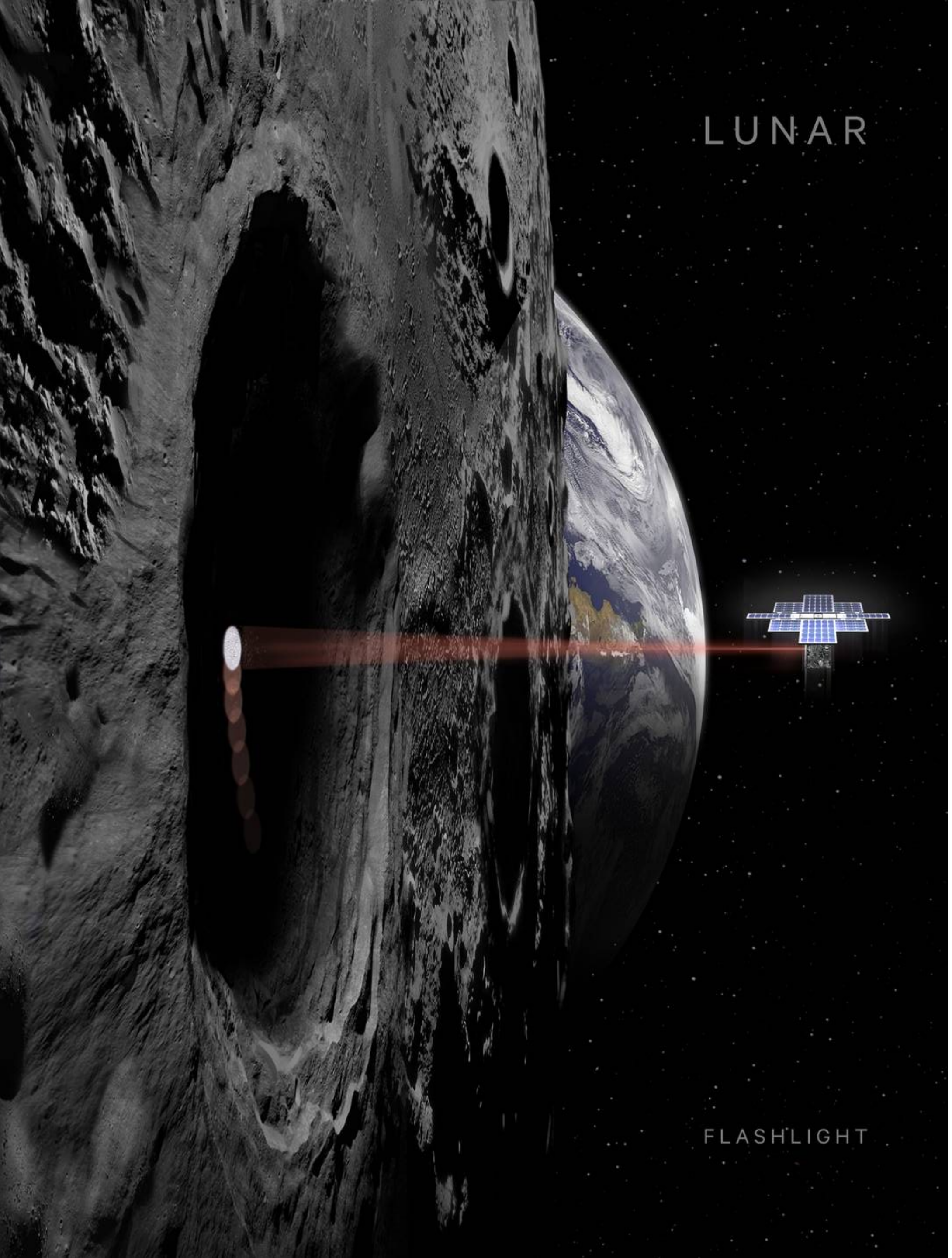

Lessons Learned in Additive Manufacturing from the Lunar Flashlight Mission

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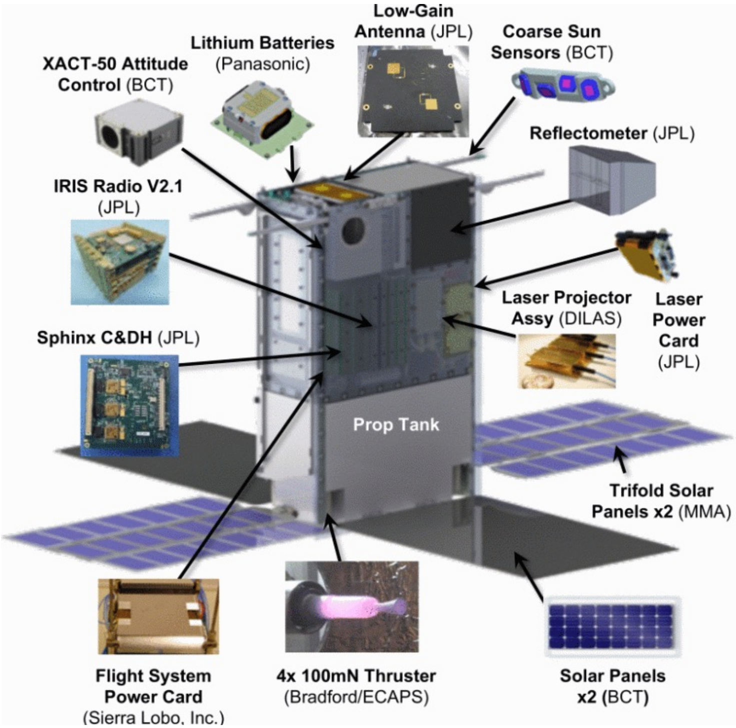
