



Integrated Rover–HDM–LunaSat Testing in a Lunar Regolith Analog Environment

COSGC GLEE (Great Lunar Expedition for Everyone) Mission

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Abstract

The Great Lunar Expedition for Everyone (GLEE) mission concept is developing a

distributed lunar science system consisting of miniature sensor platforms known as LunaSats that are deployed across the lunar surface to collect environmental and geophysical data. Validating the integrated operation of the rover, Housing and Deployment Module (HDM), and LunaSat systems in a realistic environment is a critical step toward advancing the mission’s technology readiness. To support this effort, the GLEE team conducted two system-level integration tests at the Colorado School of Mines Lunar Regolith Testbed, first in fall 2025 and again in early 2026. These tests aimed to evaluate system performance in a mission-analog environment and to assess the maturity of the integrated hardware architecture.

The Colorado School of Mines test facility provides a large enclosure filled with lunar regolith simulant and equipped with solar-simulated lighting and tracking systems for rover mobility analysis. Prior to testing, extensive preparation was conducted including hardware integration of the rover and HDM, sealing and structural upgrades to mitigate regolith intrusion, installation of updated HDM electronics, and the fabrication of simulated LunaSat payloads to reproduce mission-representative deployment conditions. During testing, the rover transported the HDM across the regolith surface before triggering an autonomous deployment sequence designed to disperse LunaSat payloads while verifying power, communication, and sensing functionality.

Testing evaluated several critical performance metrics including rover mobility in regolith, HDM power transfer from the rover, autonomous deployment functionality, LunaSat ejection behavior, solar panel orientation, and radio-frequency communication with the ground gateway. Results demonstrated successful rover traversal, consistent HDM deployment autonomy, reliable LunaSat ejection sequences, and verified RF communication and data extraction capabilities. Regolith sealing improvements showed partial success and informed further design refinements for future iterations.

These tests provide important validation of the integrated GLEE system architecture while advancing the technology readiness level of the mission toward system-level demonstration in a lunar-analog environment. The work presented in this paper discusses the preparation, execution, and evaluation of the test campaigns, including risk assessments, technology readiness evaluations, and lessons learned that inform future hardware development and field testing for distributed lunar science missions.

1. Introduction

The Great Lunar Expedition for Everyone (GLEE) mission is a distributed lunar science initiative designed to enable high-resolution, distributed measurements of the lunar surface through the deployment of miniature sensor platforms known as LunaSats. These compact, solar-powered systems are intended to collect environmental and geophysical data, including thermal behavior, regolith properties, and surface dynamics, across a wide deployment area, enabling a new paradigm of networked, in situ lunar sensing. The motivation for GLEE lies in both its scientific and educational impact: by leveraging scalable, low-cost hardware architectures and student-driven development, the mission aims to democratize access to planetary science while advancing meaningful lunar surface investigations. Achieving this vision requires not only successful subsystem performance, but robust integration of mobility, deployment, and sensing architectures into a cohesive system capable of operating under mission-representative conditions.



Figure 1: Systems Engineer, Jonathan Leites, with integrated Rover-HDM system inside Mines Lunar Regolith Test Bed (Source: Observer, February 2026).

A central challenge in progressing toward lunar deployment is the advancement of Technology Readiness Level (TRL) through system-level validation. While individual components such as the rover, Housing and Deployment Module (HDM), and LunaSats can

demonstrate functionality in isolation, TRL progression beyond component-level maturity requires integrated testing in a relevant environment. According to NASA-defined TRL frameworks, TRL 6 specifically demands a high-fidelity prototype demonstrating system/subsystem performance under conditions that approximate the operational environment (*TRL Justifications*, Taylor 2026). For GLEE, this necessitates testing within a lunar regolith analog environment that captures key surface characteristics such as granular mechanics, dust interaction, and solar-driven power constraints. Integrated system testing therefore serves as a critical bridge between theoretical design and operational feasibility, validating not only individual subsystem performance but also interdependencies such as power transfer, communication integrity, and autonomous deployment sequencing. The Colorado School of Mines Lunar Regolith Testbed provides an environment enabling controlled yet mission-representative evaluation of the full GLEE architecture.

