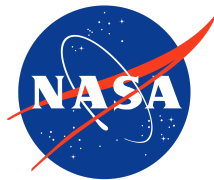




Mission Valkyr

Volatile Analysis for Lunar Knowledge
and Yield of Resources

Preliminary Design Review



Project Manager

Jasmine Wu
University of California, Irvine

Chief Scientist

Giovanna Camacho
University of
Virginia

***Deputy Project
Manager***

Torin Nelson
University of
California, Irvine

***Lead Systems
Engineer***

Joel Bhattarai
University of
Michigan

Project Engineer

Vincent Dang
University of California,
Riverside

Science Team

Carter Smirl
Santa Clara University

Engineering Team

Luis Rodriguez
Cal State Fullerton

Andrea Zabala
Foothill College

Programmatics Team

Harvey Yang
Irvine Valley College

Team Mentor

Jason Randall

Student Success Advisor

Freya Holloway
Programmatics

Table of Contents

List of Figures.....	6
List of Tables.....	8
List of Acronyms.....	11
1. Mission Overview.....	12
1.1. Mission Statement.....	12
1.2. Science Traceability Matrix.....	12
1.3. Summary of Mission Location.....	15
1.4. Mission Requirements.....	17
1.5. Concept of Operations (ConOps).....	20
1.6. Vehicle Design Summary.....	23
1.7. Science Instrumentation Summary.....	26
1.8. Programmatic Summary.....	28
1.8.1. Team Introduction.....	28
1.8.2. Team Management Overview.....	30
1.8.3. Major Milestones Schedule.....	33
1.8.4. Budget Overview.....	35
2. Overall Vehicle and System Design.....	38
2.1. Spacecraft Overview.....	38
2.1.1. Mechanical Subsystem Overview.....	54
2.1.1.1. Mechanical Subsystem Requirements.....	55
2.1.1.2. Mechanical Sub-Assembly Overview.....	60
2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans.....	70
2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans.....	71
2.1.1.5. Mechanical Subsystem Verification Matrix.....	74
2.1.2. Power Subsystem Overview.....	81
2.1.2.1. Power Subsystem Requirements.....	84
2.1.2.2. Power Sub-Assembly Overview.....	88
2.1.2.3. Power Subsystem Recovery and Redundancy Plans.....	90
2.1.2.4. Power Subsystem Manufacturing and Procurement Plans.....	91
2.1.2.5. Power Subsystem Verification Plans.....	93
2.1.3. CDH Subsystem Overview.....	94
2.1.3.1. CDH Subsystem Low-Level Requirements.....	101
2.1.3.2. CDH Sub-Assembly Overview.....	107
2.1.3.3. CDH Subsystem Recovery and Redundancy Plans.....	118
2.1.3.4. CDH Subsystem Manufacturing and Procurement Plans.....	123
2.1.3.5. CDH System Verification Plans.....	131

2.1.4. Thermal Control Subsystem Overview.....	135
2.1.4.1. Thermal Control Subsystem Requirements.....	137
2.1.4.2. Thermal Control Sub-Assembly Overview.....	141
2.1.4.3. Thermal Control Subsystem Recovery and Redundancy Plans.....	144
2.1.4.4. Thermal Control Subsystem Manufacturing and Procurement Plans....	146
2.1.4.5. Thermal Control Subsystem Verification Plans.....	149
2.1.5. Payload Subsystem Overview.....	151
2.1.5.1. Science Instrumentation Requirements.....	154
2.1.5.2. Payload Subsystem Recovery and Redundancy Plans.....	156
2.1.5.3. Payload Subsystem Manufacturing and Procurement Plans.....	158
2.1.5.4. Payload Subsystem Verification Plans.....	160
2.2. Interface Control.....	161
3. Science Mission Plan.....	165
3.1. Science Objectives.....	165
3.2. Experimental Logic, Approach, and Method of Investigation.....	166
3.3. Payload Success Criteria.....	169
3.4. Testing and Calibration Measurements.....	171
3.5. Precision and Accuracy of Instrumentation.....	172
3.6. Expected Data & Analysis.....	174
4. Mission Risk Management.....	178
4.1. Safety and Hazard Overview.....	178
4.1.1. Risk Analysis.....	180
4.1.2. Failure Mode And Effect Analysis.....	191
4.1.3. Personnel Hazards and Mitigations.....	196
5. Activity Plan.....	198
5.1. Project Management Approach.....	198
5.2. Mission Schedule.....	201
5.2.1. Schedule Basis of Estimate.....	201
5.3. Budget.....	206
5.3.1. Budget Basis of Estimate.....	206
5.3.2. Total Mission Cost.....	208
5.3.3. Personnel Budget.....	209
5.3.4. Travel Budget.....	212
5.3.5. Outreach Budget.....	213
5.3.6. Direct Costs.....	214
5.4. Scope Management.....	218
5.4.1. Change Control Management.....	218
5.4.2. Scope Control Management.....	221

5.5. Outreach Summary.....	224
6. Conclusion.....	230
References.....	231
Declaration of Generative AI and AI-Assisted Technologies.....	239
Appendix.....	240

List of Figures

Figure 1. Image Of Landing Site.....	15
Figure 2. Calculations from JMARS regarding Mission Valkyr's area of operations.....	16
Figure 3. The inclination of the slopes along the planned path of the rover.....	16
Figure 4. Mission VALKYR ConOps.....	20
Figure 5. Lunar Rover CAD.....	24
Figure 6. Lunar Rover CAD Rear View.....	25
Figure 7. RIMFAX Diagram.....	26
Figure 8. RIMFAX.....	27
Figure 9. Team Organization Chart.....	30
Figure 10. Mission Cost Breakdown.....	35
Figure 11. Main-Components Overview of Schematic.....	46
Figure 12. RIMFAX Diagrams.....	50
Figure 13. Lunar Rover CAD Front View.....	52
Figure 14. Lunar Rover CAD Internal Components.....	53
Figure 15. Power Vs. Time Graphs.....	83
Figure 16. Risk-aware pathfinding algorithm shows the effectiveness of reaching safe conditions by evaluating the optimal path at each fault and waypoint (Lamarre et al. 2024).....	95
Figure 17. Sample of the RAPF Algorithm in Python.....	96
Figure 18. CDH Software Architecture Flow Chart.....	98
Figure 19. Data Handling Flow Chart.....	100
Figure 20. Software Recovery And Redundancy.....	120
Figure 21. Kubernetes Architecture for a redundant backend architecture (kubernetes 2023).....	121
Figure 22. Code block for selecting the optimal supplier by scoring the vector aggregation of lead time, total award value, and location of the manufacturing site....	124
Figure 23. Code blocks for hyperparameter sizing the model with Grid Search and training the model with the Random Forest Regressor.....	125
Figure 24: Sankey Diagram Visualization of the CDH supplier chain with nodes: component, manufacturing facilities, supplier, and the final destination.....	126
Figure 25. Heat Flow Maps.....	136
Figure 26. System Block Diagram.....	161
Figure 27. N2 Chart.....	162
Figure 28. Lunar Rover CAD Labeled Components.....	164
Figure 29. Sites Of Interest.....	166

Figure 30. RIMFAX Specifications.....	169
Figure 31. NSS Specifications.....	170
Figure 32. RIMFAX Operational Modes.....	174
Figure 33. MATLAB simulation of a sample RIMFAX dataset for the reflection amplitude using the Blackman Window Function.....	176
Figure 34. Process of transcribing Raw data from JPL's Instrument data system into their Planetary data system.....	176
Figure 35. Total Efficiency Vs. Neutron Energy.....	177
Figure 36. Risk Analysis Block Chart.....	180
Figure 37. Team Organization Chart.....	198
Figure 38. Mission Schedule.....	204
Figure 39. Community Engagement.....	227

List of Tables

Table 1. Science Traceability Matrix.....	11
Table 2. Mission Requirements Table.....	16
Table 3. Team Introduction Chart.....	26
Table 4. Mission Phases Duration.....	31
Table 5. Allocation Excluding Margin.....	34
Table 6. Allocation Including Margin.....	34
Table 6. Power Subsystem Requirements.....	36
Table 7. Mechanical Subsystem Requirements.....	37
Table 8. Thermal Subsystem Requirements.....	38
Table 9. CDH Subsystem Requirements.....	39
Table 10. Payload Subsystem Requirements.....	41
Table 11. Overall Dimensions And Mass.....	51
Table 12. Mechanical Subsystem Top-Level Requirements.....	54
Table 13. Mechanical Subsystem Low-Level Requirements.....	55
Table 14. Mechanical Sub-Assembly Overview.....	62
Table 15. Aluminum Alloy Trade Study.....	64
Table 16. Electric Motor Trade Study.....	65
Table 17. Frame And Chassis Material Trade Study.....	66
Table 18. Inertial Measurement Unit Trade Study.....	67
Table 19. Mechanical Subsystem Verification Matrix.....	72
Table 20. Power Subsystem Top-Level Requirements.....	82
Table 21. Power Subsystem Low-Level Requirements.....	83
Table 22. Power Subsystem Verification Matrix.....	91
Table 23. CDH Subsystem Low-Level Requirements.....	99
Table 24. Computing Subassemblies Overview Chart.....	106
Table 25. Onboard Computer System Chart.....	107
Table 26. Flight Software Subassemblies Overview Chart.....	108
Table 27. Core Flight System Trade Study.....	110
Table 28. Telemetry Subassemblies Overview Table.....	113
Table 29. X/S Transceiver Antenna Trade Study.....	114
Table 30. CDH Subsystem Alternate And Primary Suppliers.....	126
Table 31. CDH Subsystem Verification Matrix.....	131
Figure 25. Heat Flow Maps.....	134
Table 32. Thermal Subsystem Top-Level Requirements.....	136
Table 33. Thermal Subsystem Low-Level Requirements.....	137
Table 34. NSA RIMFAX Specifications.....	149

Table 35. NSA NSS Specifications.....	150
Table 55. Payload Subsystem Verification Matrix.....	158
Table 36. RIMFAX Trade Study.....	171
Table 37. Neutron Spectrometer Trade Study.....	172
Table 38. Power Management System Risks.....	181
Table 39. Power Management Risks Reasoning.....	182
Table 40. Risks Table.....	184
Table 41. High Criticality Risks.....	184
Table 42. Medium Criticality Risks.....	186
Table 43. Low Criticality Risks.....	187
Table 44. Failure Mode And Effects Analysis.....	191
Table 45. Salary Of Mission VALKYR.....	205
Table 46. Final Cost Calculations for Mission VALKYR.....	207
Table 47. Allocation of personnel throughout each phase of the mission.....	208
Table 48. Personnel allocations for Mission VALKYR.....	209
Table 49. Travel Allocations for Mission VALKYR.....	211
Table 50. Outreach Allocations for Mission VALKYR.....	212
Table 51. Direct Cost Allocations for Mission VALKYR.....	216
Table 52. Change Control.....	219
Table 53. Breakdown of Activities.....	223
Table 54. Sample Social Media Posting Schedule.....	228
Appendix A. Mission VALKYR Plans for Resolution.....	239
Appendix C: Team 26 Overview.....	241

List of Acronyms

ACEEPS	Advanced Common Evolvable Electrical Power System
ADV	Advisory
BMS	Battery Management System
CDH	Command and Data Handling
CDR	Critical Design Review
CRM	Continuous Risk Management Process
DSN	Deep Space Network
EDAC	Error Detection and Correction
ERE	Employee-Related Expense
FMEA	Failure Mode and Effect Analysis
GNC	Guidance, Navigation, and Control
GPR	Ground Penetrating Radar
JMARS	Java Mission-planning and Analysis for Remote Sensing
IMU	Inertial Measurement Unit
KBPS	Kilobits Per Second
KDP	Key Decision Point
MCR	Mission Concept Review
MLI	Multi-Layer Insulation
MTDC	Modified Total Direct Costs
NSS	Neutron Spectrometer System
NVRAM	Non-volatile Random Access Memory
OBC	On-board Computer
OMB	Office of Management and Budget
PMDU	Power Management and Distribution
PSR	Permanently Shadowed Region
RFA	Request for Action
RIDM	Risk Informed Decision Making Method
RIMFAX	Radar Imager for Mars' Subsurface Experiment
RPM	Revolutions Per Minute
SEE	Single Event Effect
SDRAM	Synchronous Dynamic Random Access Memory
SRR	System Requirements Review
STM	Science Traceability Matrix
TID	Total Ionizing Dose
VALKYR	Volatile Analysis for Lunar Knowledge and Yield of Resources
VIPER	Volatile Investigation and Polar Exploration Rover

1. Mission Overview

1.1. Mission Statement

Volatile Analysis for Lunar Knowledge and Yield of Resources (VALKYR) will be a discovery class mission investigating the Permanently Shadowed Regions (PSR) located at the lunar South Pole. Mission VALKYR will advance NASA's goal to establish a sustained Human presence on the Moon. This is because PSRs are believed to contain deposits of water-ice and other volatiles that can be used to support future Human missions. Since volatiles are a potential resource for fuel and oxygen, the mission will measure water-ice abundance and characterize the elemental composition of lunar volatiles, such as hydrogen. Because more information is needed to understand how Humans can extract and use these volatiles, Mission VALKYR will provide essential scientific data to advance technologies and strategies for long-term space exploration.

A robotic spacecraft (referred to as a rover, vehicle, or system) will collect data at PSR 132 located in the de Gerlache-Kocher Massif region to gather in situ measurements with a Ground Penetrating Radar (GPR) and a neutron spectrometer. These two instruments will determine the distribution and abundance of water-ice and the temporal variance of volatiles within the top 1 meter of regolith. The discoveries to be made will provide a better understanding of how Humans can prepare for future extraplanetary missions, including those to Mars.

1.2. Science Traceability Matrix

Mission Valkyr will advance NASA's understanding of lunar resources and enable future Human missions to the Moon. Water-ice is a promising resource that can mitigate the high costs associated with resupplies from Earth (Duke 2006, 597). However, the precise abundance of water in lunar regions remains unknown (Schorghofer 2020).

The mission's science objectives focus on the spatial and temporal variability of lunar volatiles in PSRs. The mission's goals have a *spatial* component to accurately measure the amount of water-ice and a *temporal* component to characterize volatiles within 1 meter of the surface at different phases of the lunar cycle. Characterizing volatiles can potentially identify phase state distribution of hydrogen in 14 lunar days (Prem n.d.), while measuring water-ice abundance will determine if Humans can someday use these volatiles to sustain a long-term Human presence. By using two scientific instruments, a GPR and a neutron spectrometer, the mission will gather essential data on lunar volatiles which will improve resource utilization strategies for future lunar missions.