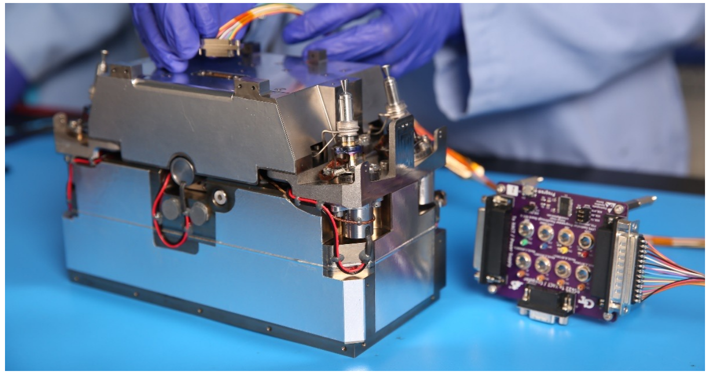
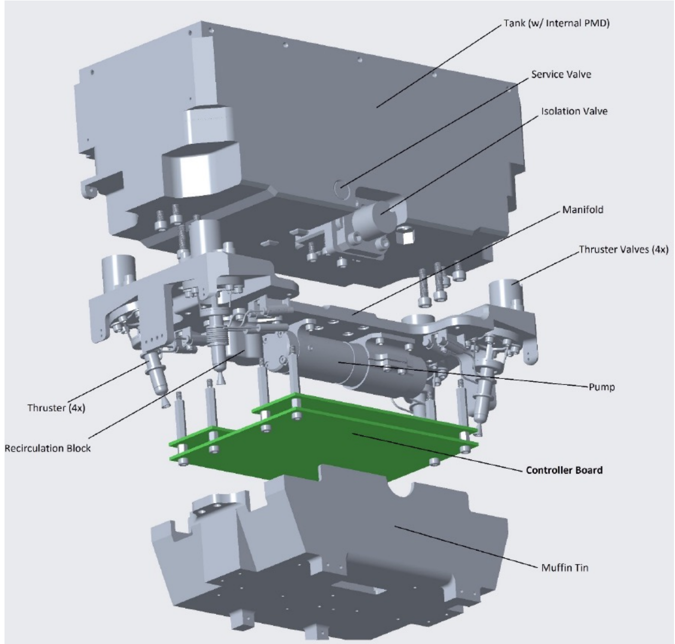
"Shoot for the Moon. Even if you miss, you'll land among the stars." – Les Brown