The Fall 2025 test served as a precursor integration milestone, establishing baseline system performance and informing subsequent design iterations. As outlined in the *Developmental Test and Evaluation (DT&E)* plan, the initial test emphasized both subsystem validation and early-stage integration, focusing on rover mobility in regolith, HDM deployment reliability, and LunaSat communication and power functionality under simulated solar conditions (*DT&E Plan*, Leites 2025). This test was intentionally structured to evaluate individual subsystem requirements while beginning to assess system-level interactions, providing critical data on deployment behavior, RF communication stability, and regolith-induced failure modes such as dust intrusion and mechanical interference (*DT&E Plan*, Leites 2025). Importantly, the Fall 2025 effort established foundational test procedures, safety protocols, and performance metrics that enabled a more advanced, fully integrated test campaign in early 2026. Lessons learned from this initial phase, including limitations in regolith sealing and deployment consistency, directly informed hardware modifications and test design improvements for subsequent system-level validation efforts.

Building on this foundation, the work presented in this paper focuses on evaluating whether the integrated rover–HDM–LunaSat system satisfies the criteria for TRL 6 through demonstration in a lunar-analog environment. Specifically, the central question addressed is: *Can the fully integrated GLEE system reliably perform coordinated mobility, deployment, power transfer, and communication functions under mission-representative conditions?* To answer this,

system-level tests were conducted at the Colorado School of Mines Lunar Regolith Testbed in both Fall 2025 and early 2026, with increasing emphasis on autonomous operation and subsystem interdependence. These tests evaluated key performance metrics, including rover traversal capability, HDM deployment autonomy, LunaSat ejection dynamics, solar orientation, and RF communication reliability. By comparing observed system behavior against TRL 6 criteria, namely, successful demonstration of a high-fidelity prototype in a relevant environment, this study assesses the maturity of the GLEE system and identifies remaining gaps toward operational readiness. Ultimately, this work contributes to the broader goal of advancing distributed lunar science architectures from concept to flight-capable systems through rigorous, systems-level validation.

2. Materials & Methods

2.1 Rover: Hardware, Regolith Mobility Design, Power Delivery Interface

The rover is the testing platform and support system for the HDM. Its primary objective is to provide power and stable transport for the HDM while it is in the testing facility.

The main design of the rover is a rectangular box with a double-rocker arm system. This double rocker system reduces the angle felt by the HDM when it is on an inclined surface. Additionally, the double rocker system ensures the rover maintains several points of contact even in rocky terrain. This is combined with four 3D printed wheels, using PLA for the rims and TPU for the tires. These tires are designed with treads similar to conventional sand tires. This combined with the flexibility of the TPU allows them to easily navigate dust environments like sand and lunar regulation. The rest of the body is built out of 1/8” aluminum sheets and tubes, providing a structurally stable base for the HDM

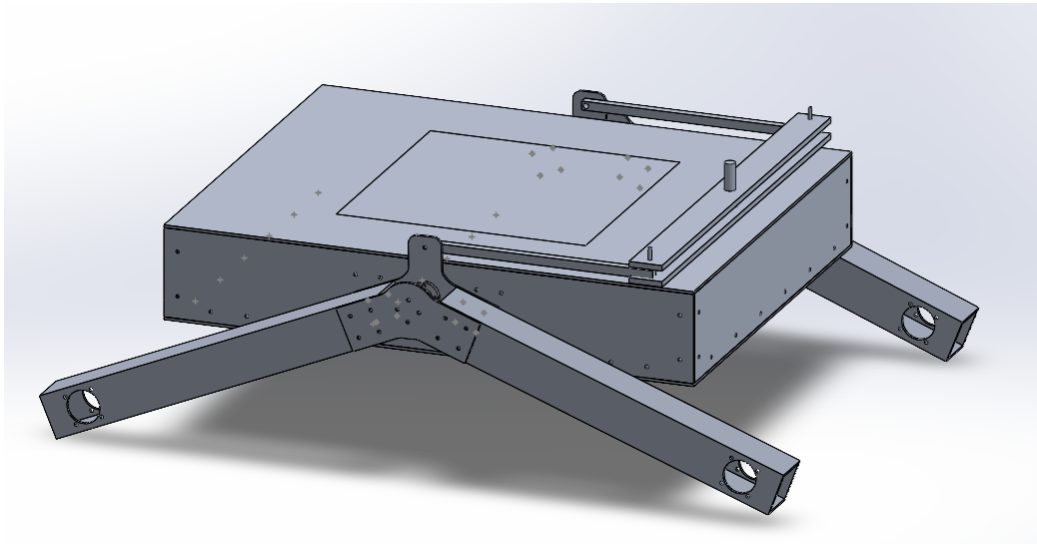


Figure 2: Final CAD design of Rover in SOLIDWORKS (Source: Robotics Team, July 2025)



Figure 3: Unfinished 3D-printed wheel prototypes showing internal structure and overall design. A ruler in the background (centimeters) provides scale. (Source: Robotics Team, April 2026)

To power the HDM, the rover has a port at the top of its chassis that feeds cables necessary for operation through cables. In addition to power, there are connections that allow remote control of the HDM using the same controller which pilots the rover. These wires are plugged into the respective system of the HDM, at which point the system becomes fully operational.

