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Space Administration

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Lunar Trailblazer Anomaly Review Board Report

August 26, 2025

Angela Melito / HQ
ARB Chair

Agenda

01 Introductions / Background
15 minutes

02 Timeline of Development Events
5 minutes

03 Timeline of Operations Events
5 minutes

04 Project Accomplishments
5 minutes

05 Root Cause Summary
5 minutes

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45 minutes

07 Lessons Learned
10 minutes

08 Near Term Opportunities
15 minutes

09 Discussion
45 minutes

Introductions / Background

Bottom Line Up Front

- The combination of many erroneous on-board fault management actions coupled with a solar array phasing error ultimately caused the Lunar Trailblazer (LTB) failure.
- Any single anomaly could have been recoverable given enough time, but the combination was too much to overcome.
- The risk management process got overwhelmed during development due to cost and schedule pressure, leading to an over- acceptance of risks vs. mitigation.

LTB Project Overview

- Category 3 / Class D mission, selected under the Small Innovative Missions for Planetary Exploration (SIMPLEx) call.
  - SIMPLEx selections intended to provided low-cost, high impact science.
  - Part of Lunar Discovery Exploration Program.
  - Managed by Planetary Science Division (PSD) at Headquarters (HQ), funded by Exploration Science Strategy and Integration Office; Program management at Marshall Spaceflight Center's Planetary Mission Program Office (PMPO).
- Principle Investigator (PI)-led (Caltech), Jet Propulsion Laboratory (JPL)-managed; spacecraft (S/C) and integration provided by Lockheed Martin Space (LMS).
- Carries two instruments; designed to map moon's surface from polar orbit and pinpoint where water is located, what form it's in and follow how the water changes over time.
- Rideshare on Intuitive Machines second mission (IM-2) on SpaceX Falcon 9 launch vehicle.
- Nominal launch and separation on 2/26/25.

LTB Project Overview, Cont.

- After separation, the spacecraft experienced an abrupt loss of signal (LOS) on 2/27/25.
- Deep Space Network telemetry showed solar arrays pointed away from the sun, and the spacecraft entered a cold state with low power and no attitude control.
- The planned early Trajectory Control Maneuvers could not be performed, and the spacecraft could not achieve its targeted lunar orbit.
- Per NASA direction, monitoring efforts for spacecraft signal continued through 7/6/25.
- Having not acquired a signal, project directed to begin close-out activities.
- Key Decision Point (KDP)-F PSD Program Management Council (dPMC) held on 7/31/25.
- Project now in Phase F of the Lifecycle, with close-out activities scheduled to end on 9/30/25.

Lunar Trailblazer Anomaly Review Board Objectives

- SMD Associate Administrator convened the Anomaly Review Board (ARB) to review the project and institutional level issues that led to the LTB loss of signal and to develop lessons learned for the development and execution of future SMD Class D project.

- Specifically, the ARB tasked to:
  - Study the issues leading to the LTB spacecraft's LOS, including technical, cost, schedule, management and contractual issues that may have led to the anomaly.
  - Review the project's root cause analysis to date and provide an independent assessment of that analysis.
  - Identify when problems began arising, the visibility and communication of the problem(s) to management, the Standing Review Board (SRB), institutional review teams, technical authorities, etc., and determine if there were missed opportunities to act earlier to prevent the technical issues resulting in the post-launch anomaly.
  - Identify lessons learned associated with LTB's Class D SIMPLEx project implementation strategy that might be crucial for mission success of future SMD Class D projects.

Lunar Trailblazer Anomaly Review Board Membership

ARB Members	Affiliation	Role / Expertise	Contact Info
Angela Melito	NASA HQ / ESSIO	Chair	Angela.m.Melito@nasa.gov
Karen Gelmis	NASA HQ / PSD	Review Manager / Ex Officio	Karen.e.gelmis@nasa.gov
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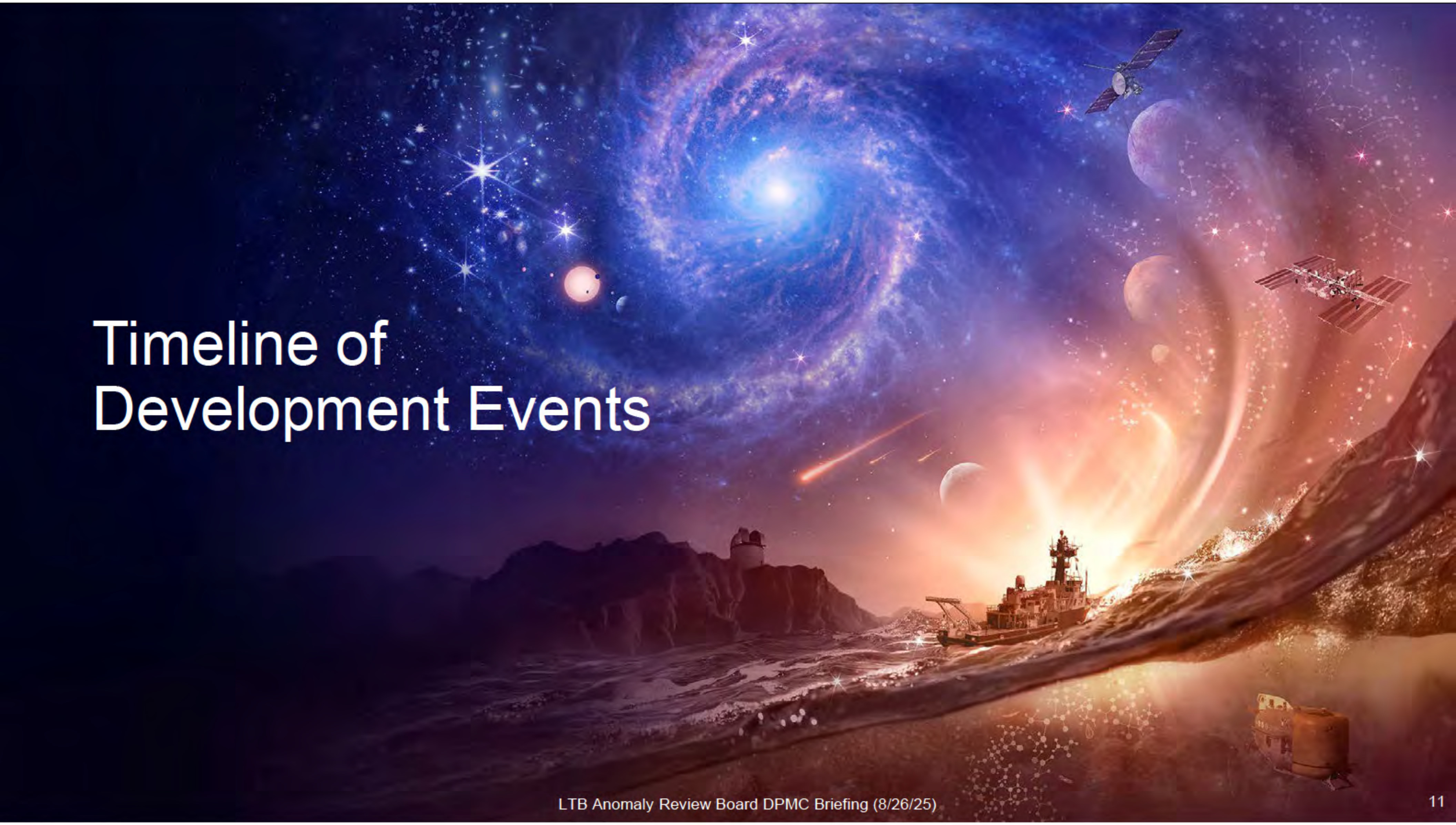
(b) (6) [redacted]	JPL / Europa Clipper	PM SME	(b) (6) [redacted]