Table 1. Science Traceability Matrix

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
Artemis III Goal 2a: Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions	Determine the water-ice abundance of the de Gerlache-Kocher Massif region within the top 1 meter of regolith to at least a +/- 5% accuracy	Identify subsurface layers to detect water-ice within 1 meter of the regolith	Detect the depth of subsurface reflections from water-ice layers over a 1 km^2 area	Frequency Range	150-300 MHz	150-300 MHz	NASA RIMFAX Ground Penetrating Radar	The system shall determine the water ice abundance of at least one of the 13 Artemis III landing site locations within 1 meter of the regolith to at least +/- 5% accuracy
				Integration Time	Continuous	Continuous		
				Sensitivity	High	High		
				Spatial Resolution	<10 cm	<10 cm		
		Determine hydrogen concentration within the lunar regolith	Detects hydrogen peaks in the thermal (<0.3 eV) and epithermal (0.3 eV to 1 keV) neutron flux range in lunar regolith samples.	Neutron Flux Range	Thermal and Epithermal	Thermal and Epithermal	NASA Neutron Spectrometer System (NSS)	
				Integration Time	1 s	1s		
				Sensitivity	0.5 wt% H	0.5 wt% H		
				Spatial Resolution	<1 m	<1 m		
Artemis III Goal 2c: Understand the transport, retention, alteration, and loss processes that operate on volatile materials	Determine the elemental composition of the lunar regolith to measure the phase state	Determine dielectric properties of subsurface layers within 1 meter of lunar regolith	Detect changes in the reflected radar signals corresponding to different materials in a 2-3 km^2 area	Frequency Range	150-300 MHz	150-300 MHz	NASA RIMFAX Ground Penetrating Radar	The system shall determine the elemental composition of the lunar regolith to measure the phase state and distribution with a +/- 5-10%
				Integration Time	Continuous	Continuous		
				Sensitivity	High	High		

near and at permanently shaded lunar regions	and distribution with a +/- 5-10% accuracy as a function of time			Spatial Resolution	<10 cm	<10 cm	NASA Neutron Spectrometer System (NSS)	accuracy
		Determine the abundance and distribution of hydrogen and other volatile compounds within the lunar regolith	Detect variations in energy and frequency with a (10^2 to 10^4 neutrons/s/cm^2) intensity	Neutron Flux Range	Thermal and Epithermal	Thermal and Epithermal		
				Integration Time	1 s	1 s		
				Sensitivity	0.5 wt% H	0.5 wt% H		
				Spatial Resolution	<1 m	<1 m		

1.3. Summary of Mission Location

The final selected location for Mission Valkyr to collect data from is the Artemis III site, de Gerlache Kocher Massif, located at -88.571°N , 282.866°E with a radius of .5km. This geographical location has historically averaged, “ -88°C (winter in polar regions) to 58°C with an average surface temperature range of -193°C (night polar regions) to 111°C (day in equatorial regions)” (Lee et. al., 2023). This region also boasts $>1\text{km}^2$ of substantial solar illumination with direct visibility to Earth with slopes of $\leq 5^{\circ}$ (Lee et. al., 2023).

This landing site is 3.41 km from the permanently shadowed region of de Gerlache which allows for solar illumination to help power usage the start of the beginning 3.41km of the operation and the ending 3.41km of the operation to and from. Imagery of the landing sight for Mission Valkyr located at -88.571°N , 282.866°E with a radius of .5km Please see the following imagery of the landing site:

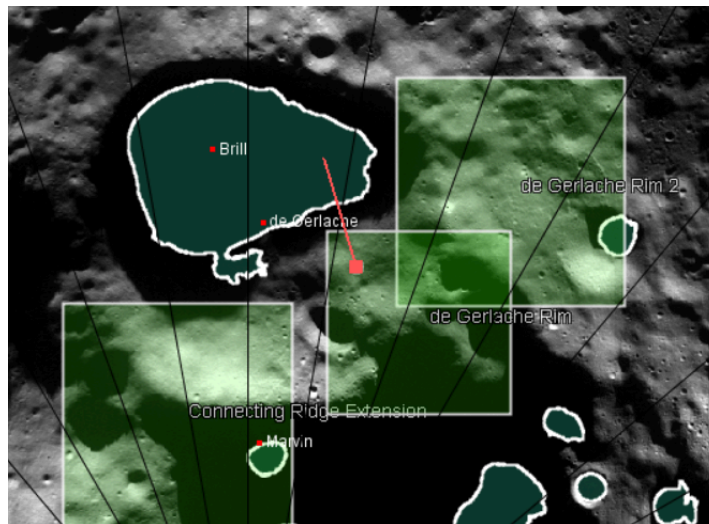


Figure 1. Image Of Landing Site

The landing site has a 2.242° slope minimum with a maximum slope of 6.26° as shown in the following figure from JMARS:

Radius :	slope :	minimu...:
0.5	2.242	6.268

Figure 2. Calculations from JMARS regarding Mission Valkyr’s area of operations.

The various geography the rover is set to encounter along the chosen path is depicted in the following chart and expected to be traversed in six days:

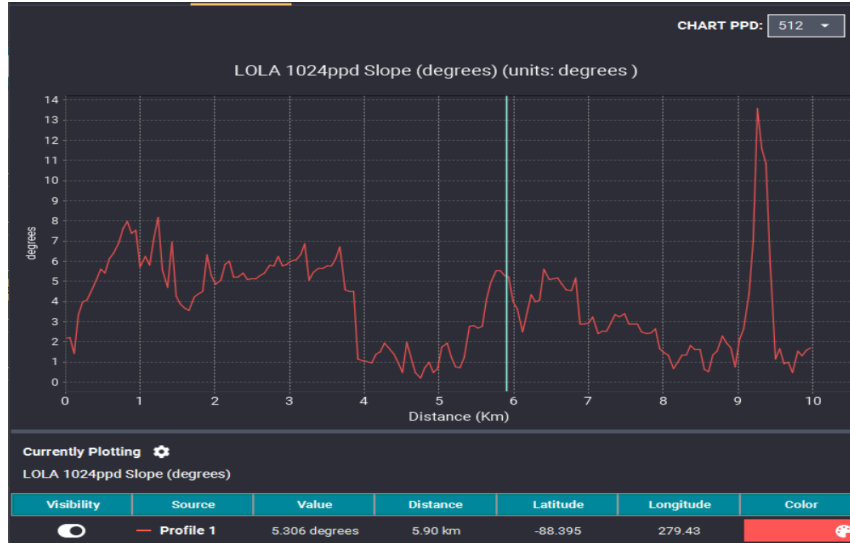


Figure 3. The inclination of the slopes along the planned path of the rover.

This path was chosen as the elevation change in slope is not drastic and to mitigate risk the rover will travel up to 9 km out before returning. This permanently shadowed region of interest was previously identified within the 5km area of confirmed ice (Lee et al. 2023). This site is a significant part of the de Gerlache Kocher Massif, containing significant traces of water, providing insight into the science objective. This landing site meets all requirements of radius, and slope inclination, and is well within the landing site constraints. Further imagery is found in Section 3.2 Experimental Logic, Approach, and Method of Investigation for the various sites of interest for this mission.

1.4. Mission Requirements

The customer has allocated a budget of \$175 million for Mission VALKYR. The vehicle is required to follow a mass constraint of 85 kg and a volume constraint of 1.5 m x 1.5 m x 1.5 m. Equipped with no more than two instruments, the vehicle should be able to perform the necessary science to determine the water-ice abundance and chemical composition of the lunar regolith during different phases of the lunar cycle. Table # describes mission VALKYR's derived system requirements based on customer constraints.

Given that the system is divided into four subsystems (Mechanical, Thermal, Electrical, and Command and Data Handling (CDH)), the system must be able to travel through rugged terrain and maintain a reasonable operating temperature despite frigid conditions. Therefore, materials selection will involve choosing proper insulation and thermal management systems. All electrical components must work properly to provide the system with sufficient power and relay communication to and from Earth using a spacecraft that travels in a circular polar orbit around the Moon as an "intermediary" place of communication. Uplink commands will be transmitted via S-band, while downlink data will be transmitted via X band.

Table 2. Mission Requirements Table

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Requirements							
MR-1	The spacecraft shall determine the water ice abundance of at least one of the 13 Artemis III landing site locations within 1 meter of the regolith to at least +/- 5% accuracy.	Provided by Mission Document	Customer	PAY-1, THER-2, MEC-1, MEC-2, MEC-3, POWER-1, POWER-3	Demonstration	All	Met
MR-2	The spacecraft shall determine the elemental composition of the lunar regolith to measure the phase state and distribution with a +/- 5-10% accuracy.	Provided by Mission Document	Customer	PAY-1, PAY-2, MEC-3	Demonstration	All	Met
MR-3	The spacecraft shall not exceed a volume of 1.5 m x 1.5 m x 1.5 m.	Provided by Mission Document	Customer	MEC-4	Inspection	All	Met
MR-4	The spacecraft shall not exceed a mass of 85kg.	Provided by Mission Document	Customer	MEC-2, MEC-4	Inspection	All	Met
MR-5	The spacecraft shall not exceed a cost of \$175.	Provided by Mission Document	Customer	All	Analysis	All	Met
MR-6	The spacecraft shall be ready for launch by September 1st, 2028.	Provided by Mission Document	Customer	All	Inspection	All	Met

MR-7	The spacecraft shall not have a Radioisotope Thermoelectric Generator, or any derivative thereof. Any radioactive material used on the spacecraft shall not exceed a combined mass of 5g.	Provided by Mission Document	Customer	PAY-1, PAY-2	Inspection	All	Met
MR-8	The spacecraft shall communicate with Earth via a relay spacecraft orbiting the Moon in a circular polar orbit at an altitude of 100 km.	Provided by Mission Document	Customer	CDH-1	Analysis	All	Met

1.5. Concept of Operations (ConOps)

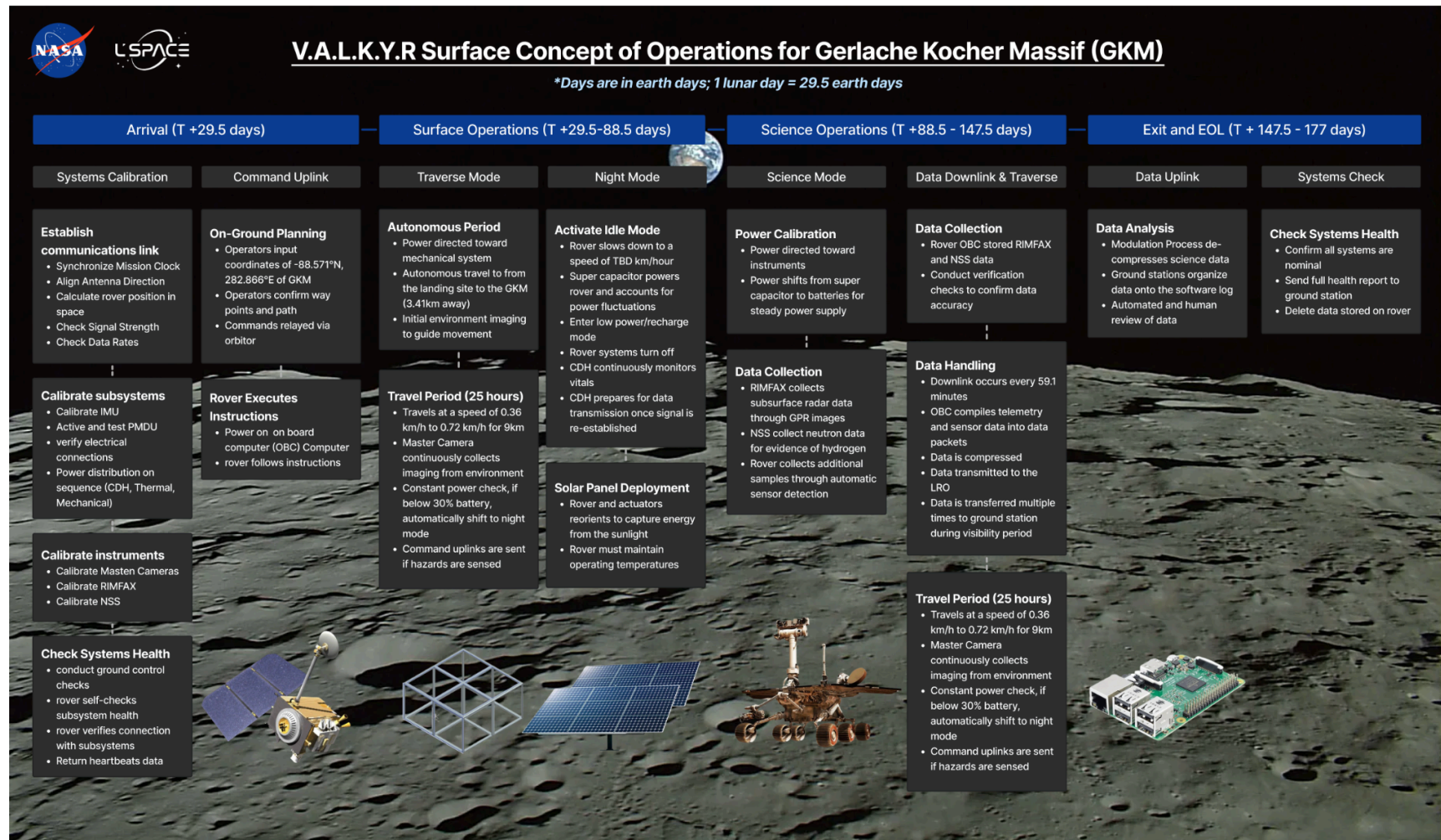


Figure 4. Mission VALKYR ConOps

The Mission VALKYR adheres to a strict and sequential procedure when designing the Concept of Operations. A collaborative review panel held between the Lead Systems Engineers and the Programmatic Team ensures that operational objectives are balanced with an acceptable risk profile. A comprehensive needs assessment is conducted in collaboration with relevant stakeholders to confirm key science objectives and prioritize sample returns. Key phases are developed in alignment with major operational scenarios, such as Night Mode, Day Mode, Science Mode, and the Loss of Signal (LOS) period. Based on historic analogous missions such as the Lunar Exploration Analogue Deployment (LEAD), the VALKYR deployment period will be conducted across 84 hours, or 3.5 earth days (Krenn et. al.). The operational period will last for 6.5 Lunar Days, or approximately 177 Earth Days (Lee et. al., 2022). This is due to the rover's average traversal speed of 0.36 km/hr to 0.72 km/hr which will take approximately 25 hours over an 18 km travel distance. This calculation also accounts for delays from disruptions of signal transmission, volatile temperature conditions during day-night cycles, and systems checkouts. System Checks are conducted to ensure nominal conditions over a volatile lunar terrain with extreme temperature fluctuations and gravitational exposure 1 / 6 that of Earth that could impact the rover's maneuverability (NASA, 2004).

The Deployment Period will be carried out immediately after the Launch, Cruise, and Arrival Period (LCA) and will endure for approximately 25 hours given an average travel speed of 0.36km/hr. Continuous monitoring from ground stations will be paired with a sequential deployment procedure and self-check assessments conducted on the rover. The communication link between the orbiting spacecraft and ground stations is first calibrated through synchronization of the mission clock and alignment of the antennas to the ground stations' line-of-sight. The RIMFAX and NSS instruments are calibrated with initial subsurface imaging to prepare for the first stage of movement.

Phase 0 of this operation will take 29.5 earth days (1 lunar day) and will begin upon landing at -88.671°N, 282.866°E. During this phase communication links will be established, subsystems and instruments will be calibrated along with a health check on all systems. This phase will end upon verification of all locations before departure.

Phase 1 of this operation will take 59 days (2 lunar days) and the rover will begin traversing across the initial 9km which will take 25 hours. There will be an idle mode activated when the environment permits as well as solar panel deployment to capture energy from the sun. An initial lunar day is given in case of the need to rest the rover, travel at a slower pace if needed over unforeseen circumstances, and accommodate time for water and ice detection along with elemental composition. The RIMFAX and GPR will be utilized upon first entry into the permanently shadowed region at -88.393°N, 279.408°E and at the final turnaround point located at -88.273°N, 277.436°E. All data

collected will be verified to confirm data accuracy before continuing traversal. This phase will end at the secondary collection point where the rover will not pass this point as there is a slope of 13.5° at this point.