2.2 HDM: Deployment Mechanism, Autonomous Launch/Reload/Jam-Recovery, Electronics Upgrades

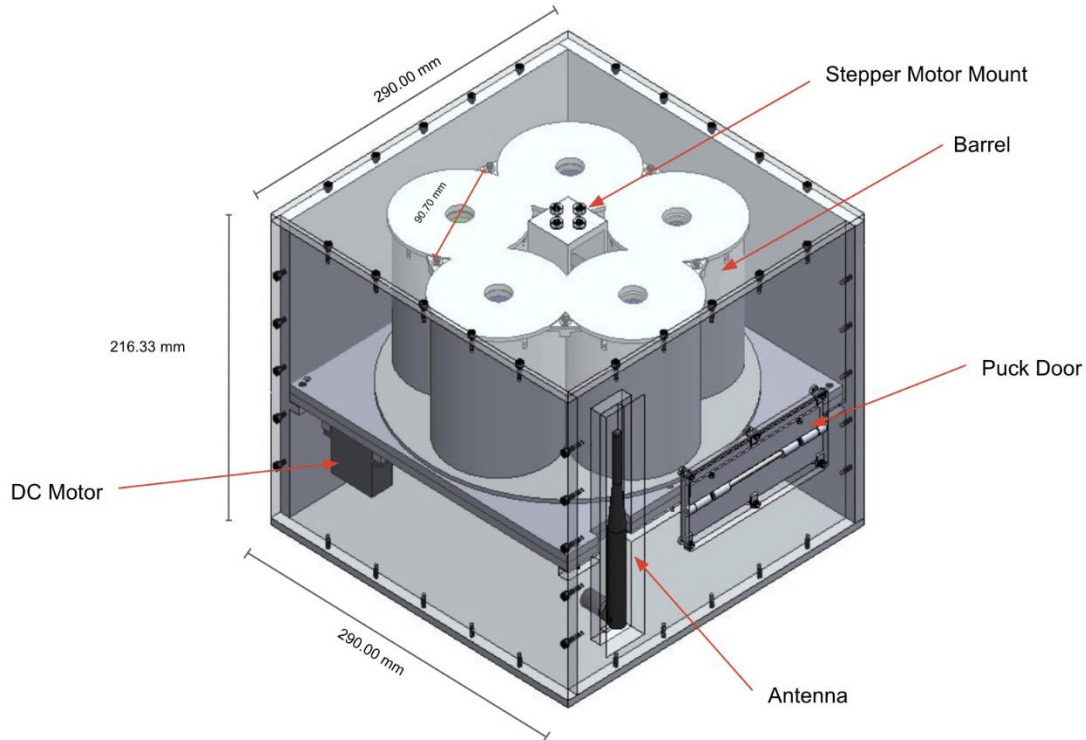


Figure 4: CAD model of the HDM with key components and dimensions labeled

The Housing and Deployment Module (HDM) is responsible for storing and deploying LunaSats in a controlled and repeatable pattern. Its main contents are a multi-column barrel, a flywheel based launch mechanism, and a track that guides the LunaSats as they are ejected from the payload. The barrel has multiple vertical columns that each hold a stack of LunaSats. During operation, a column is aligned over an opening that allows LunaSats to drop to the track level. A DC motor spins the flywheel to a specified power level that correlates to a speed, and then a pusher arm driven by a servo motor pushes the LunaSat into the path of the flywheel. After that, the puck is launched out and the next one drops into the track level. Once a full column is depleted, a stepper motor rotates the barrel to align the next column. The structure of the HDM is mostly made from laser cut acrylic, the barrel is made of PLA and the flywheel uses TPU and PLA.

The HDM is powered and controlled through the rover using both power and data connections. Commands are sent from an Xbox controller to an external ESP32 transmitted to a second ESP32 inside the rover, and then passed through TX/RX communication to an Arduino held in the bottom avionics compartment of the HDM. The Arduino controls the stepper motor, DC motor (flywheel), and servo motor (pusher arm). The wiring complexity was reduced by condensing the motor and motor driver connections into a custom PCB that is mounted on top of the Arduino. This made the system much more secure so the HDM could handle being on top of the rover.