Lunar Trailblazer Anomaly Review Board Methodology

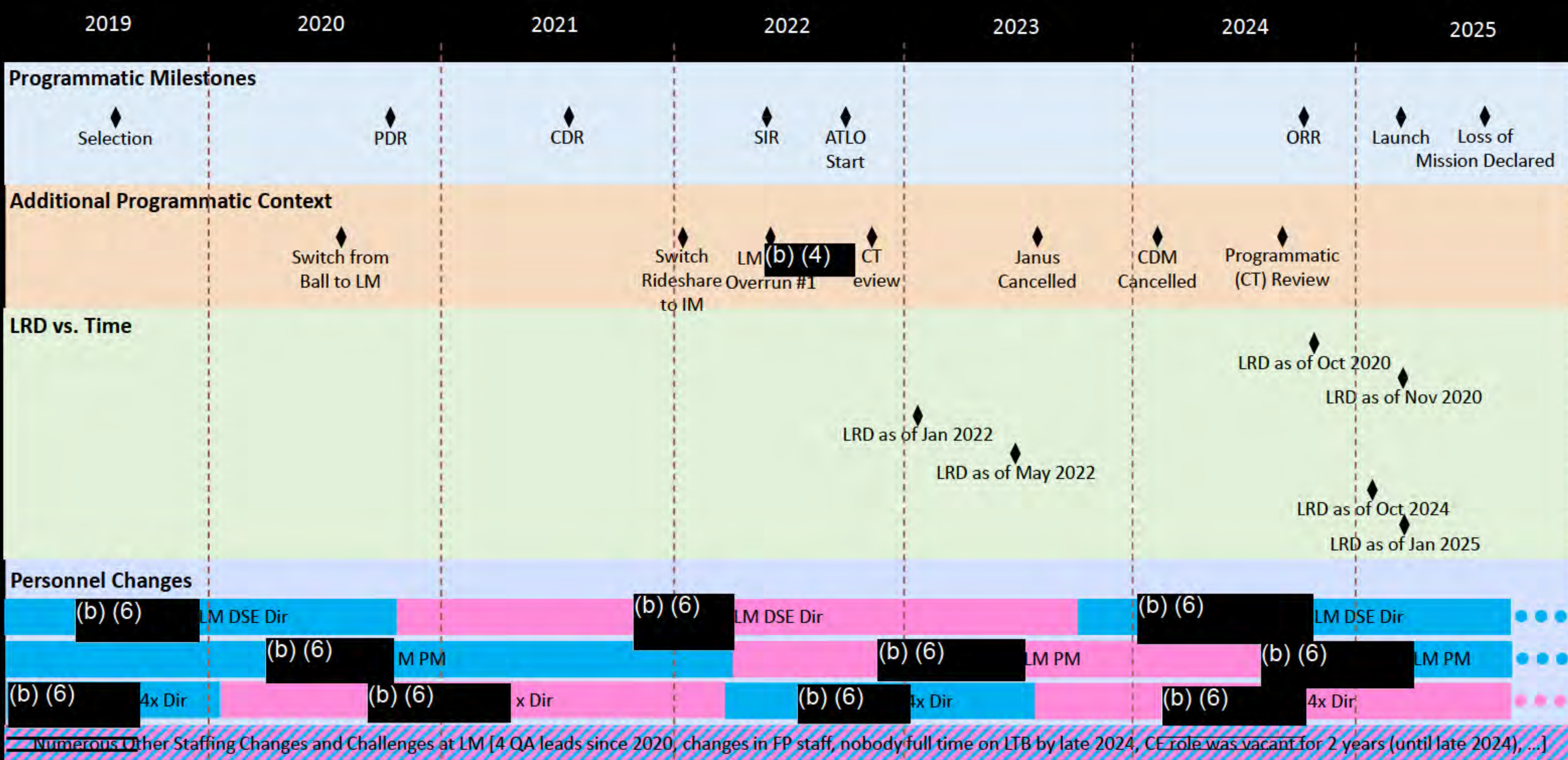
- ARB investigation consisted of a series of team meetings, a trip to JPL, and a trip to LMS to discuss and gather information needed to understand the issues underlying the LTB anomaly.
  - Interviewed over 50 people individually and in groups
  - Represented different levels of LTB project, JPL, LMS and CalTech organizations
- Ahead of the face-to-face meetings, data analysis of LTB project information was collected including, but not limited to: Project Monthly Reports, Milestone Review Data and Reports, Select Requests for Action (RFA) Closure Data, Project Risks, Decision Memos, SRB Chaired Review Slides, Timeline of Operations Events.
- Face-to-face interaction led to open discussions that were crucial to the effectiveness of the study.
- The interview sessions were followed by ARB team deliberation and discussion.
- The findings in the package are based on the review of the data and notes collected during the interview sessions.

Lunar Trailblazer Anomaly Review Board Acknowledgements

- The LTB ARB greatly appreciates the extraordinary support and professionalism provided by NASA, JPL, CalTech and LMS. All requests from the ARB were positively acted upon in a timely manner.
- The LTB project personnel with whom the ARB interacted were open, honest, forthcoming and dedicated to mission success.
- The LMS team coordinated and got approval for the Internal LMS Independent Review Team (IRT) out brief to the ARB.
- All additional documentation requests were accommodated and were sent to the ARB team.

