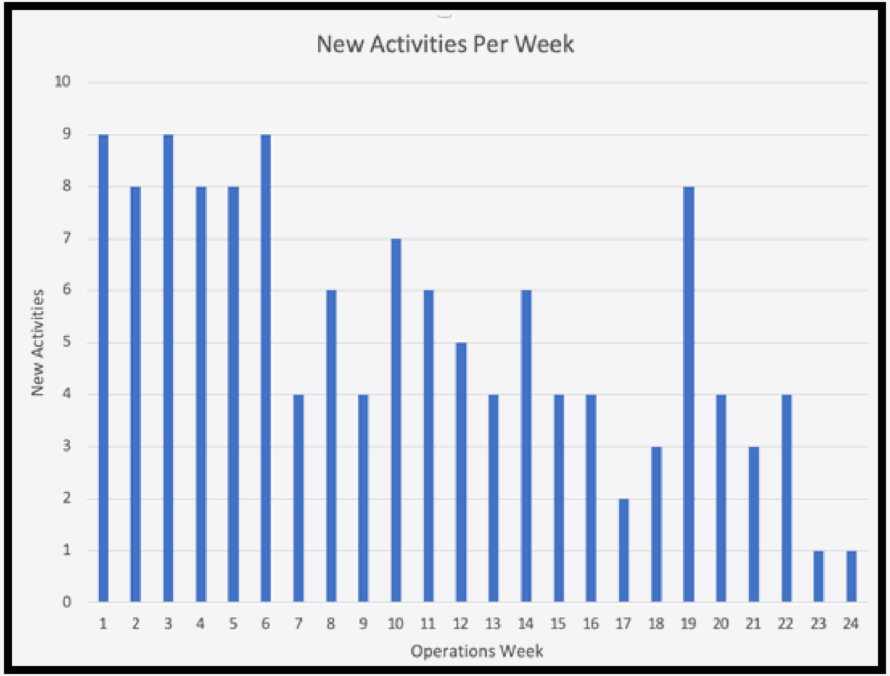
Jet Propulsion Laboratory
California Institute of Technology

Acknowledging our Sponsor:
NASA's Small Spacecraft Technology Program
Chris Baker and Roger Hunter

This was a JPL managed mission

Summary of Activities

- **Launch, Deployment & Initial Activities**
- **About 90 Unique Propulsion System Related Activities**
  - Fuel Priming and Conditioning
  - Heater & Pump Tests
  - FSW Update & BCT Table Update Safety Net
  - 1 Thruster Spin Stabilized TCMs
  - Reverse Pump Operations
  - High Pressure Tests
- **Instrument Activities**
  - PCM Heater Test
  - Payload Battery Charging
  - 10, 30, 90s Laser Firings (14 total)
  - Earth Perigee Experiment (firing at earth observatories)
  - Detector Dither Activity
- **Other Activities**
  - High Data Rate Downlink
  - Startracker Images of Earth and Moon
  - SRP Desat (one undeployed solar panel)
  - Ongoing post-Earth perigee activities such as payload dither/detector characterization, IRIS Firecode Testing, and more.



- About 130 new activities conducted on the spacecraft over 24 weeks since launch
- Averaged 6 new activities per week until we stopped prop operations
- About 200 on-console activities in total

Project did 400+ contacts with the spacecraft from Dec. 2022 through Dec. 2023!!! (~ 12 months)

Summary of Anomalies

- 29 Spacecraft Anomalies & 20 MOC Anomalies
  - All resolved or worked around except PROP
- Notable/Persistent Anomalies
  - Propulsion system issues caused by FOD
  - DSS 56: Unexplained issues binding to the station, then unexplained resolution a couple months later
  - Uplink issues
    - SLE Proxy
    - Chunk corruption
  - Eng Partition Corruption
  - Fracture of inlet tube during last attempt to correct trajectory