In order to mitigate any jamming between the pucks and the track level, a “nudge” command was added to the stepper motor control which allowed for small adjustments to be made for the barrel position, so the LunaSats were guaranteed to fall into the track. Other commands allowed the operator to specify the number of LunaSats to be deployed and the launch power level.

2.3 LunaSats: Solar Power System, RF Comms, Sensor Stack, Payload Configurations, Pre-Integration Standalone Validation (2/22 test)

Each LunaSat V7.0 has the ability to run entirely on solar power. No batteries, no wired connections, while we often test it on wired connections, the solar panel working is one of the most crucial parts of the lunasat design. When the panels see enough light, the unit wakes up and starts transmitting. The sensor suite has a temperature sensor, a three-axis accelerometer, a magnetometer, and a capacitance sensor. A radio uses the LoRa protocol to handle all wireless communication to the gateway on the HDM. We brought three payload types to Mines: twenty launch test pucks for ejection characterization, five structural V7.0 LunaSats for ejection behavior, and one fully functional V7.0 unit for live sensor, solar panel, and RF verification.

Before the integrated test, we ran a standalone validation on 2/22/2026. We put a V7.0 LunaSat on LHS-1D Lunar Highlands Dust Simulant and powered it using only a high powered lamp charging the solar panel, while we progressively buried the electronics and panels in regolith. All channels read correctly after a brief initialization window at cold start. It held and worked even while having dusting on the solar panel and electronics, and, surprisingly enough, the radio actually worked a little better surrounded by dust, we’re currently investigating why. Strength held between -70 and -81 dBm, with SNR between 9.5 and 14.0 dB.

2.4 Test Facility & Procedure:

Colorado School of Mines Lunar Regolith Simulant Test Bed:

Regolith Simulant safety procedures followed; test plan and issue mitigation was shared and verified with Mines Test Bed head researcher before test commencement. Testing took place at the Colorado School of Mines Lunar Regolith Testbed using Lunar Highlands Dust Simulant (Leites and Herzog 7). Mechanical and communication reliability in regolith were the key variables measured during this test.



Figure 5: Integrated testing apparatus at Colorado School of Mines Lunar Regolith Test Bed in February 2026 (Source: GLEE Media Team, April 2026)

University of Colorado Boulder Discovery Learning Center:

HDM Deployment Testing: High frame rate slow motion cameras were placed above, one overlooking the entire track and one overlooking the launch speed at the HDM port. One was also placed on the side, looking perpendicular to the path of the LunaSats, at ground level (Leites 1). Deployment distance was the key variable measured during this test.

LunaSat Regolith Testing: The unit under test was a LunaSat V7.0. It was placed on a bed of LHS-1D Lunar Highlands Dust Simulant. A high-intensity solar lamp was used in place of sunlight as the sole power source (Taylor 1). Message reliability and autonomous start-up in various amounts of regolith were the key variables measured.

3. Results

3.1 Rover: Traversal, Turn, Power Delivery Outcomes

The rover was able to complete all of its objectives. The system worked remotely and responded to inputs given by a controller. It was able to traverse the lunar regolith and navigate difficult terrain. The rover was able to turn in place using a tank drive control setup. It successfully provided necessary power and uplink commands to the HDM. Overall, the rover was able to completely support the HDM and enable its testing in the lunar regolith environment.

3.2 HDM: Launch Distance Data, Power-Distance Relationship, Landing Variability, Jam Event

The HDM showed consistent and repeatable deployment of the LunaSats during the integrated testing. At a constant launch power of 25%, LunaSats reached an average distance of approximately 2.25 meters, with most landings occurring within 1 meter of the mean and over half within 0.5 meters. There was no correlation observed between the launch order and the distance, which shows a stable performance throughout the deployment cycle (Leites and Herzog 12-14). Variation in the launch power showed a non-linear relationship with distance. The maximum deployment range occurred near 25% power, with higher power levels resulting in decreased distances at a rate of around 0.5 meters per 5% increase in power. This might suggest that there is reduced efficiency at higher launch powers due to the interaction with the regolith environment (Leites and Herzog 13-14). Landing variability remained centered around the indented path (straight out from the opening of the HDM) with no trends in drift, indicating that the lateral dispersion was due to the pucks skipping on the regolith rather than a mechanical issue with the HDM. A single jamming event happened during testing, this was due to the rover battery being too low while attempting to shoot a puck at a low power level. The low battery power made it so the fly wheel did not spin as much as it was supposed to and was not able to give enough energy to launch the LunaSat. This was a known issue so when the jam event happened, the battery was quickly replaced and testing resumed without any issue.