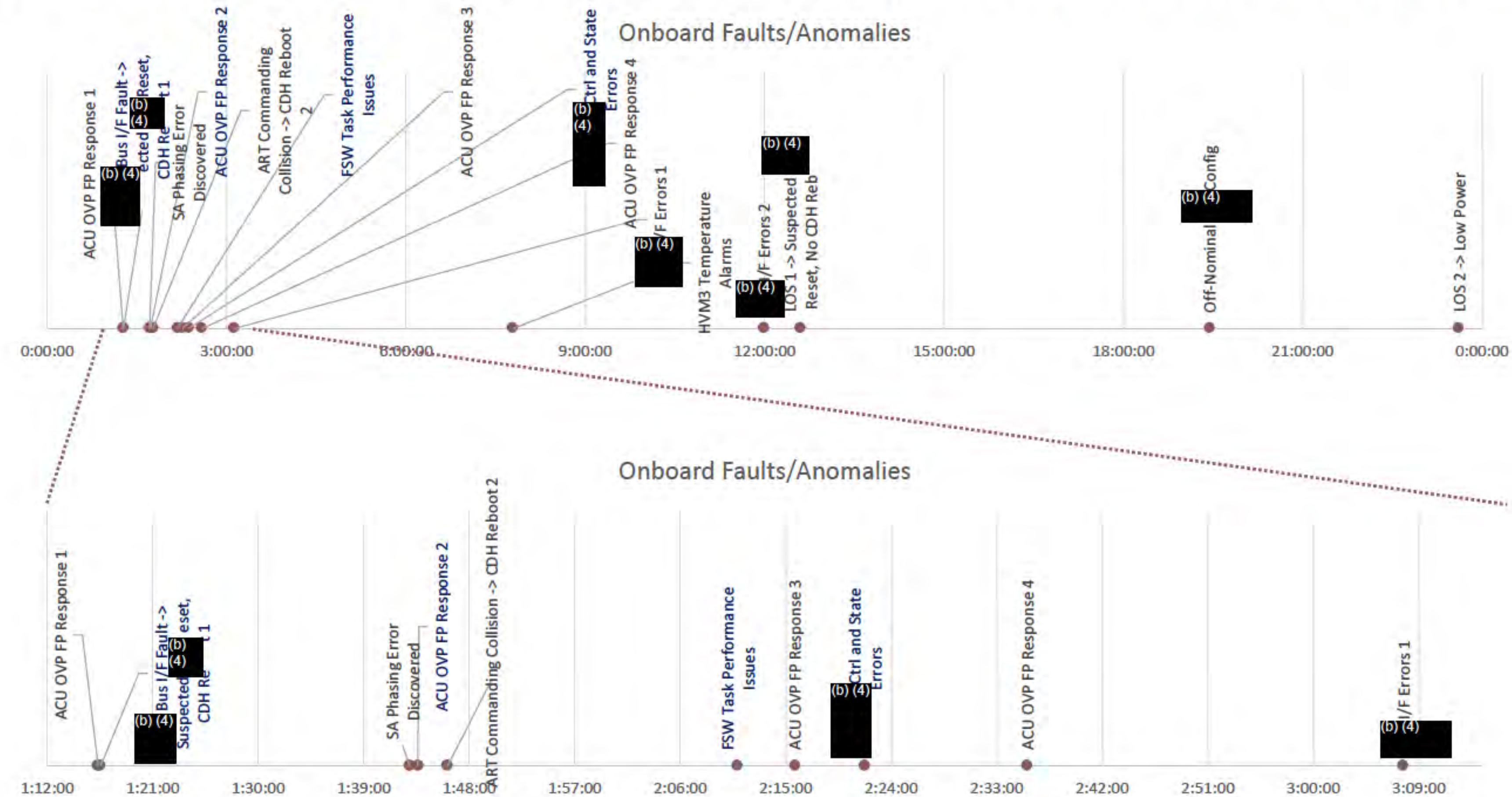

Timeline of
Development Events

Timeline of Development Events



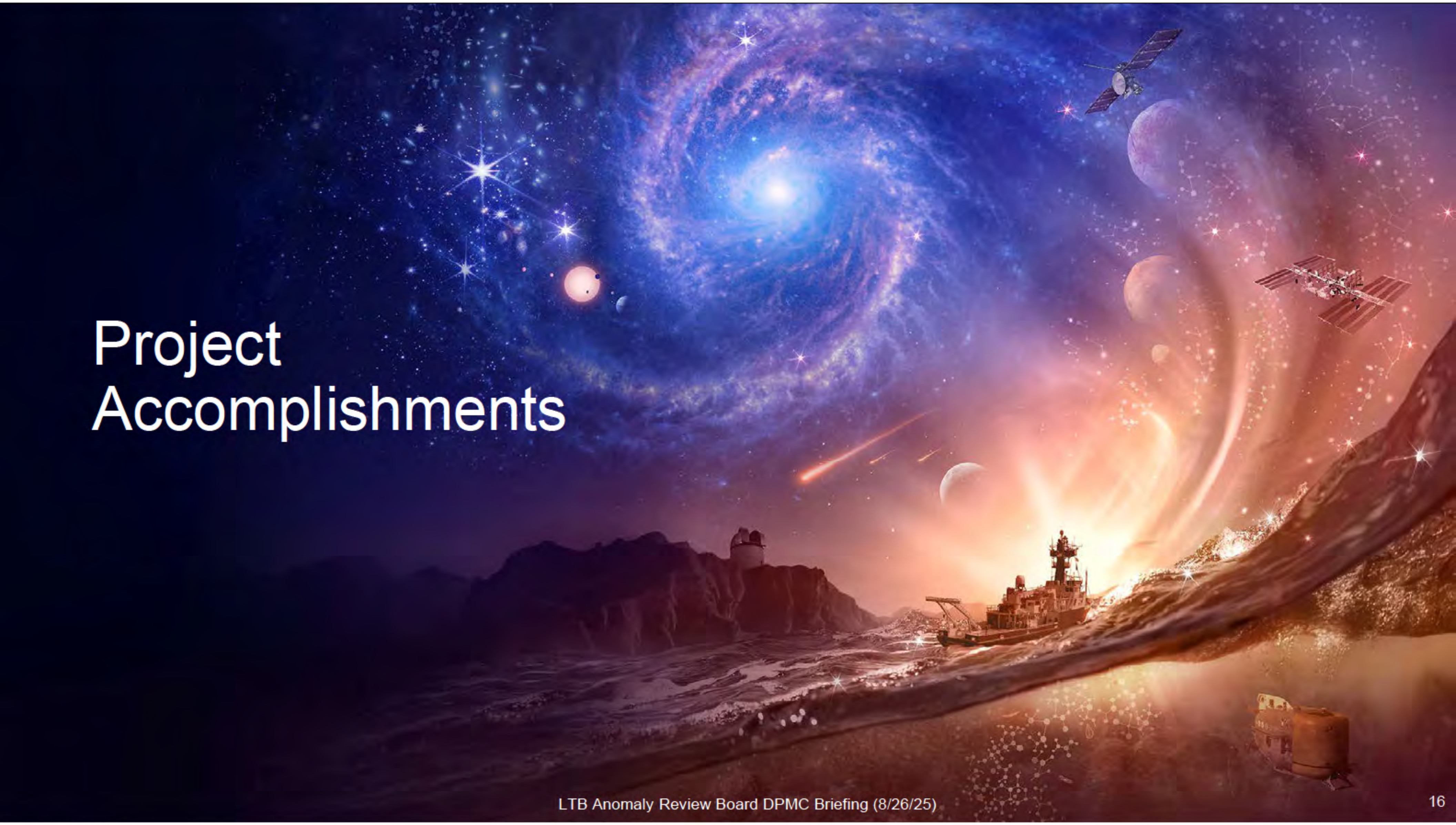
Timeline of Operations Events

JPL Anomaly Response Team Operations Timeline of Events



Sequence of Post Launch Faults	
Analog Control Unit (ACU) Over Voltage Protection (OVP) Fault Protection (FP) Response 1	False positive because of erroneously low FP threshold limit - fault tripped on low threshold value, but true hardware overvoltage of the ACU had not occurred.
Radio Bus Interface (I/F) Fault -> Suspected power supply Reset, Command and Data Handling (CDH) Reboot #1	Inference of power supply reset being root cause. Loss of downlink signal for ~ 12 minutes. Non-vol tlm showing last fault as radio interface fault (likely as a result of power supply reset removing radio power).
Solar Array (SA) Phasing Error	Sign error in transformation (hard-coded value in sequence) that is used by safe mode to point arrays. This sign error points arrays away from the sun.
ACU OVP Fault Protection (FP) Response 2	Same as ACU OVP FP Response 1 Root Cause.
Articulating Commanding Collision -> CDH Reboot #2	Bug in ACU OVP Fault Protection response sequence resulting in the safe mode sequence not being stopped/unloaded as intended by the fault response.
Flight Software (FSW) Task Performance Issues	Data implied that Central Processing Unit (CPU) utilization resulted in task starvation several minutes before the event.
ACU OVP FP Response 3	Same as ACU OVP FP Response 1 Root Cause.
FlexCore Control and State Errors	This is a secondary effect of the ACU OVP fault response (the power supply reset).
ACU OVP FP Response 4	Same as ACU OVP FP Response 1 Root Cause.
Power supply I/F Errors 1	Multiple power supply telemetry request error status event reports (EVRs).
High-resolution Volatiles and Minerals Moon Mapper instrument Temperature Alarms	Thermal believes the ground-based alarm limits were erroneous and temps were as expected.
Power supply I/F Errors 2	Multiple power supply TLM request error status EVRs.
LOS 1 -> Suspected Power Supply Reset, No CDH Reboot	Reason for reboot request indicated the radio bus I/F error. Radio being powered off by power supply.
Off-Nominal Radio Config	Electrical Power System (EPS) power box reset causing all switches to open and the initial LOS. This caused the telecom software to be out of sync with the state of the radio.
LOS 2 -> Low Power	End of the Uplink Loss Executive (ULLE) telemetry burst, detected a sudden LOS due to low power.