Phase 2 of this operation will begin the 59-day (2 lunar days) progression of the rover back to the origin of the initial landing -88.671°N , 282.866°E . The rover will continue to collect imagery upon return while handling data en route. This phase will end upon entering the initial landing.

Phase 3 of this operation will begin the 29.5 earth days (1 lunar day) to compress science data and check all system functionality before entering the End-of-Life (EOL) Stage. This phase will end with a full index of the operation and further considerations of follow-on operations based on the functionality of the rover and further intel gathered.

Overall, operations will take 177 days (6 lunar days) with two sites visited for data collection en route to ensure less risk for the rover. There will be changes to these operations from day to night ops as the average surface temperature ranges from -193°C (night polar regions) to 111°C (day in equatorial regions)" (Lee et. al., 2023) will need to be accounted for. Night modes will first begin by utilizing half of the stored energy supply before switching to the battery supply. During the day we can take advantage of the substantial solar illumination offered with this environment up to 3.28 km into our route. However, upon entering the permanently shadowed region we will reassess the rovers' capabilities for energy consumption. We will have continued communication abilities allowed by the $\leq 5^\circ$ slope required on the majority of our route to acquire direct visibility to Earth (Lee et. al., 2022).

1.6. Vehicle Design Summary

In order for our science tools to traverse the lunar environment and take valuable measurements of the lunar regolith, Mission Valkyr will utilize a rover system in order to bring the instruments from one site to another. This rover involves a few separate subsystems that are utilized to achieve this goal. These include Payload, Mechanical, Electrical, Thermal, and Command and Data Handling. Our Payload includes the NASA RIMFAX system as well as the NASA NSS in order to complete its measurements of water-ice deposits, and hydrogen. The mechanical subsystem involves our powertrain, wheels, suspension and overall frame of the spacecraft. The electrical subsystem includes the battery pack, power distribution and solar array systems used to power all the other systems. Our thermal system includes our entire thermal control system, including the chill plate and radiator to address the extreme conditions, as well as all insulation. Finally, our Command and Data Handling subsystem includes the telemetry subsystem as well as the control system. Overall the completed rover weighs in at 83.85 kilograms, and 2.5959 square meters, and 367.45 watts of maximum power drawn.

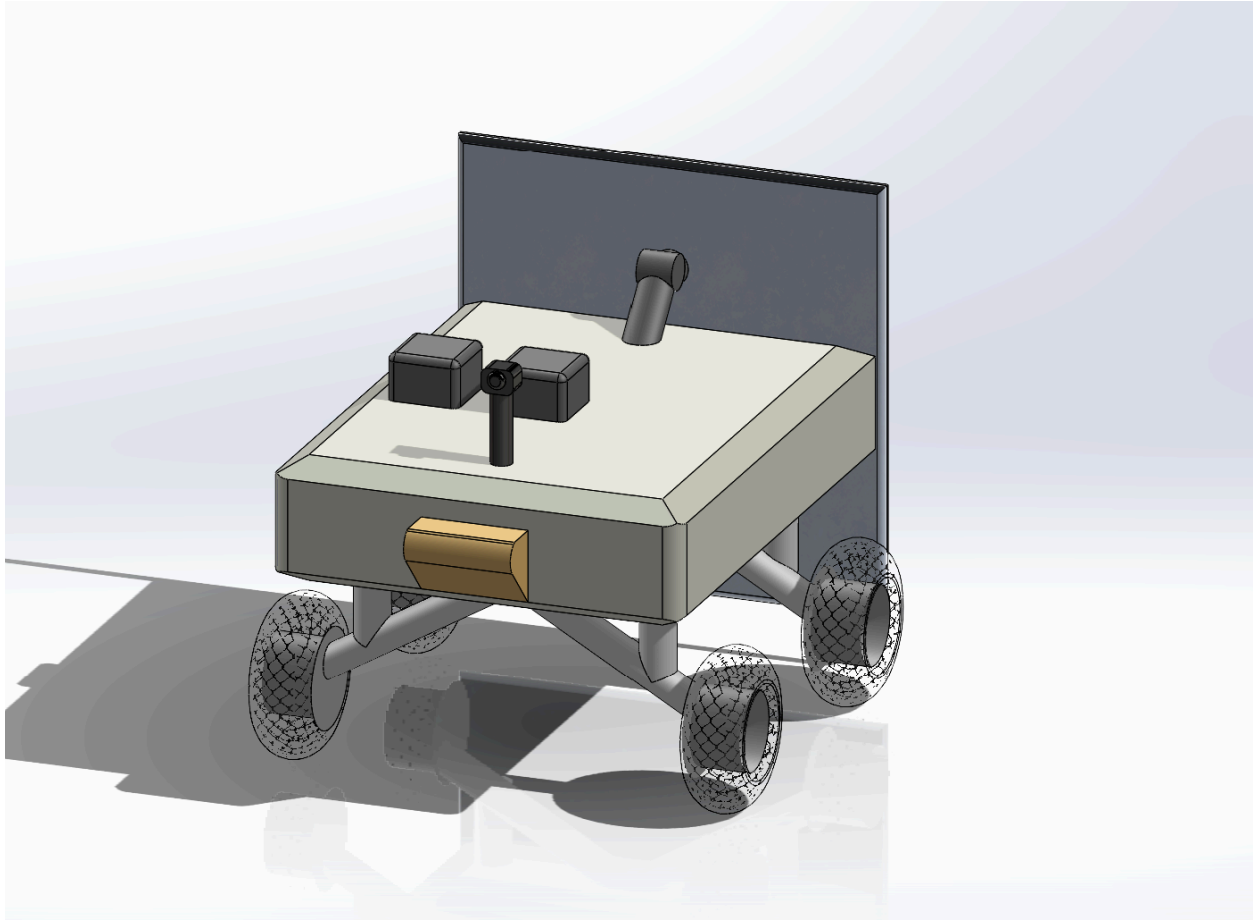


Figure 5. Lunar Rover CAD

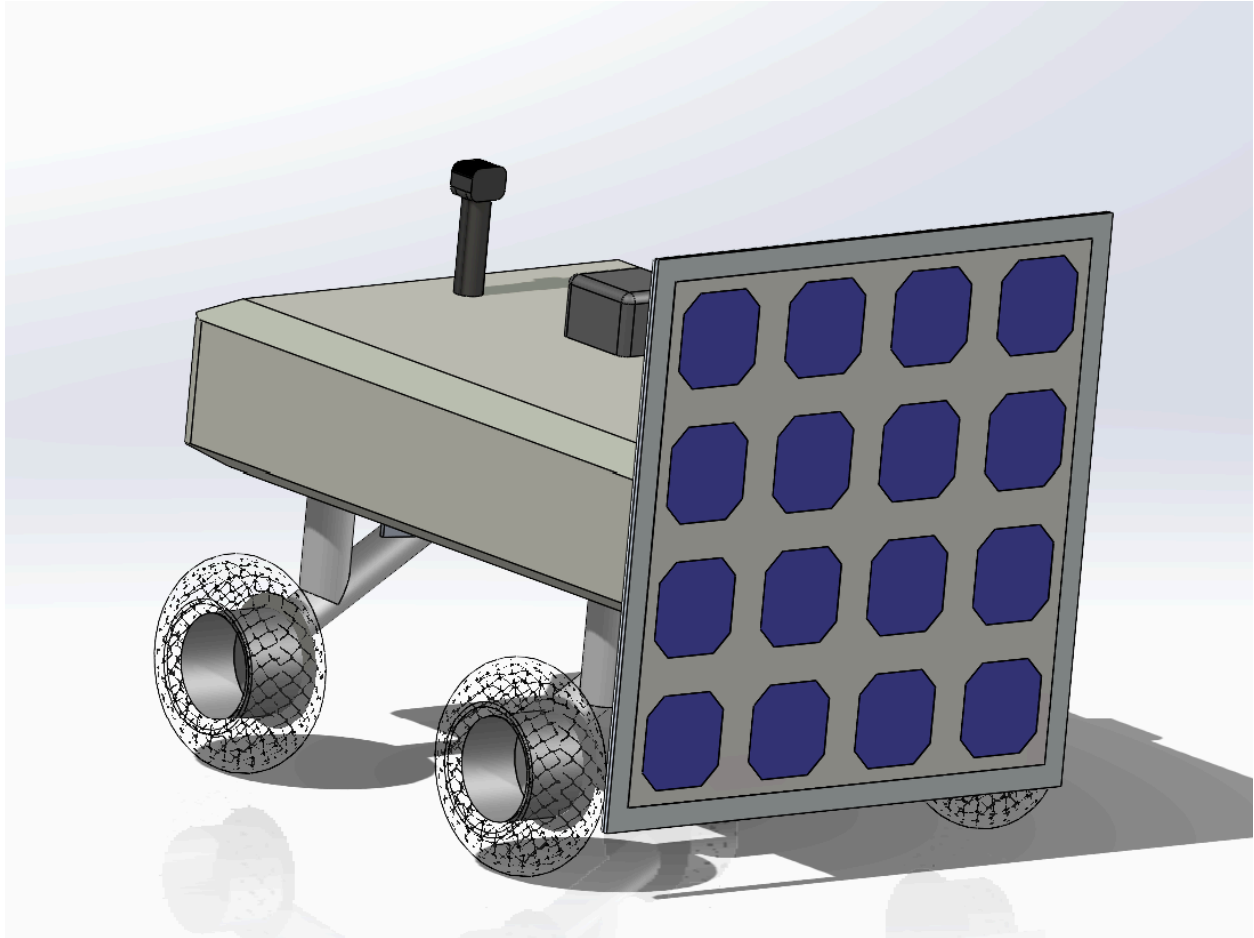


Figure 6. Lunar Rover CAD Rear View

1.7. Science Instrumentation Summary

The purpose of the payload is to collect and analyze scientific data to achieve the mission's science objectives which were derived from given and chosen science goals. The payload contains two scientific instruments: the RIMFAX Ground Penetrating Radar and the Neutron Spectrometer System. These instruments are essential for the mission as they collect and analyze data about the composition and structure of the lunar regolith in the de Gerlache-Kocher Massif.

The RIMFAX GPR generates high-resolution subsurface images by emitting radar waves within a frequency range of 150-300 MHz. These radar waves penetrate the lunar surface and reflect off subsurface layers, which will provide insight into the different materials within the regolith as well as help detect the presence of water-ice and other materials. The GPR will be mounted such that it has a clear line of sight to the ground without interference. It operates continuously, collecting data to map the distribution and depth of water-ice deposits. To maintain functionality in the extreme lunar environment, the GPR needs thermal management to function within the temperature range of -150°C to $+50^{\circ}\text{C}$ (Hamran 2020). And to prevent interference or equipment failure, the RIMFAX may be equipped with dust-resistant measures.

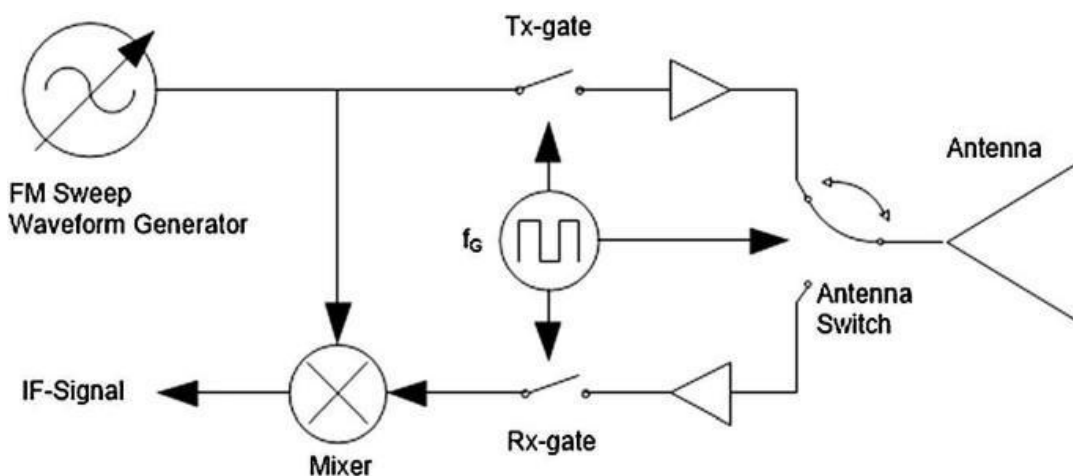


Figure 7. RIMFAX Diagram

The NSS measures the hydrogen content in the lunar regolith by detecting thermal and epithermal neutrons. These neutrons are produced by cosmic ray interactions with the lunar surface. The NSS detects the neutrons that are scattered back from the surface. Thermal neutrons have lower energy (less than 0.3 eV) and are slowed down by interactions with hydrogen atoms, making them a good indicator of hydrogen presence. Epithermal neutrons have higher energy (0.3 eV to 1 keV) and are less affected by hydrogen (Peplowski 2023). By comparing the counts of thermal and epithermal neutrons, the NSS can understand and measure the hydrogen content in the regolith. The neutron detectors will be mounted on the rover with a clear line of sight to the lunar surface. The NSS will integrate with the rover's communication subsystem, transmitting data packets up to 1 MB every second to onboard storage. It may also include radiation shielding to protect its components from cosmic radiation.

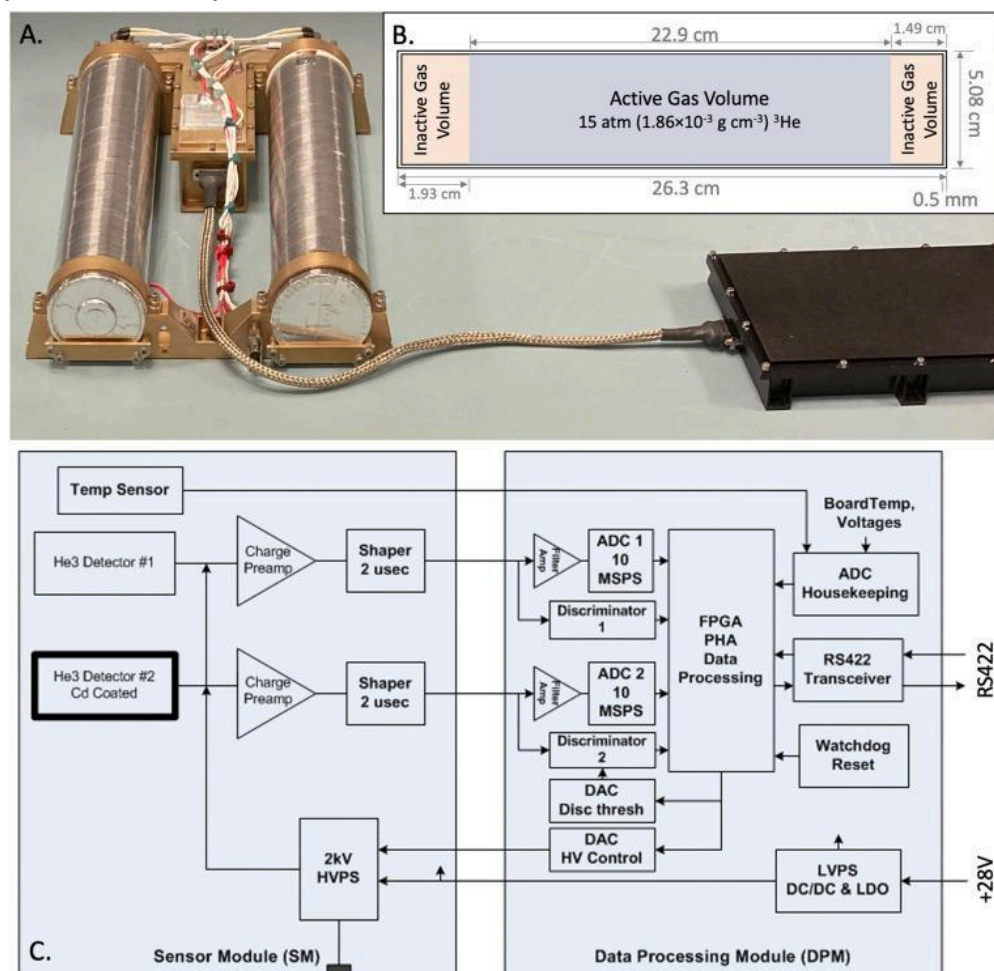


Figure 8. RIMFAX

1.8. Programmatic Summary

1.8.1. Team Introduction

Table 3. Team Introduction Chart

Team Directory			
Name	Role	Biography	Photo
Jasmine Wu	Project Manager, Computer Hardware Engineer	Jasmine is a Computer Science and Cognitive Science Major at the University of California, Irvine located in Irvine, California. She has served as the Embedded Systems and HCI Engineer at her University's Formula SAE Racing Team and several Product Management experiences across Hackathon Directing and working with Nonprofit Clients to build end-to-end software. Her expertise in cross functional management and backgrounds in human-computer interface design make her an ideal fit for Project Management.	
Vincent Dang	Project Engineer, Mechanical Engineer	Vincent is a Mechanical Engineering Major at the University of California, Riverside located in Riverside, California. He has been involved in his schools Formula SAE Racing and EcoCar Team as a Brakes and Design Associate Engineer. He also does research in Material Science and Engineering. His background and expertise in fundamental engineering courses, design teams, CAD, and working in team-based environments makes him an ideal fit for the Project and Mechanical Engineering roles.	
Andrea Zabala	Electrical Engineer	Andrea is a physics and mechanical engineering major at Foothill College, a community college. She has been involved in multiple areas of research and engineering and has gained experience in the field by participating in NASA's Community College Aerospace Scholar program, working as a summer intern at SLAC National Laboratory, and holding leadership positions such as president of the Planning Committee for Foothill Rocketry and lead in avionics for model rocketry and competitions. Her background is diverse, and she has extensive experience with electronic instruments.	