3.3 LunaSats: RF Range Verification, Solar Orientation, Sensor Data

RF communication range was validated in an outdoor test using a solar-only powered LunaSat V7.0. With no battery or wired power source, the LunaSat powered on autonomously from solar panels and maintained a link to the gateway at distances up to 150 feet. We started testing at 25, then went to 50, then 100, then 150. Testing was stopped at this range without a connection failure, meaning 150 feet represents a lower bound on our operational range. This is important because it exceeds the minimum deployment area required by mission requirements, and confirms that solar-harvested power is sufficient to sustain both onboard sensing and wireless communication simultaneously. We also made sure that the V7s that were shot by the HDM into the regolith were operational and not harmed from the ejecting maneuver.



*Figure 6: LunaSat V7 Pucks after landing in regolith at the Colorado School of Mines Test Bed
(Source: Team member photographer)*

4. Discussion

The testing met our requirements for Technology Readiness Level (TRL) 6. It showed that the Rover, HDM, and LunaSats will be able to function effectively in sync on the lunar surface. We verified autonomous loading, deployment, and transitions for the HDM while it was integrated with the mobility and payload systems (Leites 5). The power connections from the rover and the data signals stayed connected, and launching distances remained consistent

throughout the test, so the test met the performance goals for the modeled lunar conditions (Leites and Herzog 15).

The launch distances from the test don't show exactly what will happen on the moon because we tested in Earth gravity (1-G). The lunar surface gravity is about 16.6% of Earth's gravity. To find the actual distance for a horizontal launch on the moon, the test distances have to be multiplied by 6.0398 (Leites and Herzog 16). This scaling proves the HDM provides enough momentum to meet the mission's deployment requirements.

Even though the deployment worked, regolith mitigation is still a problem for the hardware. Regolith and LHS-1D simulant is fine and abrasive, which means dust can get into the deployment track and the internal electronics. To fix this, future designs need mechanical blockages (such as doors) or positive-pressure sealing. Better integrated diagnostics on the HDM to check the system health during surface operations will also be considered as part of this fix (Leites and Herzog 15).

Mechanical and interface operations work in the regolith, but the system still needs to survive the rocket launch, deep space, and surface temperatures. The analog testbed models the terrain and dust hazards, but it does not simulate a vacuum or temperature extremes. Because of this, TVAC testing and vibration testing will be added to our testing plan for next year to get the GLEE hardware ready for lunar flight (Leites and Herzog 16).

5. Conclusion

The integrated testing of the rover, HDM, and LunaSat systems represented more than a validation of individual subsystems; It demonstrates the viability of a distributed, student-driven approach to planetary science. By successfully achieving coordinated mobility, deployment, power transfer, and communication in a lunar analog environment, this work shows that complex, multi-agent systems can be developed by students using accessible, iterative engineering methods. The ability of the system to function cohesively under regolith conditions, while maintaining reliable deployment patterns and communication links, highlights the strength of the GLEE architecture as a scalable platform for future lunar exploration. These results are

particularly significant in the context of advancing Technology Readiness Level, as they bridge the gap between conceptual design and operational feasibility in a way that is grounded in real hardware performance, rather than simulation alone.

Beyond the technical outcomes, the broader value of this work lies in its implications for the future of space exploration and engineering education. GLEE represents a shift toward distributed sensing systems that prioritize coverage, redundancy, and adaptability over singular, high-cost assets. This paradigm has the potential to fundamentally change how surface science is conducted on the Moon and other planetary bodies, enabling higher-resolution data collection and more resilient mission architectures. At the same time, the project demonstrates the power of student-led, open, and iterative development in contributing meaningfully to space systems engineering. By combining hands-on testing, rapid design iteration, and system-level thinking, this work not only advances a specific mission concept but also contributes to a more inclusive and scalable model for developing space technologies. As future efforts expand into environmental testing such as thermal vacuum and vibration, the foundation established here positions the GLEE mission as both a technically credible and socially impactful step toward the next generation of lunar exploration.



Figure 7: Team members posing with HDM –Rover integrated systems post first Mines test in November 2025 (Source: Team Member Photographer)

6. References

Leites, Jonathan. *Housing and Deployment Module Component Launch Test*. CU Boulder COSGC GLEE Mission, 26 Feb. 2026.