Project Accomplishments

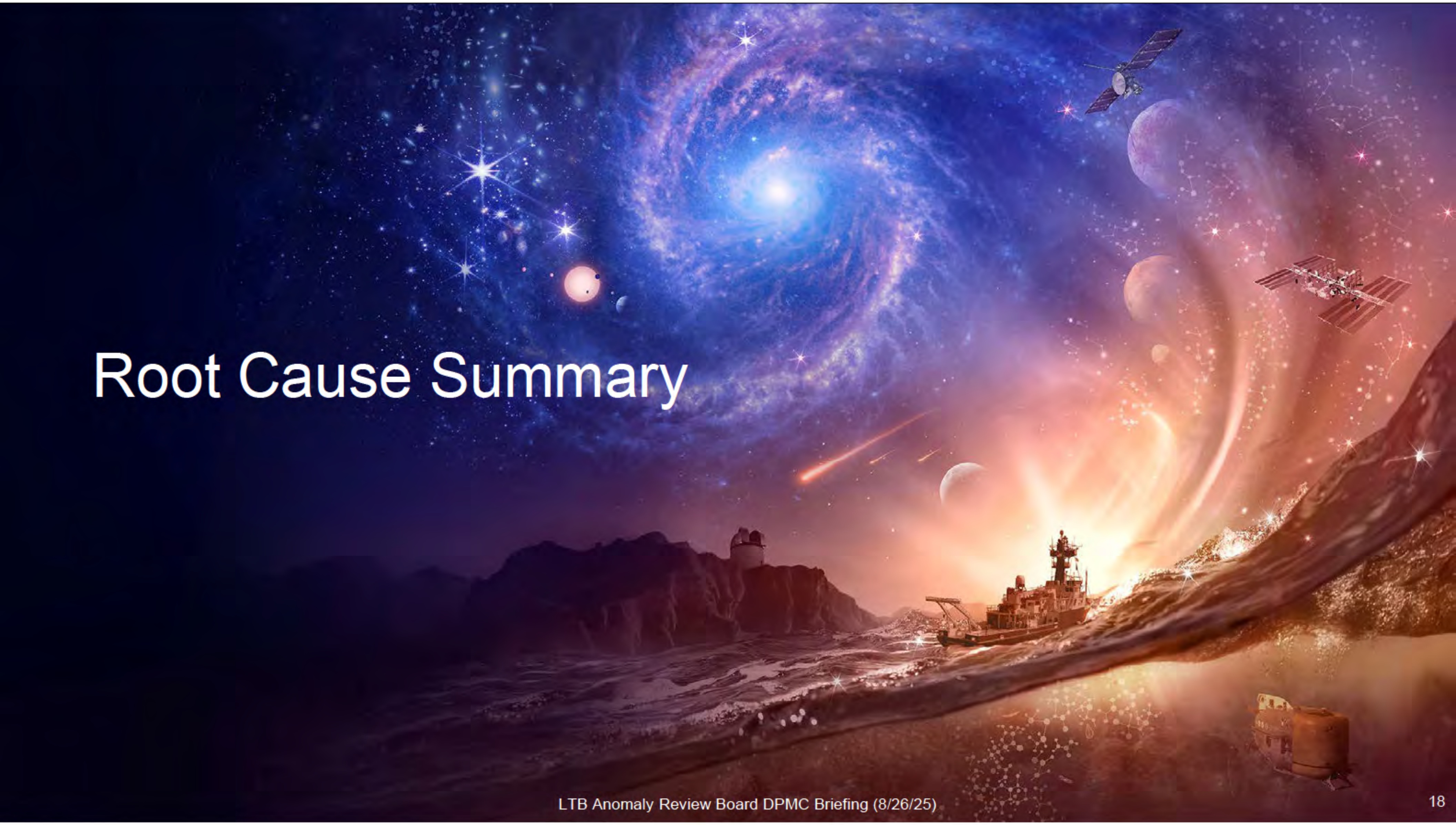


LTB Project Accomplishments

- The LTB science objectives were solid and remained stable throughout the project.
- There were no show stopping issues with instrument development, delivery, and integration.
- The small LTB team made it through a main engine replacement, extensive vibration campaign, rapid development of a SAFE card, and a move to a different rideshare and was able to meet the IM-2 launch date needs.
- The small LTB team overcame cost and schedule pressure during development and executed a highly successful launch campaign.
- Assembly, Test and Launch Operations (ATLO) had team buy in and everyone was willing to work long days and weekends to get to the launch site.
- The science is compelling, therefore copies of LTB instruments have been selected to be flown again.

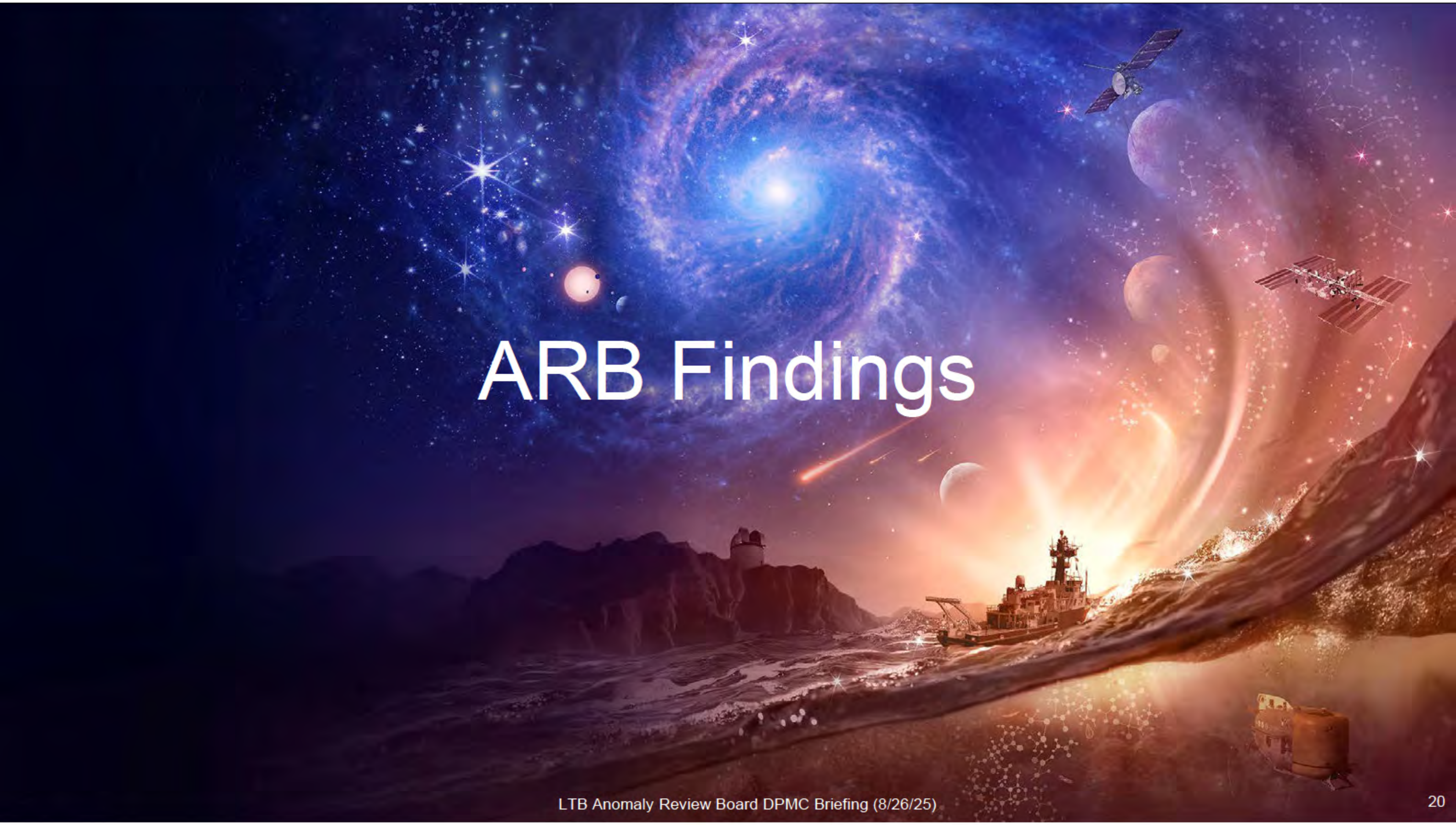
IM-2 Launch with LTB Rideshare on 2/26/25

Root Cause Summary



Root Cause Summary

- As part of the LMS interview process, the LTB ARB met with the LMS internal IRT who was asked specifically to identify root cause(s) that led to the LTB failure.
  - The LMS IRT only interviewed the LMS team.
  - The chair presented the team's findings.
  - The NASA LTB ARB agrees with the direct root causes identified and has added one additional root cause.
- The following direct root causes from the LM IRT were the following:
  - Solar Array (SA) Phasing Error (Array off Sun).
  - Power System Over Voltage Protection (OVP) detection threshold set to the incorrect value.
  - Flight Software (FSW) Sequence collision in Solar Array commanding with Safe Mode and OVP response.
  - Command & Data Handling (CDH)-to-Electrical Power System (EPS) Box Interface Fault Protection (FP) response resulting in spontaneous power system resets.
  - Fault Management led to reboot dead-end limit being reached (b) (4) [redacted]
- All contributors, data, settings, and limits ultimately resided in the FSW and sequences.
- The LTB ARB added the misconfiguration of the Commercial Off the Shelf (COTS) radio as an additional root cause.