Why We Flew

- ***Lunar Flashlight*** was a small satellite (14kg, 6U CubeSat form factor) which supported a NASA/Jet Propulsion Laboratory (JPL) led- science mission
- Launched in ***December 2022***, Lunar Flashlight focused on using laser technology to detect water within permanently shadowed regions of the moon's South Pole
- Lunar Flashlight also included several ***new technology development activities*** and intra agency partnerships (including JPL and MSFC), industry & small business initiatives and university partnerships (including Georgia Tech)
- The ***Lunar Flashlight Propulsion System (LFPS),*** developed at NASA MSFC was the first use of "green propulsion" in a deep space mission
    - New thrusters, thruster valves and pumps were flight qualified to operate in flight using ASCENT or Advanced Spacecraft Non-Toxic Energetic Propellant – developed by AFRL
    - The LFPS manifold used 3D printing (additive manufacturing) for its complex fuel flow geometry
    - The LFPS effort was developed in appx 14 months from ATP to hardware delivery for integration into the Lunar Flashlight spacecraft







What Happened

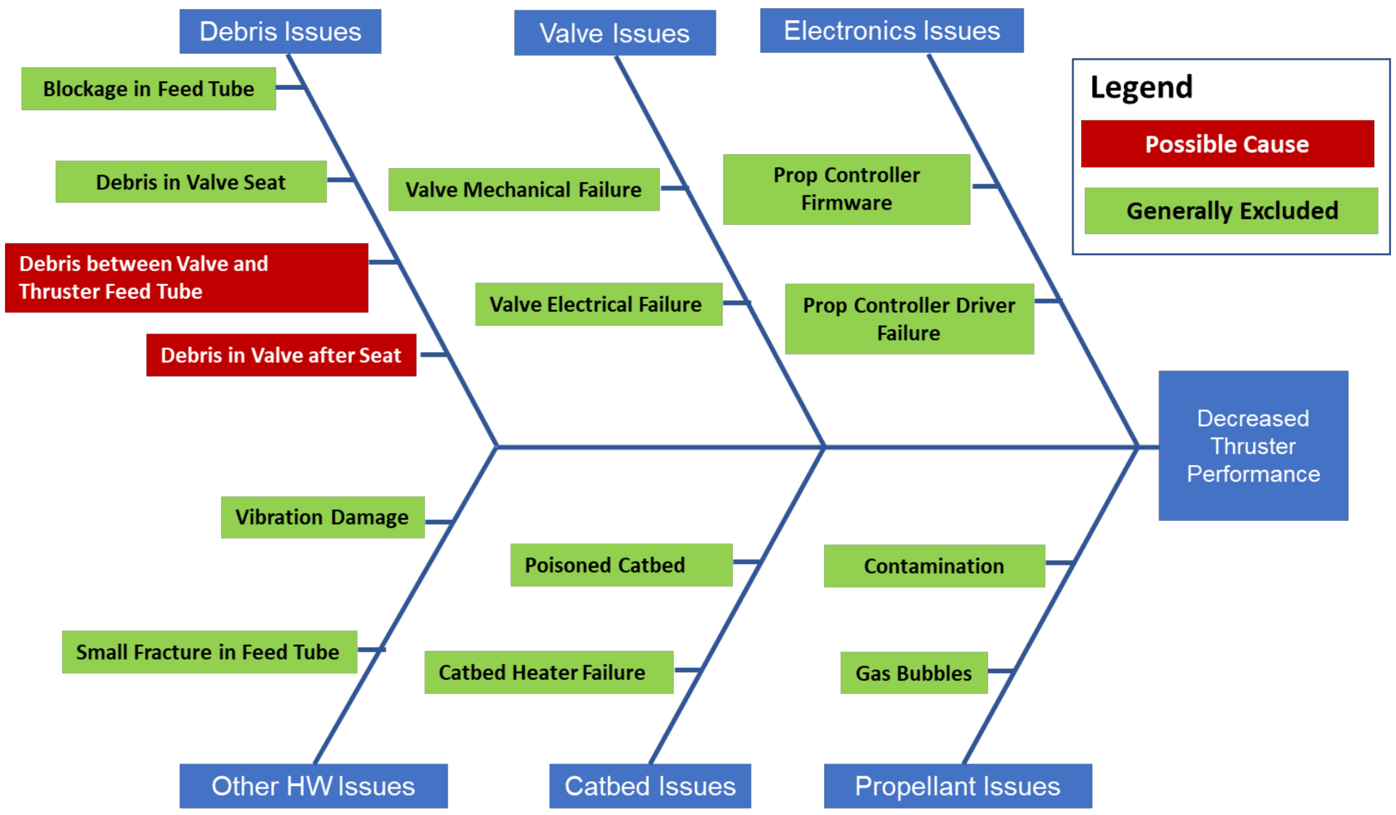
In-Flight Performance Anomalies

- Hours after launch and successful system checkouts, the spacecraft's propulsion system failed to reduce the vehicle's spin rate by the predicted amount based on telemetry readings
- Subsequent attempts to complete trajectory correction maneuvers for lunar orbit insertion were stymied by inconsistencies in thrust
- Thrust profiles often showed burns producing thrust as low as 10% nominal performance, suggesting fuel line restrictions as a potential root cause

Fault Tree Investigations

- Throughout the five months of the Lunar Flashlight mission, the joint JPL/MSFC/GT team attempted several thruster recovery schemes
- The team developed a "fault-tree" to aid in determining the cause and proposing potential solutions
- The propulsion system's thruster valves, pumps continued to operate nominally,
- The variable thrust phenomena was seen in all four thrusters – pointing to additive manufacturing powder trapped in the LFPS manifold's fuel lines near the thruster inlets as a likely candidate
- The NASA Engineering Safety Council (NESC) acknowledged this potential cause in a later independent study