Leites, Jonathan, and Emma Herzog. *Mines Lunar Regolith Test Bed*. CU Boulder COSGC GLEE Mission, Feb. 2026.

Taylor, Evan. *LunaSat Solar Power and Wireless Telemetry Test Report*. CU Boulder COSGC GLEE Mission, 22 Feb. 2026.

Leites, Jonathan. *Developmental Test & Evaluation (DT&E) Plan: GLEE Mines Test Bed Test*. Colorado Space Grant Consortium, 5 Nov. 2025

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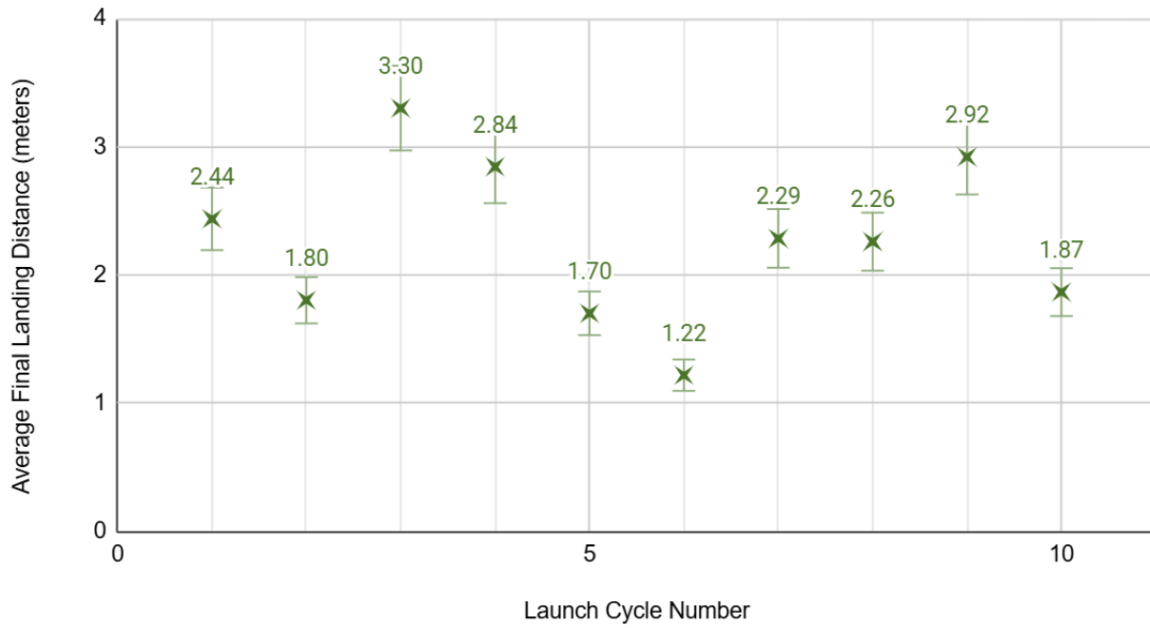
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7. Appendix

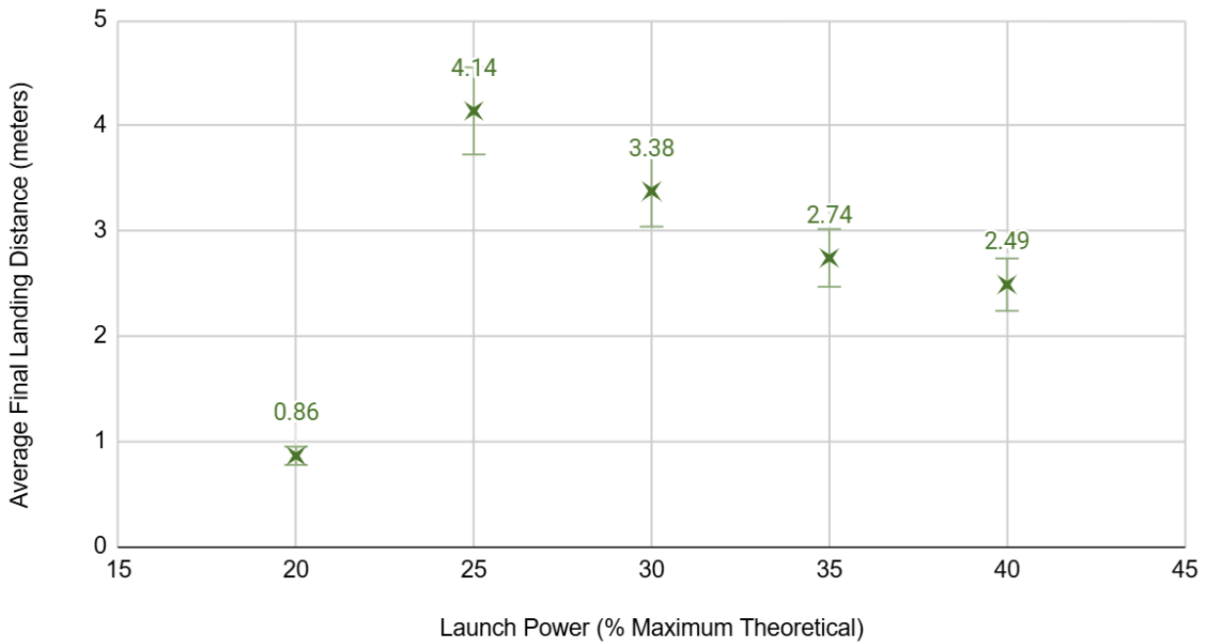
6.1: Raw Launch Data from Mines in 02/26