ARB Findings

Summary of Findings

Factors that ultimately led to Loss of Mission can be categorized at a high level into several bins:

- Technical (Pre-Launch)
- Technical (Post-Launch)
- Mission Operations
- Business Management
- Management / Oversight

Technical (Pre-Launch) Findings Summary

A SA Phasing Test Was Never Completed As Part of ATLO That Should Have Caught the SA Phasing Error
Change in Project Assumptions Over Time Led to Technical, Schedule, and Budget Impacts
Late Realization of the Lack of Technical Maturity of the Spacecraft Design
Insufficient FP Management Architecture Approach
Risk Management Process Breakdowns Led to Unrecognized Risk Acceptance
Class D Implementation Decisions with Respect to COTS Management and Safety & Mission Assurance (SMA) Support, and Fault Protection Management Led to Unrecognized Risk Acceptance
Schedule Pressure Ended Up Driving Technical Decisions, Especially During ATLO

Technical (Pre-Launch) – Solar Array Phasing Test

- LTB never conducted a true end-to-end SA phasing test
  - This test should have caught the error in the flight code that could have then been corrected before launch eliminating one of the main anomalies during the mission.
- The SA phasing test was on the Incompressible Test List (ITL), but there was a Test Like You Fly (TLYF) exception that was missed with LMS not using the final FSW and final flight ops products during testing.
- LMS did do a SA gimbal drive test to document how the SA moves with a command.
  - This test confirmed the positive angle commands to the FSW rotated each gimbal clockwise, which matched the Interface Control Document (ICD).
  - A flag denoting the fact the arrays rotated "opposite" to each other was written and closed with a note about FSW command blocks accounting for the direction change to get both array faces pointed in the same direction.

Technical (Pre-Launch) – Solar Array Phasing Test, Cont.

- A review of the SA commanding showed that the gimbal axis for each array was defined using the right-hand-rule pointing away from the vehicle as opposed to into the vehicle.
  - This results in positive angle motion in the counter-clockwise direction, which is opposite of the gimbal ICD and what was demonstrated in ATLO testing.
  - The gimbal axes were defined incorrectly on Janus as well.
- The launch array targets were hardcoded, but the target values were determined by also using the incorrect gimbal axis definitions.

Technical (Pre-Launch) – Change in Project Assumptions

- LMS selected to provide bus 4 months after project confirmation in part due to the LMS past performance on other NASA missions, having an experienced team, and having a risk reduction plan in place.
  - Junior Engineers were not backstopped by more experienced and/or Senior Engineers.
  - Primary Leads were vacant for long periods of time (FSW Lead, Chief Engineer).
  - Most of the team were not as experienced with low dollar, Class D types of missions.
- The Janus Spacecraft was to be the front runner for LMS in their new line of affordable Class D buses and was to be used as a risk reduction.
  - The cancellation of Janus impacted some of LTB risk reduction activities.
  - The Project did not use this as a stopping point and reassess the risks moving forward.
  - The plan for Janus ATLO to flow over to LTB with many of procedures in place was impacted.

Technical (Pre-Launch) – Change in Project Assumptions, Cont.

- LTB costing was based on parametric for larger missions and was dependent on successful Janus completion to bring down Non-Recurring Engineering for LTB.
  - Cost reductions due to Janus completion were impacted due to Janus cancellation.
  - LM in-house manufacturing costs for structures and prop system builds were extremely underestimated.
- Launch schedule was based on the Interstellar Mapping and Acceleration Probe (IMAP) launch as LTB was a Ride-Share on that Mission.
  - Moved to the second Intuitive Machines (IM-2) Launch which pushed up their delivery date and left little time for anomaly resolutions.

Technical (Pre-Launch) – Technical Design Maturity

- Although the LM design was technically Technology Readiness Level (TRL) level 6, LTB had TRL level 6 and TRL level 9 components being integrated together.
  - Spacecraft systems had high TRL for Low Earth Orbit (LEO), not deep space application.
  - The bus was a first-time build.
- When LMS was awarded LTB, they moved very quickly to Preliminary Design Review (PDR) and did not go through a typical Phase A to really flush out the design.
- Electronics were all new, not LMS heritage.
  - LMS didn't fully understand vendor information or had limited information from the vendor due to the COTS procurements.
- The COTS Electrical Power System (EPS),had a design that did not fully close for LTB, so work arounds needed to be developed to use the procured EPS.

Technical (Pre-Launch) – Technical Design Maturity Cont.

- The COTS FSW package destined for use on Janus and LTB and was new for LMS Deep Space Exploration.
- CalTech was going to do the majority of the sequence development, but then LMS took this one since they understood the system.
  - However, LMS could not leverage the previous heritage sequences.
- Although LMS did run the redundant FP approach to a single string system on Gravity Recovery and Interior Laboratory (GRAIL), a lot of the FP software on LTB was run in sequences as opposed to code.
  - FP was a combination of the COTS FSW package and onboard sequences.
  - LMS did not look at the sequences running simultaneously and the effect on the system.
- A lot of early flight sequences were not ready for ATLO and were being verified right up until launch.

Technical (Pre-Launch) – Fault Protection

- Heritage FP telemetry parameters were not included, like the command counter, which led to confusion of the vehicle state in flight.
- A redundant system design for fault protection was modified to a system design for single string.
- The COTS Power Supply late open circuit voltage limit discovery resulted in increased safing complexity and deployed poor Fault Management (FM) practices where there was an attempt to control systemic behavior with an unknown root cause with FM.
- The risk reduction testing for FP was limited due to the resources (money and time)
  - They were only able to run some stressing cases
- Safing architecture employed two parallel authorities rather than single authority

Technical (Pre-Launch) - Risk Management Process

- During ATLO and Environmental Testing, the risk process run and maintained by JPL to CalTech became completely overwhelmed and focused on solving the known problems as opposed to problems they could have.
- When the basic assumptions and risk posture changed on LTB, there was not a stopping point or a higher-level meeting to discuss the ramifications and possible mitigations.
- Mission success reviews were held at the end of the project, not at the beginning to lay the groundwork for mission success; so not a lot of time to react to the issues and Unverified Failures (UVFs) that were brought forward, so it turned into a risk acceptance.
  - LMS accepted 11 residual risks in their final Executive Readiness Review (ERR).
- A Guidance, Navigation and Control (GNC) Phasing Test was not on the ITL but was in the ATLO plan.
  - The Project did not conduct a pre-launch, end-to-end SA phasing test using the final FSW and final flight operations products.
  - This never made it to a risk list.

Technical (Pre-Launch) – Class D Implementation

- LTB was the first Curio platform where LMS used COTS black boxes to integrate onto the spacecraft; used common avionics and capabilities platform rather than one-off builds.
  - LMS didn’t provide certified product engineers to understand the black boxes.
  - Based the product off spec sheets with little documentation.
  - COTS subsystems were early versions which had their own issues.
  - Didn't allow for enough time in ATLO for thorough testing and troubleshooting of the Spacecraft with the COTS hardware and software.
- LMS tried to streamline the commercial product SMA plan to meet minimum requirements, but be efficient, and realized well into ATLO that they needed to add rigor to their SMA team and staff.
  - Late in the program, LMA added more rigorous SMA support on the ATLO floor and added a Mission Success Engineer to the project.

Technical (Pre-Launch) – Schedule Pressures

- There were multiple issues in ATLO to overcome and still maintain schedule.
  - C&DH hardware damaged due to a negative polarity in the harness.
  - DC/DC converter failure during initial Thermal-Vacuum (TVAC) test due to use of plastic bodied connectors.
  - Technical power system Subject Matter Expert (SME) found issues with the design and had to design and build a new card called the SAFE card after the 2nd TVAC in a rapid development effort.
    - The power SME corrected the value for the over-voltage protection system documented but never made it into the final fault protection documentation or the software.
  - First Vibe test Foreign Object Debris (FOD) from prop system was discovered due to a panel resonance issue resulting in engine damage and ultimately engine replacement and installation of isolation bracket.
    - Project had to run Vibe four times before a fully successful Vibe.
- ATLO saw many Inter-Integrated Circuit (I2C) interface errors just like what was experienced on Janus. ATLO notated every time they saw the issue, but they would see a different response with every reset.
  - The fix for this issue lived within the FSW, so LMS treated it like a fault and handled it in fault management.
- There was a bias towards expending resources on known hardware failures; not enough care was taken on UVFs, FSW development, and FP sequence development and testing.

Technical (Pre-Launch) – Schedule Pressures, Cont.