Joel Bhattarai	Lead Systems Engineer	Joel Bhattarai is a mechanical engineering major at University of Michigan. He has had involvement in Formula SAE and MASA (Michigan Aeronautics and Space Association), training him in CAD, engineering design, and working in interdisciplinary teams to prepare him to serve as the bridge between all different subsystems.	
Giovanna Camacho	Chief Scientist	Giovanna Camacho is a PhD candidate in Systems Engineering at the University of Virginia. She is an Army veteran of 11 years having served as a medical officer for 7 years. She has completed numerous internships with various entities. The following are most applicable: Army Research Laboratory, Naval Research, KBR NASA, Triton, Pratt & Miller, Aerospace, and was selected for a systems engineering position as a NASA pathways intern at Armstrong Flight Research Center. Her academic background in engineering and applied experiences make her an ideal candidate for this position.	
Luis Rodriguez	Thermal Dynamics	Luis is a Mechanical Engineering Major at California State University, Fullerton in Fullerton, California. He has worked on a robotics team at Hawthorne High and a propulsion subteam in the rocket team at California State Fullerton. His work on the propulsion subteam makes him an ideal candidate for the thermal dynamics subteam.	
Torin Nelson	Deputy Project Manager, Computer Hardware Engineer, Program Analyst	Torin has a B.S. in Computer Science with a specialization in Intelligent Systems from the University of California - Irvine. He has experience in creating and training machine-learning models, including a model that can detect settlements in Sub-Saharan Africa in need of electricity with 75% accuracy. Additionally, Torin has experience creating a search engine using a static corpus using TF-IDF scoring. Torin's attention to detail and strong work ethic make him an ideal candidate for his assigned role.	

1.8.2. Team Management Overview

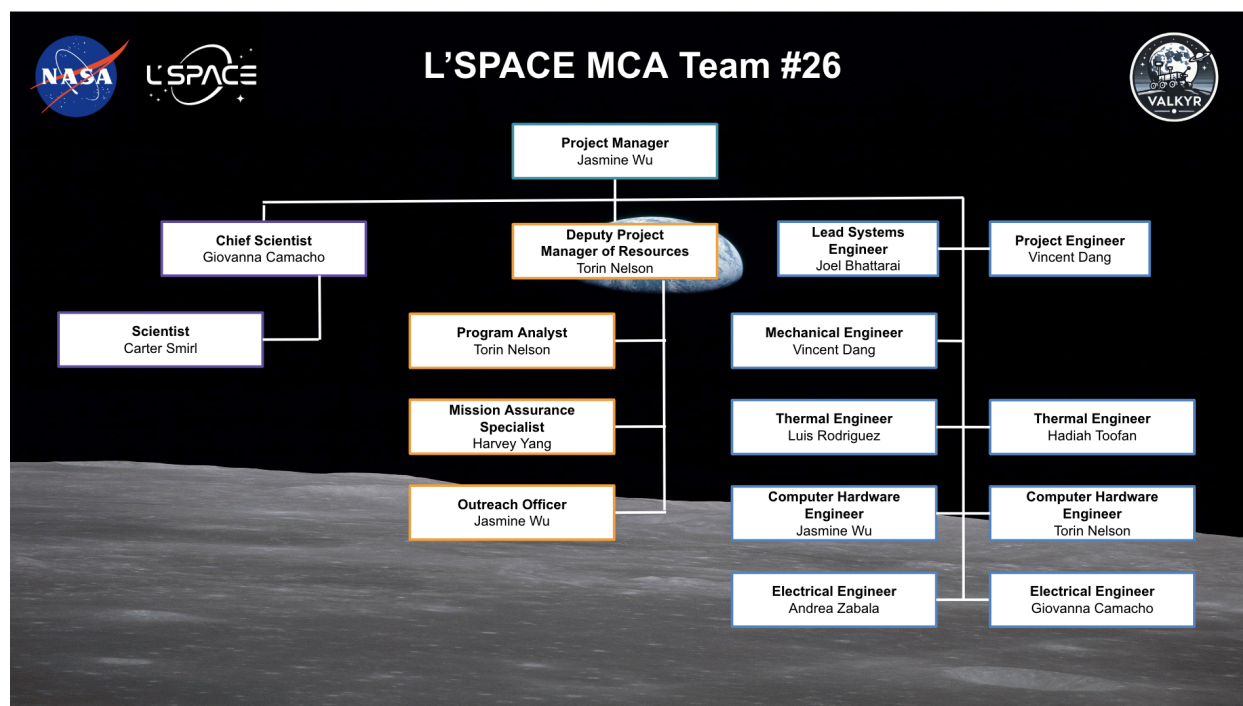


Figure 9. Team Organization Chart

Mission VALKYR is built on a lean team structure with diverse expertise that enables the team to execute quickly and effectively (Refer to Figure A). The team structure combines subject expertise and a strict hierarchy, fostering cross-team collaboration without sacrificing efficient decision-making. The team is composed of subject matter experts in the fields of 3D Design Engineering, Product Management, Computer Hardware Engineering, and R&D within the Aerospace industry which sets the foundation for a flexible and iterative environment, suitable for limited resources and addressing the mission's strict science objectives. Roles were selected based on previous expertise and time dedication varies based on the location on the hierarchy, ranging from 5-10 hours per week to several dozen. This framework proved successful under the NASA Lunar Terrain Technical Contract (LTV), where a multi-disciplinary team and an iterative development process resulted in cutting-edge autonomous vehicles that enhanced Artemis' commercial endeavors (Jost, 2024). VALKYR balances independent and collaborative work periods by encouraging collaborative brainstorming sessions for specific topics and giving each member ownership over a section, without sacrificing creative autonomy. For example, the Concept of Operations was developed by facilitating a team-wide brainstorming workshop for different actions performed by the rover. These insights were then independently compiled by the Lead Systems Engineer (LSE), Project Manager, and the Deputy Project Manager of Resources (DPMR) into a

comprehensive timeline covering 4 different rover states. Decision-making is a mixture of democratic discussion and executive authority, following a top-down, chain-of-command structure with the executive leadership team on top. Team panels are held in light of major decisions and all members are encouraged to share ideas. For operational efficiency, the executive team makes the final decision based on a thorough cost-benefit analysis of different opinions posed.

VALKYR faced a significant challenge following the departure of the team Project Manager and the Chief Scientist. To tackle this uncertainty, the entire team reconvened to communicate the vision, redefine clear roles, and host a training meeting to ensure the new Chief Scientist and Project Manager were confident and well-equipped for the transition. In addition, a team-wide meeting was held to facilitate open communication and build trust by plainly sharing the state of the team. Despite these challenges, this discussion showed that no major roadblocks were present. The VALKYR team successfully rearranged the science and engineering team to accommodate the change in leadership. 1:1 Meetings were scheduled with each team member to empathize with their unique circumstance, which successfully allocated tasks for the Mission Definition Review according to member capabilities. The executive team consistently engaged in leadership syncs to remain on the same page, re-factored the management system into a single Google Drive, and developed a clear action plan adapting to the circumstance in alignment with the team's asynchronous dynamic. As a result, the team completed the Mission Definition Review on time and increased leadership engagement significantly. When future issues arise, the team follows a structured problem-solving framework through collaborative research, resolution, and democratic expectation-setting, involving team members in the iterative problem-solving process.

Programmatics

Programmatics consists of a diverse team of Risk Managers, Financial Analysts, Schedule Designers, and Managers who are experienced with cross-functional team management, an essential component of program management. There will be approximately 2 administrative personnel which will increase to 4 during Phase D, when major initiatives regarding procurement contracts and experimentation plans will be finalized. The Programmatics team hosts weekly discussions to review major decisions impacting risks. The team collaborates on trade studies across decisions, offering a diverse slate of analysis to make the decision-making process more comprehensive.

Science

Due to the recent reduction in team size, the science team has been reduced to a more modest size of 9 for Phases C through D, with an increase to 11 during Phases E and F when science analysis is conducted on sample returns. The science team consists of a

diverse team of aerospace engineers, professionals in cutting-edge Research and Development (R&D), and scholars with connections to world-renowned University Research Labs, like Arizona State University's Space Research Institute. The team is designed to facilitate communication across diverse science disciplines. Members are invited to incorporate crowdsourced research insights from the science community into the team's research.

Engineering

Firstly, the team is extremely well equipped to address this mission, as all are engineering or science students at accredited universities with strong skills in writing, analysis, engineering, collaboration, and all other required traits. The main workflow means that when a deliverable is sent out, the team leads divide up the work, and each team leader distributes the work further to each team member. When a team member has a problem or cannot continue work on that section, they transfer the issue to the team mentor and subject-specific advisors. An open communication policy encourages members to funnel information to and from other subteams. When making a decision, the team begins with a comprehensive analysis on the situation and dependencies, creating thorough documentation, and facilitating a team-wide panel to propose and collaborate on a decision. Decisions proposed by team members are funneled to upper management for internal evaluation, before traveling up the chain-of-command to the Project Manager. Roles were determined through a democratic voting procedure and with specialized expertise and individual commitment in mind. Despite specialization, all engineers are equipped to assist in other areas due to their broad training and engineering backgrounds. The current organization chart (refer to Figure 2) identifies the "Lead" for each subject area, indicating the individual overseeing their respective groups' operations and development. The Electrical Engineer, for instance, might transition to the Lead Electrical Engineer Role when engineering development necessitates heavier involvement. In case of conflicts, collaborative research and resolution is instated, enabling team members to work together and iteratively develop solutions.

1.8.3. Major Milestones Schedule

Table 4. Mission Phases Duration

MISSION PHASES DURATION						
Mission Phase	KDPs	LCRs	Key Milestones	Start	End	Duration
Phase C: Design and Fabrication	KDP D	CDR	External Milestones ● KDP D - January 20, 2027 ● CDR - October 15, 2026 ● SRR - March 10, 2027 ● PDR - May 5, 2027 Internal Milestones ● Design Maturity Assessment ● Final Design Completed ● Identify key contractors based on the NASA Acquisition Forecast ● Fabrication and Assembly Plans approved for manufacturing review ● Finalized ground testing plans	August 13, 2026	August 12, 2027	10 months (2 months margin)
Phase D: System Assembly, Integration and Test, Launch	KDP E	TRR, LRR	External Milestones ● KDP E - January 10, 2028 ● TRR (Test Readiness Review) - November 15, 2027 ● LRR (Launch Readiness Review) - August 15, 2028 ● Official Launch - September 1, 2028 Internal Milestones ● Systems integration and testing ● Pre Launch preparations plan ● Operational readiness review ● Launch readiness review ● Travel budget and schedule plans approved ● Official Launch	August 13, 2027	September 1, 2028	9 months (3 months margin)
LAUNCH DATE: SEPTEMBER 1, 2028						
ARRIVAL DATE: SEPTEMBER 6, 2028						
Phase E: Operations and Sustainment	KDP F	ORR, MSR, EMR	External Milestones ● KDP F - October 1, 2028 ● ORR (Operational Readiness Review) - September 10, 2028 ● Mission Status Review - March 15, 2030 ● Extended Mission Review - September 1, 2031 Internal Milestones ● Surface Operations ● Data Collection and Analysis ● Comms and Data Transfer Up and Downlink ● Real-time status updates and review	September 6, 2028	April 1, 2033	55 months (5 month margin)

			• Prepare for EOM and Closeout			
RETURN DATE (EOL): FEBURARY 21, 2029						
Phase F: Closeout	NA	FDR, CR	External Milestones • Final Data Review - September 15, 2033 • Closeout Review - November 30, 2033 Internal Milestones • Final data archiving • Mission Documentation • Knowledge Capture and Dissemination (Outreach)	September 2, 2033	December 1, 2033	2 month (1 month)
FINAL ARCHIVAL OF DATA: FEBURARY 21, 2030						

The overall mission will extend from August 2024 to December 2033. The mission schedule is derived from various geopolitical and budget considerations. Due to supply chain disruptions from recent Global wartime tensions in major supplier regions and the COVID-19 pandemic, VALKYR's manufacturing and procurement schedule is extended in alignment with extended lead times ([Foust, 2022](#)). Recent shifts in component sourcing from space-grade, customized components toward standardized production has produced more partnerships with government groups such as the Space Development Agency (SDA) to drive satellite procurement. This has the potential for improving reliability and reducing time costs for testing, balancing out issues from the supply chain. However, ongoing semiconductor shortages and logistical challenges pose a continuous risk of delay for the mission. VALKYR maintains a comprehensive change control procedure (refer to Section 1.11.1) to address contingencies and schedule delays effectively.

Mission VALKYR identifies baseline assumptions to ensure standardization:

1. The launch window is timed according to the orbital mechanics of the Earth and Moon, and should only be executed during alignment periods to optimize trajectory and minimize power consumption.
2. There will be a limited communications window between the Earth and the rover. The schedule must account for Loss of Signal Periods when the rover is out of direct line-of-sight from Earth.
3. The rover will have predictable power generation and consumption based on the solar panels and battery storage, and critical operations will only operate during periods of peak power availability.
4. The lunar rover's extreme temperatures, dust interference, and gravitational anomalies will affect the rover's activities significantly and must be accounted for during the mission schedule.

5. There will not be major supply chain or contractor delays that could lead to mission cancellation. The schedule must still account for alternative suppliers and lead times.