Lunar Flashlight Propulsion Anomaly Fault Tree



What We Learned

- Small spacecraft propulsion systems are more susceptible to insufficient internal cleanliness levels
  - Small Sat needs filtration, inspection & cleaning in general, especially when using additive manufacturing
  - Because systems include such small orifices, lacking filtration increases risk of debris exposure
  - While AM does create design solutions for complex internal geometries, the whole AM design/manufacturing process should include considerations for proper hardware post processing, powder removal, and inspection details
  - It is especially important to do post processing (e.g., surface finishing) to remove sintered powder from internal fuel passages

- Broader communication with Agency/Industry on tailoring methodology for cleaning/filtration for small spacecraft given the size/schedule/cost benefits
  - Better distinctions between small spacecraft/technology demo manufacturing/cleaning approaches vs. larger spacecraft/programs/missions
  - MSFC Team is implementing lessons learned on future green propulsion projects for small spacecraft

Why It Matters

- Though the Lunar Flashlight didn't successfully get to lunar orbit several accomplishments can be highlighted
  - Successful use of university and industry partnerships to achieve an operational propulsion system
  - Demonstrated using green propulsion for a deep space mission (first of its kind)
- Lessons learned can inform other missions
  - stricter cleaning/configuration/contamination/filtration standards
  - When using AM parts – be mindful of entire workflow (design, post processing, powder removal, inspection etc.)
  - Will learn for the next "go around" for green prop: GPDM
- We've demonstrated using green propulsion in a 6U CubeSat form factor
  - The MSFC Green Propulsion team is incorporating lessons learned from Lunar Flashlight into a new small spacecraft called "Green Propulsion Dual Mode" or GPDM
  - GPDM will demonstrate the chemical and electrospray characteristics (higher thrust and higher efficiency) for in-space propulsion using ASCENT/green propellant

Lunar Flashlight's star tracker imaged Earth from approximately 70,000 km prior to its departure from the Earth-Moon system in last May