- Electrical Ground Support Equipment (EGSE) issues in the run up to launch was a significant distraction.
  - EGSE impeded system level testing which may have shed some light on the COTS Power Supply interface issues.
  - The fundamental close loop simulation had to run on the flight computer and not EGSE.
- The COTS Power Supply resets documented as Problem Failure Reports (PFRs) and then UVFs. Power SME realized the design was not ideal for LTB needs, but there was not enough time to change power subsystems, so the project had to find ways to work around the design.
  - Out of the 4 PFRs related to this, 2 were seen in during operations.
- The switch to being a Ride Share on IM-2 paced all decision making due to accelerated launch schedule.
  - LMS didn't have time to regroup and make technical changes/reduce risk and mostly just tried to learn as fast as they could to keep the project going.

Technical (Pre-Launch) – Schedule Pressures, Cont.

- Right before LTB shipped to the launch site, they loaded a new safe mode configuration and ran an abridged version of the launch (b) (4) [redacted] but they were mated at that point so could not move the gimbals.
  - This was due to the final launch trajectory that came in late and made the star tracker not able to be acquired.

Technical (Post-Launch) – Findings Summary

Combination of in-flight anomalies overwhelmed the team and with little time to make adjustments resulting in ultimately losing the Spacecraft (S/C)
Due to the SA phasing error and the inability to correct it in time, the S/C ended up in a low state of charge inhibiting further recovery efforts
Misconfiguration of the COTS radio during spacecraft resets was a major contributor to the loss of the spacecraft

Technical (Post-Launch) - Combination of Anomalies

- Because of the other anomalies happening outside of the SA phasing error, the team had to deal with those while the system was resetting unnecessarily, and the SAs were mis-pointed.
  - The team fixed the SAs but did not update the non-volatile state so every time the system reset it went back to the mis-pointed configuration.
  - The power system OVP threshold was set to an incorrect value and was not corrected in time, leading to numerous resets putting the S/C back into the wrong configuration.
  - FSW collisions added to the overall anomaly issues.
    - FSW collision in the SA commanding with the safe mode and OVP response.
    - A flawed design of the EPS OVP sequence employed a sequence abort command that was not compatible with the FSW.
  - Power resets occurred due to the C&DH to power system box I/F response.
    - FM for the C&DH-to-EPS I/F was unreliable needing many attempts to work.
  - Fault Management led to reboot dead-end limit being reached (b) (4) [redacted]

Technical (Post-Launch) - S/C Low State of Charge

- The S/C COTS radio came up misconfigured after the system reset and the third time the radio came up after a reset it finally came up configured properly but then but then lost power within five minutes due to a low battery state of charge (brown out).

Technical (Post-Launch) - Misconfiguration of the Radio

- There were 4 hours (between ULLE1 and ULLE3) where the ops team could see the spacecraft carrier and expected to have been able to send commands to resolve anomalies that were seen.
- The team had prepped to turn the solar panels toward the sun and uplink the files to correct the safe mode and over voltage trip limits.
    - However, the improper radio configuration did not allow commanding or telemetry.

Mission Operations Findings - Staffing

The operations team staffing mix was not optimal and the true readiness was not robust.
There was no formal Anomaly Response Team (ART) for any portion of mission operations, and when the anomalies occurred there was no clear person in charge.
The team underestimated the complexity of the simulation environments to prepare for Missions Operations; although they planned four Operations Readiness Tests (ORTs), the ORTs were not detailed enough to prepare the team for the issues that occurred and the way the issues cascaded and compounded.
The off-nominal ORT did not expose the limits to the resources and lack of an ART. Depending on the issue, the team worked it on console, or a subset went to a side room and the ACE and Systems Engineer (SE) monitored the spacecraft.
Project team performed a final Flight Parameter Review, but the exercise was more of an education session for the Mission Ops team than figuring out the right parameter values given what they learned throughout ATLO.

Mission Operations Observations– Staffing

- Mission operations was planned with three shifts, however there were not enough personnel to fully staff the shifts even for critical operations.
- LMS staffing did not have enough depth for the level of contingencies encountered during the first 3 days after launch; the team was single string in many competencies and therefore in some cases team members worked 24+ hour shifts.
  - There was an on-call list for every type of anomaly to supplement Caltech and LM commissioning team. These folks were not present at ~0430 PT at loss of signal. SMEs were online to supplement by ~0600-0800 PT.
- CalTech operations team did not have the experience for off-nominal operations, and once anomalies got 1-2 levels deep the LMS team held the expertise while CalTech retained responsibility.
- The Mission Operations Manager (MOM) had more experience with science operations than mission operations and spent more time in the room on the console than working with the Anomaly Team once the cascade of issues began.
- Mission Operations staffing relied heavily on students in the ACE console positions and as some of the leads, and LMS residents were only set up for 2 shifts.
  - The JPL personnel working operations did not all have familiarity working with LMS.
- LMS SE Team participated in the ORTs "by the drink" as needed.

Mission Operations Findings - Technical

The operations team from JPL and CalTech did not have command dictionaries, command libraries, and spacecraft/system knowledge to handle issues. The FSW was a 'black box' for them.
During the evaluation and recovery states, it took days for some of the data to get communicated to the Anomaly Review Team to help assess the current situation.
The operations architecture and plan did not fundamentally fit the requirements of early operations for a low-cost mission.
Command encryption was added to the project requirements and during safe mode the command authentication was not well understood making it unclear what commands had been received.
LTB had descoped some of the telemetry and fault protection, and this impacted the initial stages of recovery efforts.

Mission Operations Observations– Technical

- A power subsystem SME review of the battery state of charge after separation and before loss of signal would have raised a serious flag.
- The mission operations architecture is LMS heritage, but the systems themselves were new and from different vendors. It seemed they were a step removed from where they normally would be for an in-house development.

Business/Contract Management Findings Summary

Programmatic factors greatly contributed to design errors and accepted risks that were not properly understood or mitigated prior to launch.
The launch date uncertainty (launch as a free variable) drove the team to frame every decision in terms of launch schedule.
Lack of a regular conversation with NASA program and HQ leadership regarding liens and threats to Unallocated Future Expenses (UFE) limited visibility and understanding of the cost situation.

Business/Contract Management – Programmatic Factors

- The fact that Caltech held the contract, while unique, seemed to be transparent to the JPL team, due to the strong relationship between the JPL Project Manager (PM) and LMS
  - This was not necessarily the case for LMS, where they saw challenges with the learning curve of the Caltech procurement folks that they don't see with NASA Centers like Goddard Spaceflight Center or JPL
- Reserves were only able to be held by the JPL project for scope at JPL (instrument, SE, Mission Design and Navigation (MDNav), SMA, PM, etc) and, therefore, reserves on Caltech and the LMS contract had to be held at PMPO
  - The team established a quick (~2d) process to release the reserves, as PMPO viewed these as Project UFE and not Mission Directorate (MD) UFE
  - Even with this streamlined process, the number of liens and contract mods made this a distraction for the PI, PM, and LMS
- A key challenge with Class D is that the overall budget, relative to the cost of a Full Time Equivalent (FTE), does not provide the leverage to solve multiple problems or to spend those reserves on strategic/robustness/what-if types of endeavors

Business/Contract Management – Launch Date Uncertainty

- The launch date uncertainty, including shift of the launch date to the left from late 2024 to late 2023 when the decision was made to go with IM-2 instead of IMAP, drove the LM team to frame every decision in terms of launch schedule
  - The launch date was a moving target throughout, and the team never could take a step back and regroup and solve problems broadly
  - There was an opportunity and consideration to switch out the power subsystem but was taken out of the decision space due to the perceived launch date, combined with the cost pressures
- The combined schedule and cost pressure made it a challenge to manage risk
  - The focus was on solving the problems the team knew about and not the problems that they hadn't found yet (i.e. understanding the true risk posture of the mission as it approached launch)
  - In the end game, the budget concerns drove the LM team to micromanaging charging to the hour

Business/Contract Management – Cost/Risk Visibility (1/2)

- There were issues early on with 533s reflecting the true financial situation
  - The project was surprised by an LMS upper (b) (4) [redacted] significant percentage of the contract value) that didn't show up in the 533s
  - There was a labor overrun that was masked by an underrun of materials
  - The post-pandemic surge in manufacturing costs also contributed to this
  - The LMS team did not do a variance analysis at a depth sufficient to catch this, as they would likely have done on a larger project

Business/Contract Management – Cost/Risk Visibility (2/2)

- Even without a risk process being performed at LMS, the LMS team did look at risk, dollarize the risks, and communicate this dollarized risk list to the project as part of the project risk process.
  - The total value of this was on par with the cost increases, according to the LMS team.
  - It does not appear these cost risks were communicated/understood across the project, PMPO, and NASA HQ.
  - It appeared after the 3rd payload manager took over, LM stopped requesting dollars for mitigations for ATLO challenges or risks.
- LM finished ATLO with (b) (4) [redacted] reserves left and had a ~6week pause to lower charging before launch, however there were no request to the project to utilize the reserves.
- It does not appear that there was a liens/threats management process where the PM regularly communicated with PMPO and PSD.
  - Liens and Threats were documented in the Quarterly packages, but they were largely reflective of major programmatic changes and not the kinds of things that emerge and consume UFE.