1.8.4. Budget Overview

The mission's budget has been cut by 22%, a change from \$225,000,000 to \$175,500,000. As a result, a flat cut across the board was given to each subsystem congruent with these budget cuts. As a consequence, the percentage allocation for most subsystems was changed after the flat cut to keep each subsystem within budget. In terms of percentage allocation, Personnel increased, Travel increased, Payload decreased, CDH decreased, Thermal decreased, Power increased, Facilities increased, and mechanical was increased. These increases and decreases in percentage allocation were made with specific reasoning, detailed below, about mission success and current cost estimates. Additionally, our reserve margin has been cut from 15% to 13% to accommodate for the budget decrease. The chart below shows the new budgeting allocation for Mission VALKYR, excluding the margin for clarity.

Mission Cost Breakdown Without Margin

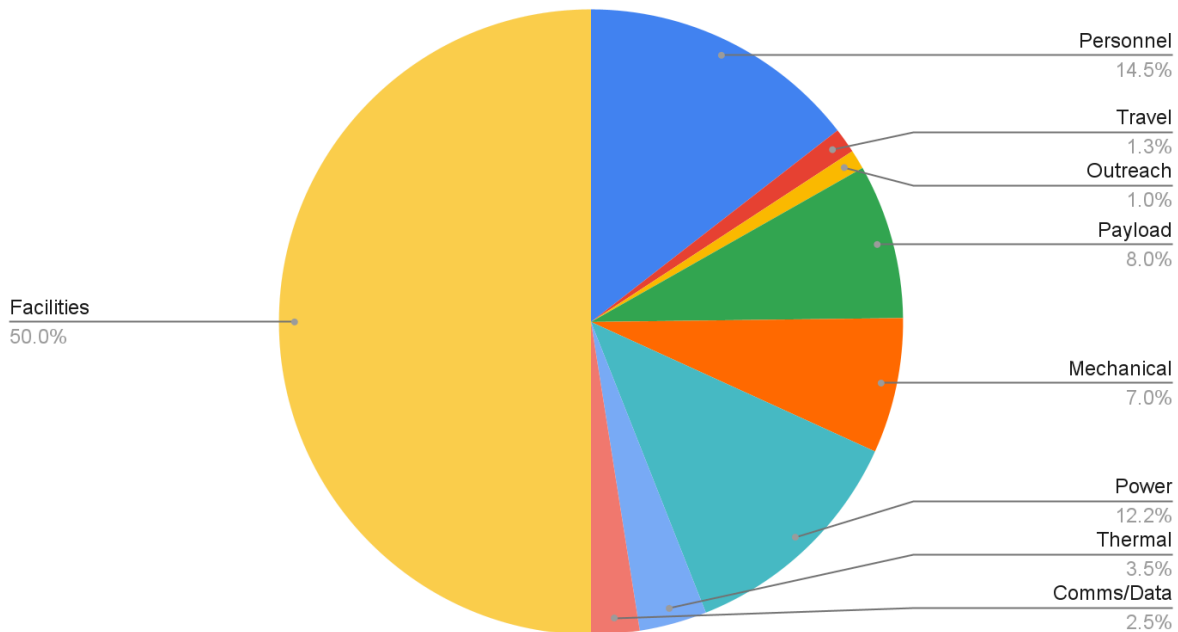


Figure 10. Mission Cost Breakdown

A comparison of the previous budget allocation and the current one is detailed in the table below.

Table 5. Allocation Excluding Margin

Sub-Category	Previous Allocation	Current Allocation
Personnel	12.50%	14.50%
Travel	1.00%	1.30%
Outreach	1.00%	1.00%
Payload	27.50%	8.00%
Mechanical	5.00%	7.00%
Power	10.00%	12.20%
Thermal	7.50%	3.50%
Comms/Data	10.50%	2.50%
Facilities	25.00%	50.00%

Margin is not included in this table for clarity. Margin is the first aspect of the budget that is calculated so that it is clear what the margin-excluded budget is. The margin for mission VALKYR is 6.5%. The raw figures for the budget for each subsystem, including margin, is detailed below.

Table 6. Allocation Including Margin

Total Budget	\$175,000,000
Margin Adjusted Budget	\$164,500,000
Reserve Margin	\$10,500,000
Personnel	\$23,852,500
Travel	\$2,138,500
Outreach	\$1,645,000
Payload	\$13,160,000
Mechanical	\$11,515,000
Power	\$20,069,000
Thermal	\$5,757,500
Comms/Data	\$4,112,500

Facilities	\$82,250,000
------------	--------------

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

Table 6. Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Top Level Power Requirements							
POWER-1	The power system shall supply sufficient energy to maintain operating components for the duration of the mission.	The system requires power to operate all components properly and efficiently.	MR-1	POWER-2	Test	All	Met
POWER-2	The power system shall supply an approximate between 300W and 400W of power.	Components must be supplied with enough power to work properly.	POWER-1	POWER-1	Test	All	Met
POWER - 3	The electrical system and components shall survive extreme conditions such as microgravity, moon dust, and temperature drops, as well as make use of redundancy.	The system shall withstand the harsh environment to which it will be exposed.	MR-1, THERM-1	THER-2,THER-3, MEC-4	Test	Mechanical, Thermal	Met

POWER-4	The subsystem will have a power reservoir used to store excess energy.	Extra energy stored in the reservoir may be used during periods when the vehicle is idle.	POWER-1	POWER-2	Test	All	Met
---------	--	---	---------	---------	------	-----	-----

Table 7. Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical Requirements							
MEC-1	The system shall be able to travel to Permanently Shadowed Regions up to 10 km from the landing site and traverse over no more than a 15 degree incline and on rough terrain.	The system should be able to travel to areas of interest in order to meet mission objectives and gather data.	MR-1	MEC-2, MEC-5	Demonstration	Mechanical	Met
MEC-2	The suspension and frame shall ensure that the lunar rover is stable, can withstand the terrain, and protects the system from shock and vibrations.	The system must be able to operate in harsh lunar environments and extreme temperature gradients.	MR-1	THER-1, POWER-3	Test	Mechanical	Met

MEC-3	The goals of the scientific research or mission (science objectives) should be achievable using a Ground-Penetrating Radar and neutron spectrometer.	Instruments are used to determine the elemental composition of the lunar regolith.	MR-1, MR-2	PAY-1	Inspection	All	Met
MEC-4	Structural component materials shall be chosen based on needed thermal properties, vehicle strength over rough terrain, instrument stability, and mass.	Select materials based on vehicle design for strength, thermal requirements, and instrument use.	MR-3, MR-4	THER-2, THER-4	Analysis	All	Met
MEC-5	The lunar rover will include a Guidance, Navigation, and Control (GNC) system that detects imbalances and helps the rover adapt to the terrain. This ensures the rover will be able to continuously maneuver on new terrain.	The lunar rover will be able to detect and adapt to instability over the lunar surface.	MEC-1, MEC-2	MEC-5.1	Demonstration	Mechanical, CDH	Met

Table 8. Thermal Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Thermal Requirements							

THER-1	The system shall be able to survive and operate in the conditions of Lunar space travel	Ensures the system and components and frame dont break during travel due to the technology inside of the rover	MEC-2	THER-2	Test	Thermal, Mechanical	Met
THER-2	The system shall be able to withstand and operate under low lunar surface temperatures of TBD °C to TBD °C and withstand thermal cycling.	Ensures the system and components work to not malfunction under extreme temperatures.	MR-1, MEC-4	THER-3	Test	All	Met
THER-3	The insulation must withstand the mechanical stresses of landing and launch..	All components of the rover shall withstand a soft landing on the lunar surface.	Customer	TBD	Test	Thermal, Mechanical	Met

Table 9. CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Command and Data-Handling (CDH) Reqs							

CDH-1	The spacecraft shall receive uplink commands from Earth and downlink telemetry data via a relay satellite	Command execution and data transmission are important for mission operations.	MR-8	CDH-1.1, CDH-1.2, CDH-1.3, CDH-1.4, CDH-1.5, CDH-1.6, CDH-1.7	Test	CDH	Met
CDH-2	The subsystem shall operate reliably in the lunar environment for 14 lunar days.	The subsystem must be able to withstand the harsh lunar environment for uninterrupted mission operations and data collection.	MR-1, MR-2	CDH-2.1, CDH-2.2, CDH-2.3, CDH-2.4	Demonstration	CDH	Met
CDH-3	The subsystem shall collect, manage, and store analog and digital data.	Mission control must be able to monitor and analyze telemetry and science data.	MR-1, MR-2	CDH-3.1, CDH-3.2, CDH-3.3	Inspection	CDH	Met
CDH-4	The subsystem shall have recovery and redundancy features to ensure continuous operation and mission success.	The spacecraft must be able to recover from failures and hazards.	MR-1, MR-2, MR-8	CDH-4.1, CDH-4.2, CDH-4.3, CDH-4.4, CDH-4.5	Inspection	CDH	Met
CDH-5	The subsystem shall monitor and support the mechanical, thermal, power, and payload subsystems.	Coordinated operation throughout the spacecraft ensures mission success.	MR-1, MR-2, MR-7, MR-8	CDH-5.1, CDH-5.2, CDH-5.3, CDH-5.4, CDH-5.5	Demonstration	CDH	Met

CDH-6	The subsystem shall execute necessary commands when prompted and perform onboard autonomous functions.	The spacecraft must be semi-autonomous given that the relay satellite performs a circular polar orbit around the Moon.	MR-1, MR-2	CDH-6.1, CDH-6.2, CDH-6.3, CDH-6.4, CDH-6.5, CDH-6.6	Test	CDH	Met
-------	--	--	---------------	---	------	-----	-----

Table 10. Payload Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Payload Reqs							
PAY-1	The system shall include two scientific instruments.	Instruments are needed in in order to collect data for achieving the mission's science goals and send them back to earth.	MR-1, MR-2		Inspection	Payload,CDH	Met
PAY-2	The power subsystem will provide a continuous 10 W power supply to the RIMFAX system.	Stable and adequate power ensures high sensitivity and consistent performance.	MR-3		Inspection	Payload,CDH	Met

PAY-3	The antenna will be mounted on a stable part of the rover ensuring a clear line of sight to the ground without interference from other rover components.	Proper placement ensures high spatial resolution and clear imaging of subsurface layers and structures.	MR-1		Inspection	Payload,CDH	Met
PAY-4	The neutron detectors will be mounted on the rover with a clear line of sight to the lunar surface, avoiding shadowing from other rover components.	Proper placement ensures accurate detection of neutron flux and hydrogen concentration.	MR-5		Inspection	Payload,CDH	Met

Overview:

Our goal is to gather information about the lunar regolith in the PSR's of the moon. In order to accomplish this we will create a rover which will travel from one location of interest to another. The important subsystems for this rover are power, mechanical, thermal, command and data handling, and payload. The purpose of the mechanical subsystem is to provide locomotion to the rover and deal with all the moving parts, that includes deployment of solar panels, instrumentation, etc. The command and data handling subsystem will control all the other subsystems so that they can work in harmony in order to achieve their mission. The purpose of the payload subsystem is to house the instrumentation and conduct the proper data collection on the lunar regolith. The power subsystem will provide power to all the other subsystems and the thermal subsystem will maintain working conditions for the spacecraft. With these five subsystems, the spacecraft will be able to achieve its goals.

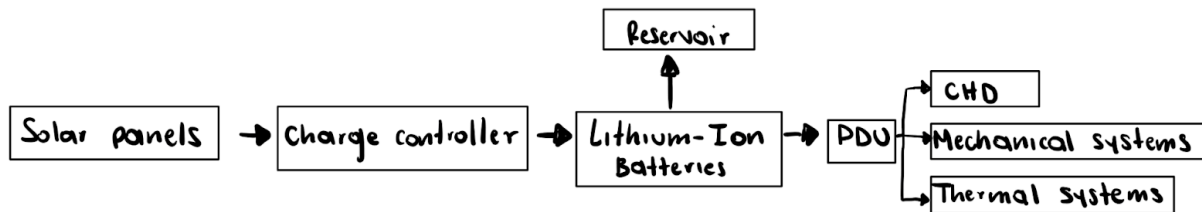
Power:

The power subsystem serves the purpose of powering the vehicle; it can be thought of as the heart of all systems. It comprises multiple components and subsections which are categorized into four major top-level requirements shown in the table listed below.

Its main focus is to address the storage, distribution, and management of power to each subsystem that comprises the lunar vehicle. To do this, it will rely on an array of solar panels along with high-energy-density batteries and a power management and distribution unit (PMDU). With this in mind, the subsystem will work by taking advantage of the extended periods of sunlight, using the solar panel to collect the energy that will be transformed and stored in lithium-ion batteries using charge controllers. This energy will later be distributed by the PMDU to the respective subsystems in order of priority as established in one of the top-level requirements.

During this process, smooth operation during the mission is ensured, as well as reliability and success, by having a well-designed power grid capable of handling circumstances such as energy spikes and functioning in temperatures as low as approximately -40K.

The following chart contains a more in-depth explanation of the requirements mentioned above, as well as a sketch of the power grid and details of each component categorized by mass, weight, volume, etc.



Main components - Overview of schematic

- Solar panels
- Lithium ion batteries
- Power Management and Distribution Unit (PMDU)
- Science Instruments
- Mechanical system
- Thermal system
- CHD system

Figure 11. Main-Components Overview of Schematic

Mechanical:

The purpose of the mechanical subsystem is to ensure that the lunar rover is not only built properly but also to create a strong foundation for the rover to perform properly following customer requirements as well as working with other subsystems to gather the most effective data. The mechanical subsystem is in charge of the rover's functionality through design of the structure, suspension, locomotion, and GNC system. Each part focuses on ensuring the safety, risk mitigation, and ensuring accuracy of the lunar rover. The goal of the mechanical subsystem is to design the components per other engineering subsystems as well as following designs that ensure structural integrity throughout the mission, mission constraints, and mechanisms that fit the mission's needs.

Some of these require tasks and roles to be met to work efficiently. The lunar rover must be ensured to work properly on the moon's surface by combining multiple systems. The mechanical subsystem will be the base of the rover and will include the frame and chassis built from strong and lightweight material. The rover must be able to maneuver and respond properly in all expected and unexpected terrain. To do this, the rover should have components connected to the frame by the means of a suspension system

that is durable and responsive to the terrain. The structure and suspension will ensure the lunar rover has a solid base to hold all the components and instruments. In order for the system to maneuver properly, it must include the right components such as wheels and electric motors that work in accordance with the suspension and GNC. The mechanical subsystem will determine the proper wheels for the lunar surface and the most efficient electric motors for its needs by working alongside the electrical subsystem. The mechanical subsystem is also in charge of the Guidance, Navigation, and Control (GNC) system. The GNC is responsible for sensing terrain and ensuring the system makes proper adjustments for the lunar rover's stability and maneuverability. Components of the GNC include a gyroscope, accelerometer, and sun sensors. The mechanical subsystem will ensure that the instruments are able to operate properly by adjusting them as needed.

Thermal:

The purpose of the thermal subsystem is to ensure that the rover maintains its structural integrity and the optimal functioning of its electronics throughout the mission. The safety and operational condition of the rover are paramount, requiring the system to consistently manage and mitigate thermal stresses that could lead to material fatigue, deformation, or failure. This necessitates careful selection of materials and the implementation of an effective cooling system, designed to provide the necessary thermal regulation for mission success.

As the rover encounters a wide range of temperatures in space, the thermal subsystem must actively monitor these fluctuations, with the Command and Data Handling (CDH) system playing a critical role in facilitating this process. The CDH system enables the rover to assess internal and external temperature conditions, allowing for real-time adjustments to maintain thermal efficiency.