INPUTS				OUTPUTS				COMMENTS
POWER (%)	TEST ID	BARREL #	# IN BARREL	LANDING DISTANCE (m)	FINAL DISTANCE (m)	LATERAL DISTANCE (m)	LANDING VERIFIED	
LAUNCH TEST								
25	1.01	1	1	2.4384	2.4384	<0.1	Y	
25	1.02	1	2* stuck in barrel	1.8034	1.8034	<0.1	N	Barrel jam, fixed
25	1.03	1	3	3.302	3.302	<0.1	Y	
25	1.04	1	4	2.8448	2.8448	<0.1	Y	
25	1.05	1	5	1.7018	1.7018	<0.1	Y	
25	1.06	2	1	1.2192	1.2192	<0.1	Y	
25	1.07	2	2	2.286	2.286	<0.1	Y	
25	1.08	2	3	2.2608	2.2608	<0.1	Y	
25	1.09	2	4	2.4384	2.921	<0.1	Y	
25	1.1	2	5	1.8669	1.8669	<0.1	Y	
POWER TEST								
20	2.01	3	1	0.8636	0.8636	<0.1	Y	
25	2.02	3	2	3.2512	4.1402	0.4572	Y	
30	2.03	3	3	2.9718	3.3782	<0.1	Y	
35	2.04	3	4	2.4638	2.7432	0.3048	Y	
40	2.05	3	5	2.032	2.4892	0.127	Y	
FULL BARREL TEST								
25	3.01	4		2.3622	3.302	<0.1	Y	
25	3.02	4		2.2352	2.2352	<0.1	Y	
25	3.03	4		2.9591	3.302	<0.1	Y	
25	3.04	4		2.2352	5.1054	0.3048	Y	
25	3.05	4		1.3208	1.3208	<0.1	Y	