Management/Oversight Findings Summary

The level of institutional oversight for the LTB project, limited primarily by Class D implementation approach and institutional priority, was insufficient to provide needed monitoring and guidance to navigate the issues encountered during Development.

Management / Oversight – Class D Implementation

- Generally, there was a mismatch in expectations for Class D implementation between JPL, CalTech, and LMS
  - Each institution had a different view and treatment of risk for LTB
  - This impeded the team's ability to understand (and therefore manage and/or accept) the risk
  - There were numerous examples of mismatched expectations, understanding, and acceptance of risk across all organizations at various levels

Management / Oversight – Class D Implementation

- Within Project:
  - Project followed SMD's Class D Implementation Plan, specifically tailoring out some management processes to streamline development / reduce cost and allow for innovative, lower cost approaches
    - Example: Project Status Reporting
      - ❑ Monthly charts provided as a contract deliverable, but not briefed as cost-saving measure
      - ❑ Questions addressed on ad-hoc basis, thus losing opportunity to discuss/query issues real-time and potentially root out larger issues
  - Small Class D budget limited team size to the extent that staffing was sufficient to deal with "known fires", but not enough to penetrate and find unknowns
    - Project installed a JPL in-person resident at LMS to provide insight, but left in 2023
    - Was never replaced

Management / Oversight – Class D Implementation

- At JPL:
  - Type 2 project, managed at Directorate level within standard JPL framework
  - While JPL's 4x organization has done numerous Type 2 / Class D missions, this was the first with a system contractor
    - Team not practiced in how to achieve the insight/oversight function in a Class D environment
    - JPL Earth Science has successfully executed a number of these, but it's not apparent 4x reached out for insights, lessons learned, etc. that would have helped LTB
  - Project met weekly with 4x management, however, applied level of technical and oversight support tended to be sporadic
  - LTB Quarterly reports provided, but usually got a pass for briefing, thus losing opportunity to discuss/query issues real-time and potentially root out larger issues

Management / Oversight – Class D Implementation

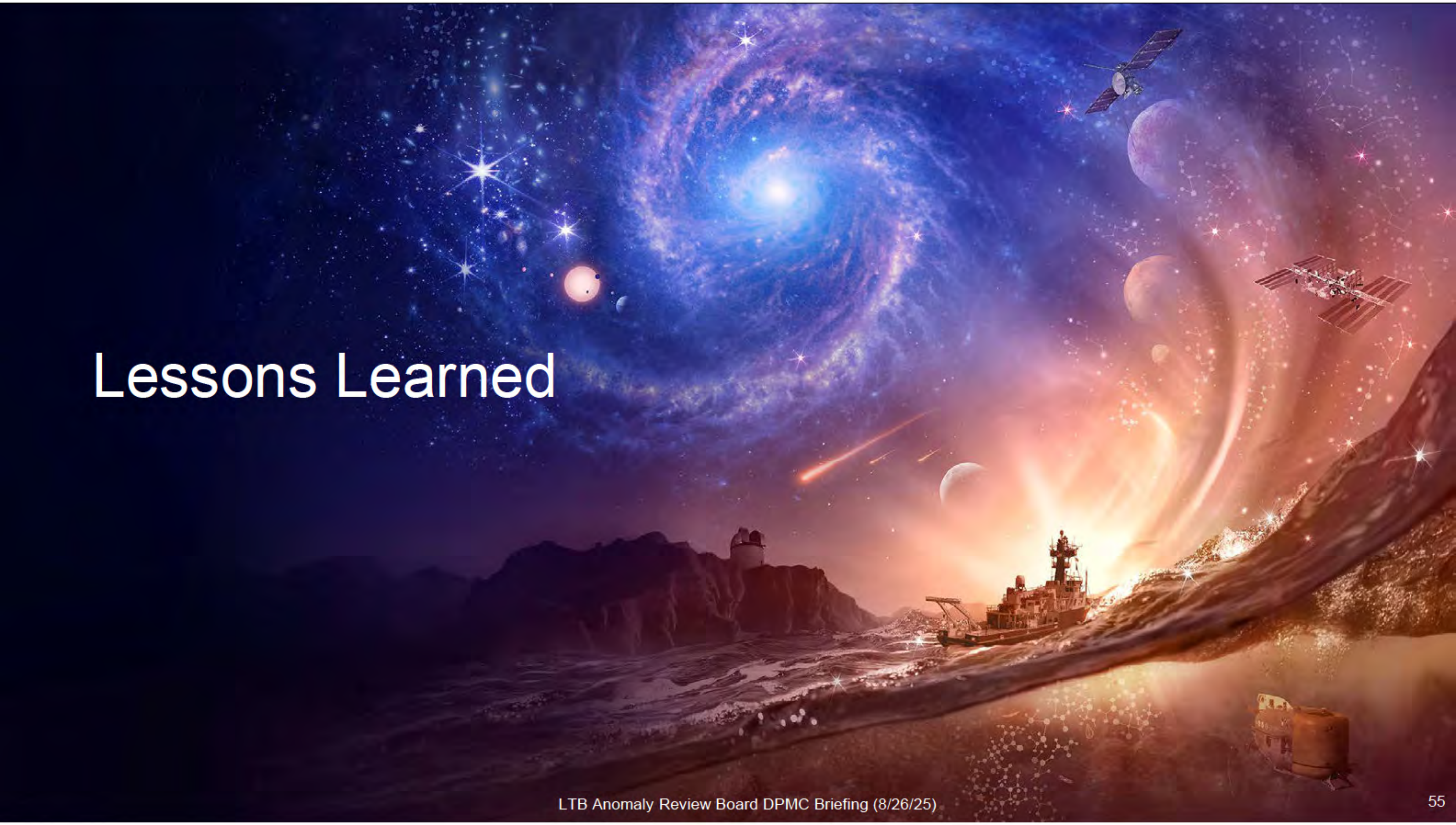
- At LMS:
  - Did not provide more experienced resources to backstop lesser experienced project team members
    - Class D projects seen as learning opportunities for younger engineers to get experience quickly
    - Only started providing additional support after problems started occurring
  - Class D projects didn’t have expectation for rigor on reviewing UVFs and associated risks
    - 11 UVFs presented at the ERR
    - Leadership viewed this as risky, but accepted due to LTB being Class D

Management / Oversight – Institutional Priority

- At JPL:
  - At the time, busy with other projects (Psyche, M2020, Clipper); LTB never THE topic of conversation
  - Trusted LMS as a system contractor, and took a more hands-off approach
  - 4x management never identified FSW or FP as a risk or issue throughout the lifecycle

Management / Oversight – Institutional Priority

- At LMS:
  - With cancellation of Janus, LMS focus on Curio product line got lost
  - Multiple LTB project and LMS leadership changes occurred starting after LTB PDR
    - Every deep space person assigned to LTB by LMS to lead the mission had less experience with deep space programs
    - LMS leads on project were overtaxed and multiple personnel changes created a chilling effect on the team
    - The FSW team was leaderless for a long time, isolated from the rest of the team, and without a chief engineer.
    - During architecting, FP role was held by an engineer with multiple other jobs.