The thermal management strategy includes both active and passive components. The radiator, an active component, will extract excess heat from the rover, while the Multi-Layer Insulation (MLI) blankets, serving as passive components, will prevent excessive heat absorption, protecting the rover from the harsh thermal environment of space. Chill plates are incorporated to ensure that critical components do not overheat, delivering precise cooling as needed. To prevent freezing, heating tapes and pipes will distribute heat across the rover, counterbalancing the cooling effects of the chill plates and radiators, ensuring a balanced thermal environment across all components. This integrated approach is essential to safeguarding the rover against the extreme conditions it will encounter during its mission.

The lunar rover must operate effectively on the Moon's surface while maintaining stable conditions, especially when encountering lunar dust. The mechanical subsystems are crucial to the mission, and ensuring their reliability is a top priority. The rover must be

capable of maneuvering and responding appropriately to both expected and unexpected terrains. To achieve this, the rover will be equipped with a thermal management system designed to maintain a consistent temperature, which is critical as the rover navigates various types of lunar terrain.

The thermal system is strategically designed to ensure optimal performance, with components positioned to maximize efficiency in both heating and cooling. Active systems will be in place to protect the rover from the pervasive lunar dust, which poses a significant threat to the mission. The dust could infiltrate the rover and compromise critical components, so a robust sealing mechanism is essential to prevent dust ingress and safeguard the rover's internal systems. By addressing these challenges, the rover will be better equipped to complete its mission and fulfill all necessary tasks.

CDH:

The purpose of the CDH system is to transmit and store mission objective and telemetry data. All science mission objective data will pass through the CDH system for analysis and storage and is therefore essential for any and all science mission objectives. Telemetry data is also stored and collected to ensure full functionality of the rover at all times and is used to diagnose and resolve potential issues that arise involving any subcomponent, including CDH itself. The CDH system uses an omnidirectional antenna to continually transmit data to an already orbiting satellite. The rates at which data is transmitted to the satellite is dependent on what data is being transmitted. The categories of data are as follows: science objective data, thermal data, and mechanical data. Science objective data includes the NSS and RIMFAX data. Thermal data includes temperature and heater data. Mechanical data includes battery health, battery charge, and gyroscopic data. The rates for these categories are as follows: science objective data is transmitted every second, thermal data is transmitted every fifteen seconds, and mechanical data is transmitted every 30 seconds.

Payload:

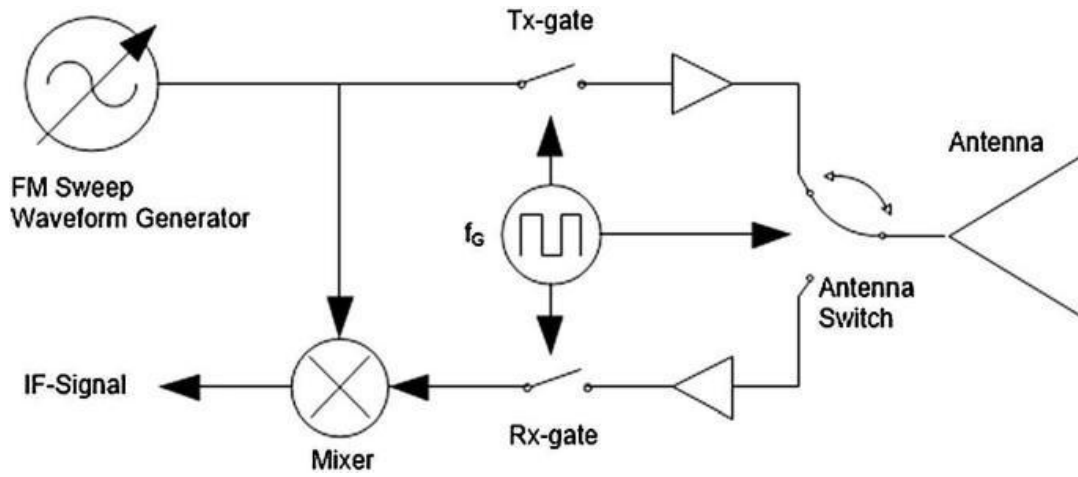
The purpose of the payload is to collect and analyze scientific data to achieve the mission's science objectives which were derived from given and chosen science goals. The payload contains two scientific instruments: the RIMFAX Ground Penetrating Radar and the Neutron Spectrometer System. These instruments are essential for the mission as they collect and analyze data about the composition and structure of the lunar regolith in the de Gerlache-Kocher Massif.

The RIMFAX GPR generates high-resolution subsurface images by emitting radar waves within a frequency range of 150-300 MHz. These radar waves penetrate the lunar surface and reflect off subsurface layers, which will provide insight into the different materials within the regolith as well as help detect the presence of water-ice and other materials. The GPR will be mounted such that it has a clear line of sight to the ground without interference. It operates continuously, collecting data to map the

distribution and depth of water-ice deposits. To maintain functionality in the extreme lunar environment, the GPR needs thermal management to function within the temperature range of -150°C to $+50^{\circ}\text{C}$ (Hamran 2020). And to prevent interference or equipment failure, the RIMFAX may be equipped with dust-resistant measures.

The NSS measures the hydrogen content in the lunar regolith by detecting thermal and epithermal neutrons. These neutrons are produced by cosmic ray interactions with the lunar surface. The NSS detects the neutrons that are scattered back from the surface. Thermal neutrons have lower energy (less than 0.3 eV) and are slowed down by interactions with hydrogen atoms, making them a good indicator of hydrogen presence. Epithermal neutrons have higher energy (0.3 eV to 1 keV) and are less affected by hydrogen (Peplowski 2023). By comparing the counts of thermal and epithermal neutrons, the NSS can understand and measure the hydrogen content in the regolith. The neutron detectors will be mounted on the rover with a clear line of sight to the lunar surface. The NSS will integrate with the rover's communication subsystem, transmitting data packets up to 1 MB every second to onboard storage. It may also include radiation shielding to protect its components from cosmic radiation.

Figure 12. RIMFAX Diagrams



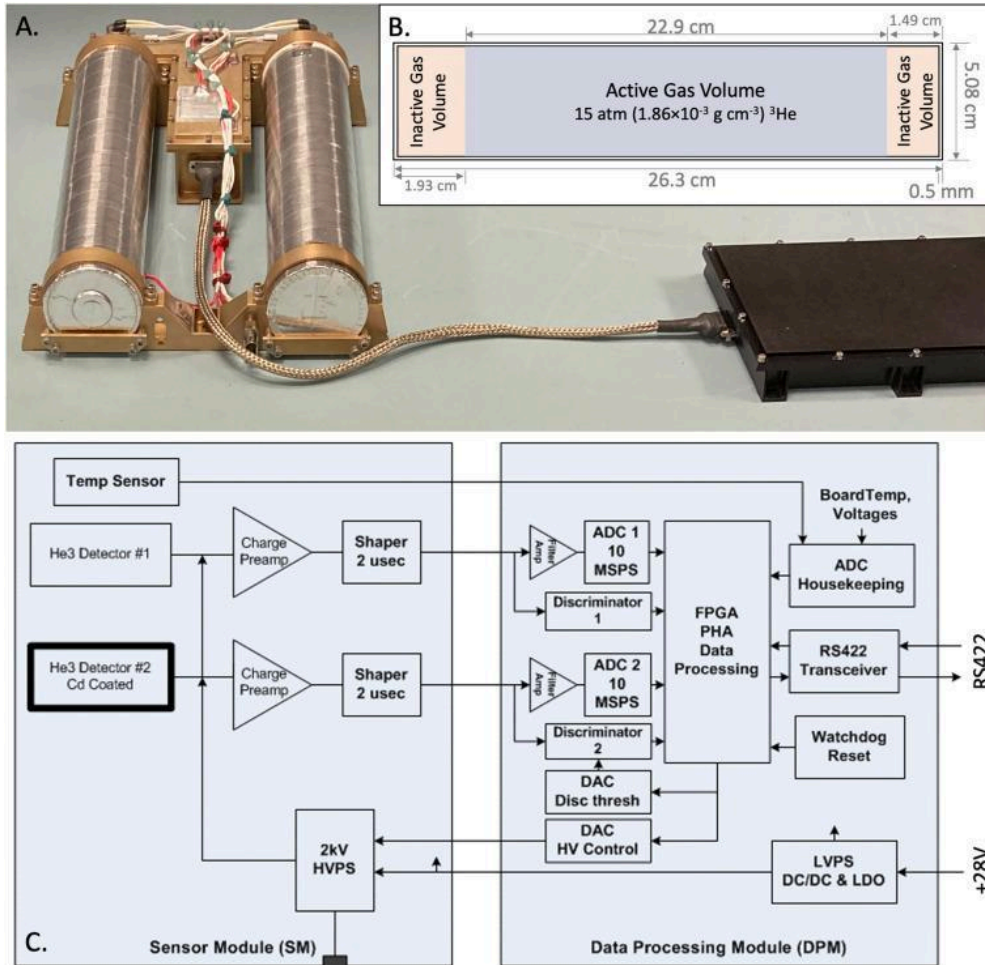
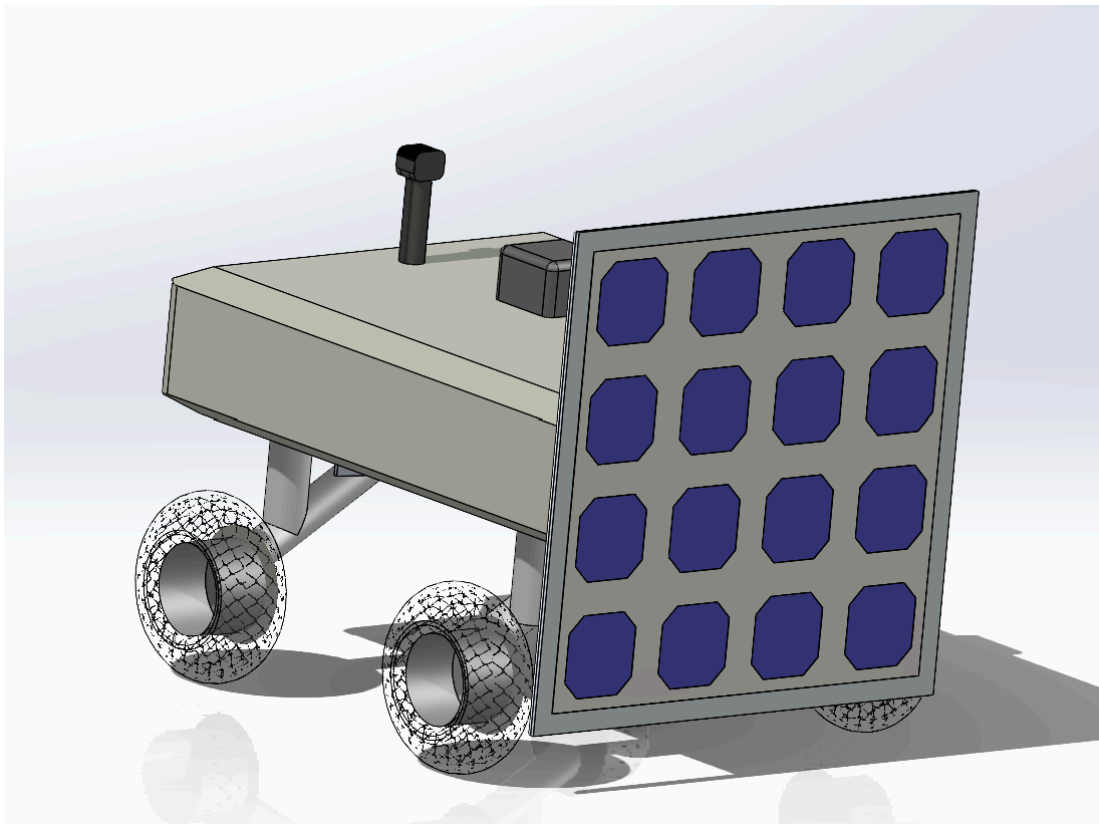
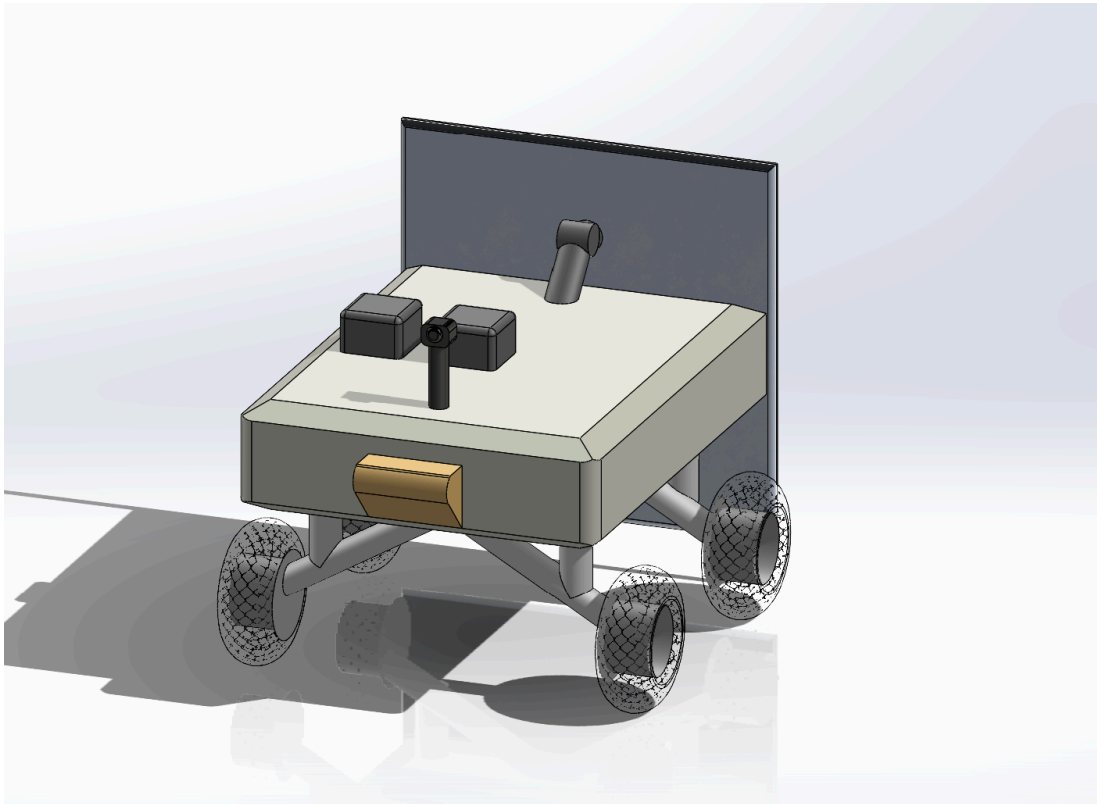