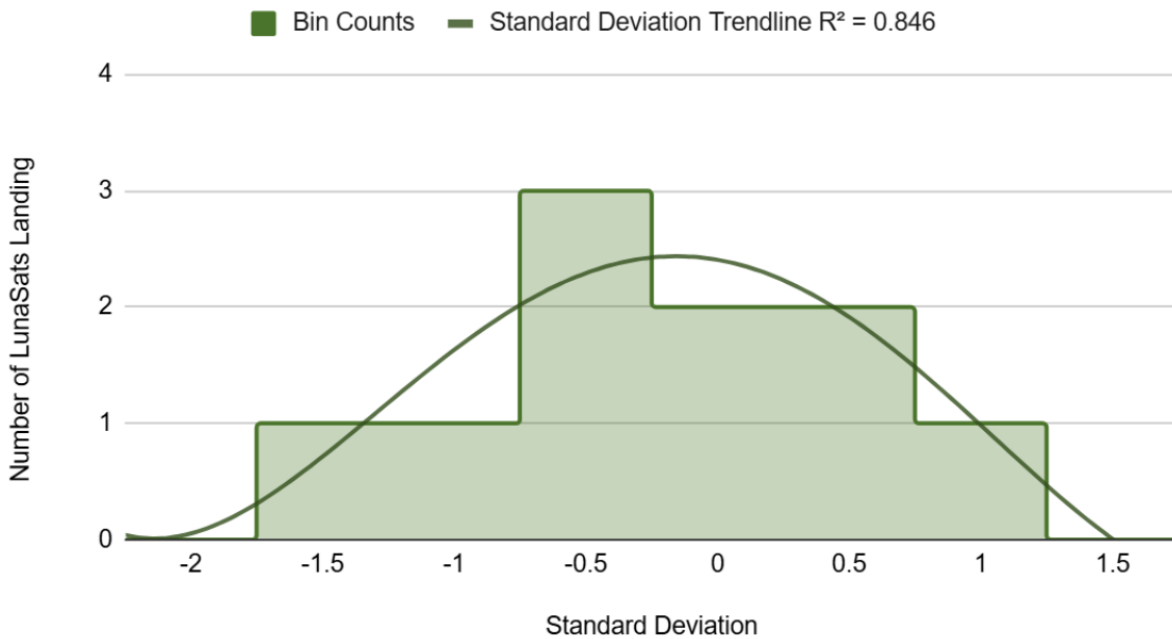
Final Launch Distances at 25% Power



Final Launch Distances at Varying Power



Landing Distance Variability



6.2: Requirements being tested for Mines 02/26

Requirement #	Description
MO-01	Following Requirements are from Mission Objectives Tab 01
1.1.2	The HDM shall constrain and protect all GLEE hardware.
1.2.2	The GLEE Payload shall meet IP60 standards for dust ingress protection in pre-deployment configuration.
1.2.4	The mass of the GLEE payload shall not exceed 35 kg
1.2.5	The GLEE Payload shall consume no more than 6.25W of power during nominal operation
1.2.6	The GLEE Payload shall consume no more than 56W peak power during all mission phases
1.2.7	The HDM shall have inhibits preventing premature LunaSat deployment (Dual Fault Tolerance)
1.2.9	The GLEE Payload shall abide by any commands given by lander operators to deploy the payload at any time if, i.e. if payload must be deployed sooner or before fully landing in the event that GLEE poses a risk to the lander mission
1.2.12	The GLEE Payload shall survive for the duration of the lander's mission duration

MO-02	Following Requirements are from Mission Objectives Tab 02
1.4	The LunaSats shall all fit securely into the HDM.
1.10	The HDM shall disperse LunaSats uniformly over a wide area on the lunar surface.
1.18	The avionics system payload shall interface with the HDM.
2.17	The HDM shall carry and deploy a minimum of 50 LunaSats.
2.20	The HDM shall deploy LunaSats such that LunaSat sensors and solar panels remain intact and are properly oriented to collect solar energy and lunar data
2.34	Deployment mechanisms shall interface with the OBC for deployment and activation of failsafe procedures
2.40	The GLEE Payload shall survive steady state stress states described in the Notes
3.18	The HDM shall deploy LunaSats within a minimum area of 250 m² reaching at least 2 m from the Lander and no farther than 50 m from the Lander
MO-03	Following Requirements are from Mission Objectives Tab 03
1.2	LunaSats shall remain operational throughout the duration of the mission.
1.7	Each LunaSat shall wirelessly communicate with the lander's On-Board Computer.
2.12	Each LunaSat shall have solar panels that generate an operational power supply of 246 mW for the duration of the mission.
2.38	The LunaSats shall each be able to communicate with the lander within a distance of 220 m

6.3: Required Materials for Mines test 02/26

Physical Equipment & Materials	Quantity	Provider
Housing and Deployment Module - fully fabricated	1	Structures Team
Mobility Payload – fully fabricated	total: 1	
Payload Rover	1	Robotics Team
HDM and Rover Battery	1	

LunaSat(s)	total: 31	
Launch Test Puck(s)	20	GLEE Mission
Integrated V7.0 Launch Test LunaSat(s)	5	Structures Team
Functional Integrated V7.0 LunaSat(s)	1	LunaSat Team
Backup LunaPuck(s)	5	
Contingency Hardware Toolkit		
Pliers, screws, nuts, bolts, files, etc.	1	COSGC
Contingency Electronics Toolkit		
Soldering kit, jumper cables, misc. wiring, etc.	1	COSGC, Emma Herzog (P.M.)
Misc. Testing Equipment		
Particle Respirator	1	COSGC/Jonathan L. (S.E.)
Transportation Padding	2 sheets	Jonathan L. (S.E.)
Transportation Bungie Cords	2	Jonathan L. (S.E.)
Software Needed	Version	Provider
HDM Protocols		Structures Team
Rover Protocols		Robotics Team
LunaSat Protocols		Avionics Team