Lessons Learned

Lessons Learned

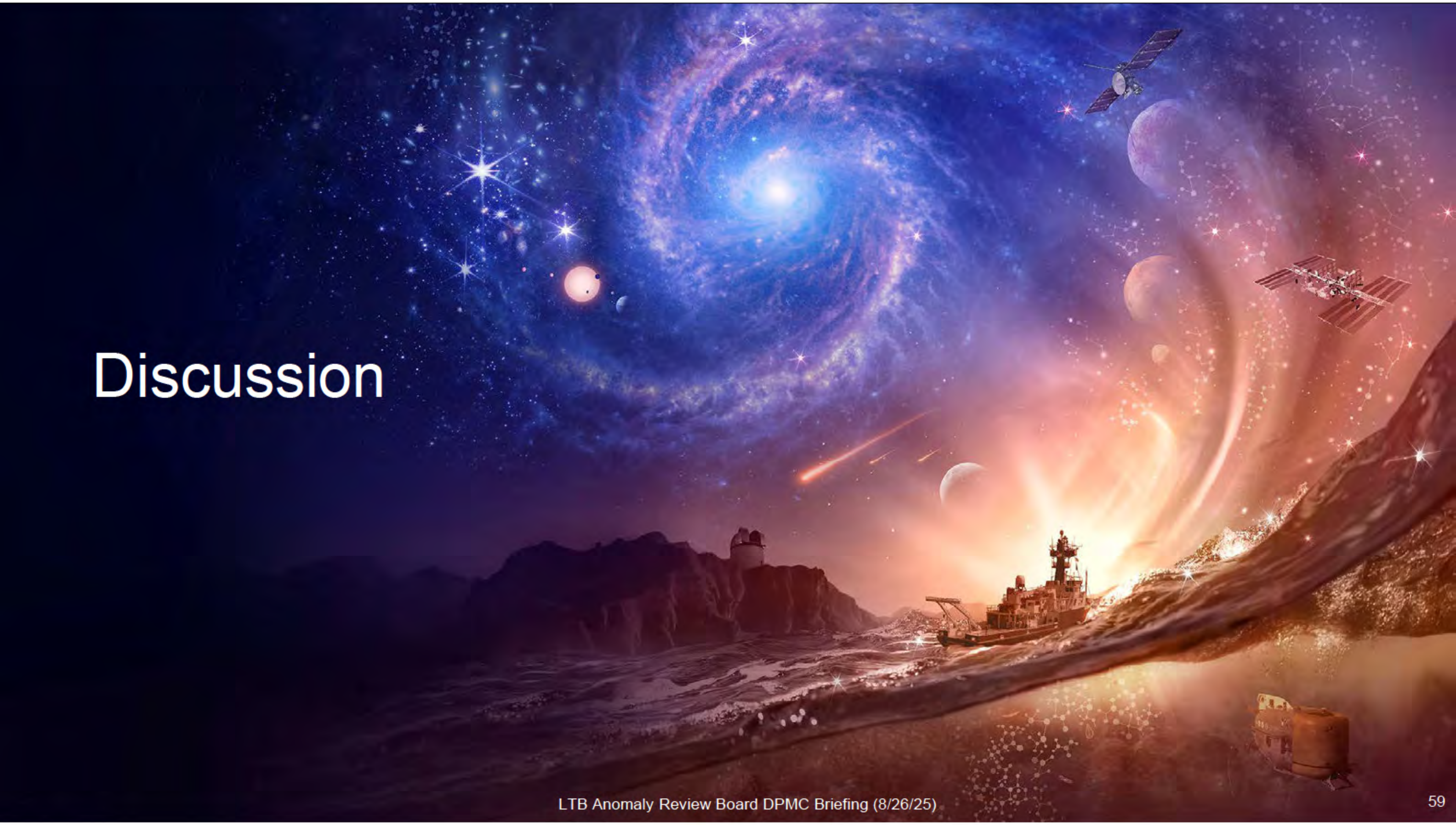
Class D projects must ensure their plans include time to look for weaknesses in the system, team, interfaces, etc. to ensure that risk is understood, even if that risk is determined to go unmitigated.
It is important to ensure all organizations and team members get to a common understanding on risk that is being accepted (not just which mission assurance requirements will be followed), meaning "to assess and accept the risk, you must understand the risk"; if understanding the risk is too expensive or takes too long to achieve, then all stakeholders need to understand that as an unquantified risk.
Achieving appropriate Institutional oversight of Class D missions is a challenge that needs to be explicitly planned for, addressed, and right sized.
On a Class D mission that assumes for risk, ensure that the safety net of fault protection can adequately mitigate some of the risks.
Right size the time and amount of testing at the integrated level when using more COTS hardware and software. Reliance on vendor testing won't get you system level insight and integrated testing will help drive out issues and possible deficiencies in the COTS procured hardware.
Develop and document best practices for system architecture and integration of black boxes, such as the need to focus on validation of the system ('does it do what we need it to do over the various phases of the mission') and not just what the requirements say.
Engineering Test Units are a premium on cost constrained Class D Missions, but use the risk process to decide which COTS hardware carries the most risk and think about ordering an engineering unit for early testing before Integration and Test
Develop a higher fidelity FlatSAT sim when dealing with a lot of COTS components.
Utilizing student operators can be a good thing, but you need to have the right S/C expertise including an ART in the room through commissioning.
Ensure the staffing plan covers both the younger engineers that are then back stopped by more experienced engineers.
To maintain institutional memory and understanding of agreements, risk posture, and key support assumptions, transitions of key leadership should include briefing with the Project and both incoming and outgoing management and explicitly cover key challenges, assumptions, and needs.

Near-Term Opportunities

Near-Term Opportunities

- Escapade
  - The LTB ARB met with the Escapade team for an hour to talk to them about general lessons learned
  - The LTB ARB will be meeting with the Escapade SRB to talk to them about specific LTB lessons learned before they go to Operational Readiness Review (ORR).
- Janus
  - If Janus gets pulled back out of storage an initial review of the design and LTB lessons learned should be held.
  - The gimbal axis definition should be updated and tested thoroughly with the end-to-end SA phasing test.
- Future SIMPLEx Announcement of Opportunity (AO)
  - Reassess the cost cap for a SIMPLEx mission. Is it reasonable or too low?
  - Look for successes of Class D Missions with a similar budget and requirement set as the SIMPLEx missions and interview those teams to see how they were able to achieve success.
  - Think about design, development, and test best practices for Class D missions that can be placed in the AO call and in the contract. Have the SE go over these best practices with the team to see if the project plans to deviate from them and assess those risks.

Discussion



Backup

Acronyms

ACU	Analog Control Unit
AO	Announcement of Opportunity
ARB	Anomaly Review Board
ART	Anomaly Response Team
ATLO	Assembly, Test and Launch Operations
CDH	Command and Data Handling
COTS	Commercial Off The Shelf
dPMC	Division Program Management Council
DSN	Deep Space Network
EGSE	Electrical Ground Support Equipment
EPS	Electrical Power System
ERR	Executive Readiness Review
EVR	Event Report
FOD	Foreign Object Debris
FP	Fault Protection
FSW	Flight Software
FTE	Full Time Equivalent
GNC	Guidance, Navigation and Control
GRAIL	Gravity Recovery and Interior Laboratory
HQ	Headquarters
I/F	Interface
I2C	Inter-Integrated Circuit
ICD	Interface Control Document
IM	Intuitive Machines
IMAP	Interstellar Mapping and Acceleration Probe
IRT	Independent Review Team
ITL	Incompressible Test List
JPL	Jet Propulsion Laboratory

Acronyms

KDP	Key Decision Point
LMS	Lockheed Martin Space
LOS	Loss of Signal
LTB	Lunar Trailblazer
MD	Mission Directorate
MDNav	Mission Design and Navigation
MSFC	Marshall Spaceflight Center
ORT	Operational Readiness Review
OVP	Over Voltage Protection
PDR	Preliminary Design Review
PFR	Problem Failure Report
PI	Principal Investigator
PMPO	Planetary Mission Program Office
PSD	Planetary Science Division
RFA	Request for Action
S/C	Spacecraft
SA	Solar Array
SIMPLEx	Small Innovative Missions for Planetary Exploration
SMA	Safety & Mission Assurance
SME	Subject Matter Expert
SRB	Standing Review Board
(b) (4) [redacted]	
TCM	Trajectory Control Maneuver
TLYF	Test Like You Fly
TRL	Technology Readiness Level
TVAC	Thermal-Vacuum
UFE	Unallocated Future Expense
ULLE	Uplink Loss Executive
UVF	Unverified Failure