Figure 13. Lunar Rover CAD Front View



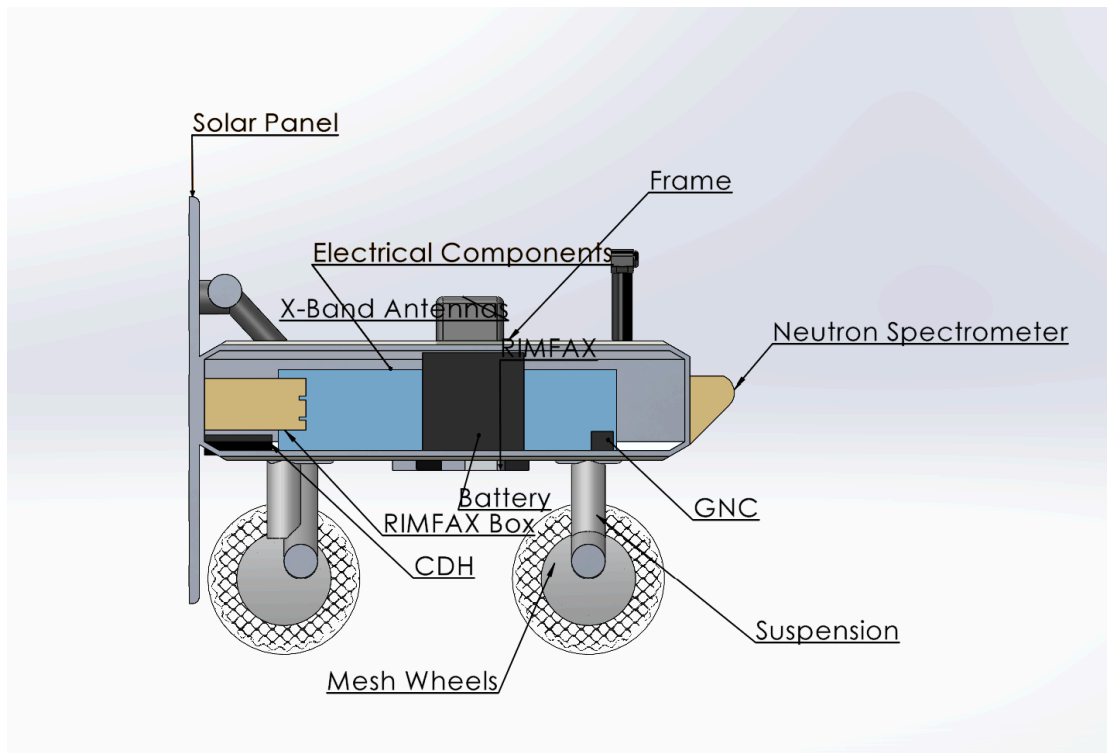


Figure 14. Lunar Rover CAD Internal Components

Table 11. Overall Dimensions And Mass

Subsystem	Total Mass [kg]	Total Volume [m ³]	Max Power Draw [W]
Mechanical	54.33	0.1235	48.59
Thermal	8.78	2.2524	242.50
Electrical	14.97	0.1981	58.00
CDH	1.17	0.0059	6.86
Payload	4.60	0.0160	11.50
Total	83.85	2.5959	367.45
Available (inflation/manufacturing adjusted)	1.15	0.7791	32.56

2.1.1. Mechanical Subsystem Overview

The mechanical subsystem ensures the vehicle is built correctly and provides a strong foundation for its performance according to customer requirements. It collaborates with other subsystems to gather effective data. This subsystem controls the rover's structure, suspension, locomotion, and Guidance, Navigation, and Control (GNC) system. Each part focuses on safety, risk mitigation, and accuracy. The goal is to design components that ensure structural integrity, meet mission constraints, and fit the mission's needs.

The mechanical subsystem includes the frame and chassis from strong, lightweight materials. It ensures the rover can maneuver and respond to various terrains. Components are connected to the frame by a durable, responsive suspension system, providing a solid base for all components and instruments. Proper wheels and electric motors, selected in collaboration with the electrical subsystem guarantee effective maneuvering. The GNC system is also managed by the mechanical subsystem and includes components such as Sun Sensors and Inertial Measurement Unit (IMU). It senses terrain and makes adjustments for stability and maneuverability. The mechanical subsystem ensures these instruments operate properly by making necessary adjustments based on other subsystems' needs such as power output, CDH and thermal data, and the science instruments needs.

The mechanical subsystem is designed to follow all mission requirements and constraints as well as ensure the safety, stability, durability, and reliability of all other subsystems. The material and suspension system were chosen and designed by the mechanical subsystem to withstand loads and stress of up to 450MPa and be light enough to follow mass constraints. The transmission system can move at 10 RPM and the electric motors for each wheel would need about 0.863 - 1.727 Watts which reduces the power consumption, allowing other subsystems to be powered. Watts. The IMU has a gyroscope operating range of 358 degrees/second to 1620 degrees/second and the accelerometer has an operating range of 12 g to 70 g. The system will be utilizing a 2-axis Coarse Sun Sensor which has a field of view of 360 degrees, an accuracy of ± 1 deg (null) and ± 5 deg (linear range). All of the mechanical components are designed to ensure the lunar rover reduces issues and risks to guarantee proper and accurate data collection.

2.1.1.1. Mechanical Subsystem Requirements

Mechanical Subsystem Top-Level Requirements

The mechanical subsystem top-level requirements were derived from customer requirements and constraints, science goals, and mission requirements. The lunar rover needed to follow customer constraints such as mass and dimensional constraints of 85 KG and 1.5m x 1.5m x 1.5m volume. MEC-1 was chosen due to the mission requirements to explore the Permanently Shadowed Regions given by the mission requirements document. MEC-2, MEC-4, and MEC-5 were chosen to ensure that the lunar rover met these constraints and did so for the success of the mission. The rover needs to not only be able to explore the lunar regolith but also do it safely and efficiently to ensure the most accurate results. MEC-3 was chosen to meet science mission objectives and worked in accordance with the science team to operate instruments properly.

Mechanical Subsystem Low-Level Requirements

The mechanical subsystem's low-level requirements were derived from top-level requirements. The lower-level requirements are based on the top-level mechanical requirements listed above. MEC-1.1 and MEC-1.2 are derived from MEC-1 because the requirements describe how and what will be done to travel on the Permanently Shadowed Region and lunar terrain. MEC-2.1, MEC-2.2, and MEC-2.3 were derived from MEC-2 which describes the components and how they will keep the rover balanced, stable, and safe. MEC-3.1 is derived from MEC-3 which describes the mechanical role in the use of the science instruments. MEC-4.1 is derived from MEC-4 which works in accordance with MEC-2 in ensuring the rover is durable and able to withstand loads on the terrain. MEC-5.1 is derived from MEC-5 which describes components and uses for the GNC system.

Table 12. Mechanical Subsystem Top-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical Requirements							
MEC-1	The system shall be able to travel to Permanently Shadowed Regions up to 10 km from the landing site and traverse over no more than a 15 degree incline and on rough terrain.	The system should be able to travel to areas of interest in order to meet mission objectives and gather data.	MR-1	MEC-2, MEC-5	Demonstration	Mechanical	Met
MEC-2	The suspension and frame shall ensure that the lunar rover is stable, can withstand the terrain, and protects the system from shock and vibrations.	The system must be able to operate in harsh lunar environments and extreme temperature gradients.	MR-1	THER-1, POWER-3	Test	Mechanical	Met
MEC-3	The goals of the scientific research or mission (science objectives) should be achievable using a Ground-Penetrating Radar and neutron spectrometer.	Instruments are used to determine the elemental composition of the lunar regolith.	MR-1, MR-2	PAY-1	Inspection	All	Met

MEC-4	Structural component materials shall be chosen based on needed thermal properties, vehicle strength over rough terrain, instrument stability, and mass.	Select materials based on vehicle design for strength, thermal requirements, and instrument use.	MR-3, MR-4	THER-2, THER-4	Analysis	All	Met
MEC-5	The lunar rover will include a Guidance, Navigation, and Control (GNC) system that detects imbalances and helps the rover adapt to the terrain. This ensures the rover will be able to continuously maneuver on new terrain.	The lunar rover will be able to detect and adapt to instability over the lunar surface.	MEC-1, MEC-2	MEC-5.1	Demonstration	Mechanical, CDH	Met

Table 13. Mechanical Subsystem Low-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Lower Level Mechanical Requirements							
MEC-1.1	The wheels shall be able to conform to the terrain and provide traction and strength.	The system should be able to travel to areas of interest in order to meet mission objectives and gather data.	MEC-1	MEC-1.2	Demonstration	Mechanical	Met

MEC-1.2	There shall be an electric motor and gearbox that provides torque and power to the wheels to move.	The system must be able to operate in harsh lunar environments and extreme temperature gradients.	MEC-1	MEC-1.1	Demonstration	Mechanical, Power	Met
MEC-2.2	The suspension must absorb all/ most energy and shocks.	The lunar rover must be able to withstand any external load to ensure components are safe.	MEC-2	MEC-4.1	Test	Mechanical	Met
MEC-2.3	The suspension system shall keep the lunar rover in a balanced and stable position.	Keeping the lunar rover stable and balanced will ensure it maneuvers properly and instruments work with high accuracy.	MEC-2	MEC-4.1, MEC-2.4	Test	Mechanical	Met
MEC-2.4	The suspension system will assist the wheels in maneuverability and keep the wheels in contact with the surface.	For the wheels to work properly, they need to be connected to the body of the lunar rover by the suspension system.	MEC-2	MEC-1.1	Test	Mechanical	Met

MEC-3.1	The lunar rover will hold and maneuver components such as power supply, instruments, communication devices, solar panels, thermal instruments, and lights.	The lunar rover will hold all other components to gather data and work according to other systems.	MEC-3	MEC-5.1	Inspection	All	Met
MEC-4.1	The chassis and frame will be designed from a material that is lightweight, strong, and cost-effective.	The frame is the base of the lunar rover and needs to be strong enough to hold all components, instruments, and loads.	MEC-4	MEC-3.1	Analysis	Mechanical	Met
MEC-5.1	The system shall include sensors that shall be able to detect imbalances and adapt the rover's stability, acceleration, navigation, and sun direction based on changes in the terrain.	In the case that the system is off balance and not stable, there needs to be a detection system in order to restore balance.	MEC-5	MEC-5.1	Demonstration	Mechanical, CDH	Met

2.1.1.2. Mechanical Sub-Assembly Overview

The Mechanical falls into 4 mechanical categories: structure, suspension, locomotion, and GNC.

Structure

The lunar rover shall be designed with a strong and lightweight frame made out of aluminum alloy 2024. Aluminum alloy 2024 is strong, lightweight, and has a maximum stress load of 450 MPa and a density of approximately 2.7 g/cm³ depending on the aluminum alloy used. The frame will be designed to withstand the load of all the components and will be lightweight to meet the mass constraint of 85 kg. The material is important in supporting the rover and the uneven terrain which was discussed in the Physical Environmental Hazards (MCR, 1.5). The material of the frame will be durable enough to withstand all the shocks, vibrations, and loads from the terrain and other components by using Aluminum alloy on all parts of the frame. The TRL for the material is 6 due to its previous uses in lunar rovers.

Suspension

A double wishbone suspension system will allow the vehicle to explore the Moon's surface. It is used for shock absorption, improved mobility, and maintaining consistent ground contact. With excellent handling and control, the rover will have precise wheel movement and enhanced performance on uneven terrains. It uses two pivoting arms, known as wishbones, and this type of suspension allows the wheels to react and act separately from the others due to wishbone arms. Each wishbone or arm has two mounting points on the chassis and one joint at the knuckle. To withstand loads such as braking and acceleration, the arms need two ball joints at the body. The shock absorber, a spring-damper system, and a coil spring are attached to the wishbones to regulate vertical movement. Using mechanical springs combined with dampers that do not rely on fluids can provide a good balance of suspension and damping without temperature sensitivity issues. The suspension system is important in ensuring the rover's safety on the lunar surface which is labeled as a Physical Environmental Hazard (MCR, 1.5). The suspension system will include absorbers and durable material to ensure that it can handle the loads, slopes, and shocks on the lunar surface. The TRL is 3 because a double wishbone suspension has not been tested on past rovers.

Transmission

In the rover's transmission system, a gearbox is needed for torque adjustment, speed conversion, and terrain adaptation. They allow for speed changes and adjust the torque from the electric motor to achieve different performance needs. The vehicle also has a

two-speed automatic transmission. It is designed to work with electric motors, two gears forward, and one rear gear. It is also possible to create an algorithm that handles all aspects of automatic gear shifting. The harmonic drive also reduces motor speed by a factor of 80:1, allowing for uninterrupted power delivery to the wheels without manual gear changes. This means that if the motor spins at 800 revolutions per minute (RPM), the wheels will spin at 800 divided by 80 which is 10 RPM. Each drive unit includes a mechanical brake that is actuated automatically by sensors, eliminating the need for manual operation (Mobility Performance of the Lunar Roving Vehicle, 6). The transmission system may be prone to terrain and temperature risks as stated in the Physical Environmental Hazards section of the MCR (MCR, 1.5). The transmission system was chosen to ensure that it would be able to withstand high temperatures and low temperatures on the surface of the moon as well as being able to withstand any shocks or loads. The transmission will be mounted to the rover in a way to ensure that it will be maneuverable on the terrain. The TRL for this component is 4.

Locomotion

The lunar rover must be able to maneuver on the surface of the Moon's terrain, and wheels play a crucial role in adapting to rough conditions. In addition, solar radiation can degrade the rubber wheels which makes it difficult to design (Good Year 2009). The vehicle's wheels are designed with hundreds of steel wires that interconnect to create a durable and absorbing mesh. This design does not require the wheel to be inflated, meaning it is less prone to getting flat tires. If a spring wire breaks, the hundreds of wires will hold the structural integrity together.

The mesh design can support higher loads and conform to the terrain, even over large rocks and debris (Kilkenny 2017). In addition to strength and load, traction and stability are an important aspect of wheel design because the wheels need to keep the lunar rover balanced for other components to work properly. The mesh wire can also provide good traction and durability (Kilkenny 2017). For the size of the wheel, the diameter must be large enough to overcome obstacles and be able to distribute the weight properly. NASA's Volatile Investigation Polar Exploration Rover (VIPER) rover design contains a wheel diameter of about 0.5 m and a width of 0.2 m, which makes it optimal for traversing over the lunar south poles. The diameter and width of the wheels can contribute to the overall power output and decide how much power and torque need to be provided. The wheels are prone to terrain risks and issues as highlighted in the Physical Environmental Hazards section (MCR, 1.5). To prevent issues with terrain and dust the wheels have been designed to conform to the terrain. They are made of flexible yet durable material to ensure that they can withstand any type of uneven terrain or dust. The TRL for the wheels is 5 due to current testing on rovers such as VIPER and other Martian rovers.

For the wheels to move, there must also be an electric motor that provides torque and

power to the wheels. Determining which electric motor to use is based on the power needed to move the lunar rover at a desired velocity. Based on the VIPER rover, the maximum speed planned for the mission vehicle is 20 cm/s (0.2 m/s) and the prospecting speed would be 10 cm/s or 0.2 m/s (Fluckiger 2021). Based on the mass, gravity on the surface of the moon, and the speed of the lunar rover, the power output can be calculated. For the lunar rover to travel at 0.1 m/s - 0.2 m/s, the power supplied to each wheel would need to be about 0.863 - 1.727 Watts (W). Knowing the amount of power that each wheel needs will determine an electric motor for each of the four wheels, which will be from Lin Engineering BL17E19-01. A hazard that will be taken into account is temperature risks which is highlighted in the Physical Environment Hazard section (MCR, 1.5). Temperatures on the surface can fluctuate from 121 °C in daylight and 133 °C at night. To prevent this electric motors have been chosen to be able to operate in these low or high-temperature conditions. The TRL for this component is 4.

Guidance, Navigation, and Control

The GNC system is responsible for sensing and detecting the terrain to make proper adjustments for the lunar rover's stability and maneuverability. Several components can go into the GNC system, such as reaction wheels, magnetic torques, thrusters, star trackers, sun sensors, and Inertial Measurement Units (IMU). An IMU is an important component that senses the terrain and keeps the lunar rover in balance. Most IMUs include two main components, a gyroscope and an accelerometer. The purpose of a gyroscope is to measure any angular change in the system when moving on terrain that is rough or imbalanced (Yost 2024). The purpose of an accelerometer is to measure the velocity change in a system or the acceleration in multiple axes to ensure the system can maneuver on the lunar surface safely. Based on trade studies, the IMU that was chosen was the Honeywell HG1700. The system has a mass of 0.9 kg and a power consumption of about 5 Watts. It has a gyroscope operating range of 358 degrees/second to 1620 degrees/second and the accelerometer has an operating range of 12 g to 70 g (Honeywell). The IMU also has a data rate of 100 Hz for the guidance and 600 Hz for control which is optimal for transferring data (Honeywell). The Physical Environmental Hazard that is highlighted is the risk of temperature change (MCR, 1.5). The component is at risk for high or low-temperature disruption on the surface of the moon. To prevent this, the component has been chosen from a manufacturer that can withstand intense temperature fluctuations. The TRL for the IMU system is 5.

In the case that the lunar rover is not able to seek enough energy from the Sun due to positioning, sun sensors will help aim the solar panels perpendicular to the sun to produce more energy. Sun sensors are used to estimate the direction of the Sun and aim the solar panels directly toward it to absorb solar energy. The system will be utilizing a 2-axis Coarse Sun Sensor which has a field of view of 360 degrees, an

accuracy of ± 1 deg (null), ± 5 deg (linear range), a mass of 0.13 kg, and dimensions of 0.089 m x 0.089 m x 0.043 m (Redwire Space). The sun sensors may be at risk for malfunction due to the terrain which is highlighted in the Physical Environmental Hazards section (MCR, 1.5). The sun sensor relies on being in an optimal area of operation and may be disrupted due to the uneven terrain. This will be prevented by ensuring the rover is stable by relying on other systems such as the suspension and frame. It has also been chosen because of the wide range of operations which can lower the risks of the sensors not working properly. The TRL for the sun sensors is 4.

In addition to the sun sensor, electric actuators will ensure that solar panels maneuver properly to the most optimal angle and that instruments are displaced as needed. These electric actuators use electricity to convert kinetic energy into motion via an arm. The system will include a linear actuator which will communicate with the sun sensors, instruments, and CDH subsystem to ensure that the components move properly. The electric actuators may be at risk of malfunction due to the terrain as highlighted in the Physical Environmental Hazard section (MCR, 1.5). These hazards will be prevented by ensuring that the system is stable through other components such as the suspension and frame. The TRL for this component is 5.

Master Camera

A master camera will be used to capture all the activity and data occurring on the lunar surface. The master camera will be responsible for relaying visual information back to mission control in real-time to ensure all components are working properly and adjustments can be made in case of malfunctions. The master camera will be the SFP-C1640 from Imperx. It is a low-power camera with a global shutter, up to 434.2 FPS at 8 bits, 7 microseconds to 16 seconds, and captures at 1632 x 1248 (Imperx). Terrain is a risk that is highlighted in the Physical Environmental Hazards section (MCR, 1.5). The master camera will be subject to malfunction due to the vibrations and shocks to the terrain. To prevent this, the master camera will be mounted properly to the lunar rover to ensure it is stable as well as relying on the suspension and frame components to keep the rover balanced. The TRL for the master camera is 6.

Table 14. Mechanical Sub-Assembly Overview

Component/Sub assembly	Description of Function	Requirement	TRL	Mass [g]	Length [m]	Width [m]	Height [m]	Total Volume [m³]	Max Power Draw [W]
Chassis / Frame Material (Aluminum Alloy 2024)	Aluminum Alloy material will be used to design the chassis and frame of the rover.	MEC-4	6	46000	1.5	1.15	0.35	0.60375	0
Wheels (Steel Spring Mesh)	Steel Spring Mesh design for the wheels attached to the suspension and chassis to traverse over the lunar terrain.	MEC-1	5	3590	0.4	0.17	0.45	0.0306	0
Honeywell HG1700 (IMU)	Inertial Measurement Unit includes a gyroscope and accelerometer that detects imbalances and adapts the rover's stability, acceleration, and navigation based on changes in the terrain.	MEC-5	5	900	0.065	0.051	0.0725	0.000541	5
Lin Engineering Brushless DC Motor BL17E19-01	Electric motor for the wheels and provides torque for them to operate.	MEC-1	4	1282.04936	0.04699	0.04191	0.04191	0.00008253549622	30
2-speed automatic gearbox	It is needed for torque adjustment, speed conversion, and terrain adaptation	MEC-1	4	15.00	0.01395	0.006	0.006	0.0000005022	1.2
double wishbone Suspension	It is used for shock absorption, improved mobility, and maintaining consistent ground contact the (cost is a little higher because the type of material used	MEC-2	4	2,000	0.9	0.2	0.5	0.09	0

	to make it will be aluminum and carbon fiber).								
sun sensors (SSOC D60)	A Sun sensor is a navigational instrument used by spacecraft to detect the position of the Sun.	MEC-5	4	35	0.04	0.03	0.012	0.0000216	0.35
Electric Actuator	A mechanical device used to convert electricity into kinetic energy in either a single linear or rotary motion.	MEC-3	5	49.31	0.2159	0.1143	0.0762	0.001880415 594	7
Master Cam	Most red light camera systems in operation today use wet film technology that requires exposed film to be retrieved, processed, developed, and converted into digital images daily.	MEC-5	6	461	0.0881	0.066	0.066	0.000383763 6	5.04
Total	N/A	N/A	4	54332.35936	N/A	N/A	N/A	0.1235098169	48.59

Table 15. Aluminum Alloy Trade Study

Aluminum Alloy					
Criteria	Explanation	Grade	Weight	Aluminum Alloy 2024	Aluminum Alloy 6061
Tensile Strength	Material must be durable and able to withstand heavy loads which include all instruments, components, and movement.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	7
Density	Density of the material can determine the overall mass of the volume used.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7
Cost	The material must be cost-effective to meet the cost allowance of \$12,705,120 under the remaining mechanical components.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	7
Thermal Conductivity	The material should be able to conduct heat to protect components.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	8
		TOTALS:	100%	82.50%	72.50%

Table 16. Electric Motor Trade Study

Electric Motor					
Criteria	Explanation	Grade	Weight	Lin Engineering Brushless DC Motor BL17E19-01	Lin Engineering Brushless DC Motor BL17E28-01
Power (Wattage)	Lower power consumption can ensure the system does not overheat or require a long time to recharge.	10 = high, 5 = medium 1 = low 0 = Fail	30%	6	8
Mass	Four motors need to be lightweight to meet mass constraints.	10 = high, 5 = medium 1 = low 0 = Fail	20%	9	5
Cost	Four motors need to be cost-efficient to meet cost constraints.	10 = high, 5 = medium 1 = low 0 = Fail	20%	9	5
Torque	The motor must meet the RPM for the rover to travel the calculated speed.	10 = high, 5 = medium 1 = low 0 = Fail	15%	6	8
Thermal / Heating Properties	Ensure the motors do not overheat and should be able to function in extreme temperatures.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	8
		TOTALS:	100%	75.00%	65.00%

Table 17. Frame And Chassis Material Trade Study

Frame / Chassis Material					
Criteria	Explanation	Grade	Weight	Aluminum Alloy	Carbon Fiber
Durability	Material must be durable and able to withstand heavy loads which include all instruments, components, and movement.	10 = high, 5 = medium 1 = low 0 = Fail	25%	6	9
Mass	Desire material should be lightweight to meet the mission requirement weight of 85kg.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	8
Cost	The material must be cost-effective to meet the cost allowance of \$12,705,120 under the remaining mechanical components.	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	4
Temperature	The material should be able to withstand PSR temperatures	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	7
		TOTALS:	100%	80.00%	70.00%

Table 18. Inertial Measurement Unit Trade Study

Inertial Measurement Unit (IMU)						
Criteria	Explanation	Grade	Weight	Honeywell HG1700	Northrop Grumman LN-200S	Safran STIM300
Mass	IMU should be lightweight in order to follow mass constraints.	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	7	10
Cost	IMU needs to be lower cost in order to stay within budget constraints.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	5	9
Accelerometer	The accelerometer must be reliable to have accurate navigation and velocity data.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7	4
Gyroscope	The gyroscope must be accurate in order to ensure rover balance and stability.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	7	5
Power Usage	IMU's power consumption must be lower in order to allow more power efficiency in the system.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	5	9
		TOTALS:	100%	77.50%	65.00%	70.00%

2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans

The mechanical subsystem will need to be able to mount sensors to help solar panels operate and in the case that the lunar rover is not able to determine the position for sunlight, sun sensors will be put into place to help the panels operate. This is essential to power all the components in the system. Solar panels will also be able to maneuver in order to align perpendicular to the sun in order to ensure maximum power generation.

The mechanical subsystem deals with the locomotion aspects of the lunar rover, so to ensure that the rover will move properly on lunar terrain, there needs to be a system to detect imbalances and help in correction. An IMU will be put into place to ensure that the rover is balanced and making necessary adjustments when needed on rough terrain or sloped areas on the lunar surface. This assures that even in unplanned circumstances where the terrain is rougher than expected the rover will remain fully operational.

Dust mitigation is also a risk that will be fixed by using dust seals, dust-resistant materials, and dust-mitigating bearings and materials for the locomotion system. During the mission, the rover will undergo high amounts of force and load, especially on the frame and suspension system, which requires there to be a supporting system attached to the rover. Shock absorbers will be incorporated into the suspension system and will act as a cushion for the rover.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans

Mission VALKYR's mechanical subsystem and components will include several suppliers and manufacturers. This is due to the wide range of components that need to be incorporated into the mechanical subsystem. Some manufacturers include Good Year, Boeing, Maxon, and Honeywell. Lead times will also vary due to the wide variety of components and their need to be catered to our system.

Aluminum Alloy 2024 (Frame and Chassis)

The supplier will be AAAAirsupport. Carbon Fiber is an alternative material that can be used to build the frame and chassis due to its strong, lightweight, and cost-efficient properties. Lead times range from 26 to 73 weeks based on previous rovers such as the ExoMars rover or the Lunar Rover Vehicle (LRV) which took about 73 weeks. These lead times were determined by design refinement, design finalization, material and supplier procurement, and previous developments from the SICSA (SICSA 15). The lead times will be similar for the backup due to similar suppliers.

Wheels (Spring Steel Mesh)

The component will be Spring Steel Mesh Wheels supplier will be Good Year. Titanium wire mesh can be an alternative, however it may not be as cost-efficient. The manufacturer would be Boeing. These wheels were chosen due to their ability to adapt and shape to the terrain which will help the lunar rover be more stable on the lunar surface. Lead times for the wheels will be about 73 weeks based on the previous procurement of the Lunar Rover Vehicle (NASA/TM, 2009). The lead times will be similar for the backup due to similar suppliers.

Inertial Measurement Unit

The primary component and supplier will be the Honeywell HG1700. The manufacturer will be Honeywell. The alternative IMU and supplier will be the Northrop Grumman LN-200S. These IMUs were chosen because they are reliable and help the rover adapt to the terrain and remain stable. Lead times for IMUs from similar manufacturers such as Avnet and MicroStrain are about 17 to 18 weeks due to testing, development, and research (Avnet, LSM6DSOTR). The lead times will be similar for the backup due to similar suppliers.

Brushless DC Motor

The primary component will be the Lin Engineering Brushless DC Motor BL17E19-01. The supplier will be Lin Engineering. The alternative supplier and product will be the Lin Engineering Brushless DC Motor BL17E28-01. These motors were chosen because they are reliable and power efficient even in dusty and uneven terrain. Lead times for

the Lin Engineering Brushless DC Motors are about 10 business days for each wheel and 10 days to ship which are provided by the products data sheet (Lin Engineering 1). The lead times will be similar for the backup due to being the same supplier.

2-Speed Automatic Gearbox

The primary component will be the GPX 6 Space Planetary Gearhead. The manufacturer is Maxon. The alternative component will be the GPX 8 Space Planetary Gearhead. These gearboxes from Maxon were chosen because they are compatible and reliable with the lunar wheels and have great heating properties. The manufacturer will be Maxon. Lead times for GPX gearboxes are about 16 to 24 weeks based on previous gearboxes developed by GPX (Maxon, Planetary gearhead GPX 22). The lead times will be similar for the backup due to being the same supplier.

Double Wishbone Suspension

The component will be built in-house to meet the specific mission requirements. It will be constructed with aluminum alloy. The suspension will be unique to the lunar rover which is why it must be developed and built in-house. The alternative solution will be to purchase parts of the suspension system that could be purchased separately and then put together but this may not be efficient and might not meet the mission requirements constraints. This suspension system was chosen because it is reliable at keeping the rover stable and supports heavy loads. Lead times for the suspension system are about 69 to 104 weeks based on previous lunar rovers such as the Lunar Rover Vehicle which varied due to their complexity and designs. The lead times will be similar for the backup due to similar suppliers.

Sun Sensors

The primary component will be the Solar MEMS SSOC - D60 Sun Sensors. The manufacturer and supplier will be Solar MEMS. The alternative component will be the Sensor Pyramid. The manufacturer will be Redwire. These sun sensors were chosen because they have a wide field of view and reliable operating range and temperature. Lead times for the sun sensors are about 8 to 10 weeks which was given by the manufacturers (Solar MEMS, 1). The lead times will be increased by about 4 to 8 weeks for the backup due to similar suppliers.

Electric Actuator

The primary component will be the UH-1 Barber Coleman Linear Actuator. The manufacturer and supplier will be Midwest Aerospace, LTD. The alternative component

will be the Linak L18 IC Linear Actuator. These actuators were chosen because they are reliable, can operate under heavy loads and have efficient power usage. The manufacturer is Linak. Lead times for the linear actuators are about 2 to 3 weeks which was given by the manufacturer and based on previous actuator arms. The lead times will be similar for the backup due to similar suppliers.

Master Camera

The primary component will be the Imperx SFP-C1640. The manufacturer is Imperx. The alternative component will be the Imperx B1610 CCD Camera. These cameras were chosen because they have a wide field of view, minimal power consumption, and great heating properties. The manufacturer is Imperx. Lead times for Imperx cameras are about 4 to 12 weeks which was given by the manufacturer and previous cameras on lunar rovers such as the Lunar Rover Vehicle (LRV). The lead times will be similar for the backup due to being the same supplier.

2.1.1.5. Mechanical Subsystem Verification Matrix

Table 19. Mechanical Subsystem Verification Matrix

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MEC-1	The system shall be able to travel to Permanently Shadowed Regions up to 10 km from the landing site and traverse over no more than a 15 degree incline and on rough terrain.	Demonstration	The lunar rover needs to be able to traverse over the terrain and do so successfully. This is shown through successful operation and adjustments will be made to ensure mission completion. A physical model is needed for demonstration.	A similar environment will be created and the lunar rover will be placed within the environment for demonstration. Data will be gathered on whether the rover can traverse over various inclines, declines, and terrain. Velocity, acceleration, and power consumption will be observed to see if the rover can perform properly on the test terrain. The demonstration will also work in accordance with testing procedures such as vibration testing, shock testing, stress testing, materials capability testing, and pressure testing. Equipment needed includes stress gauges, environmental test chambers, hydraulic actuators, shakers, and computer software. The expected result is that the lunar rover will be able to maneuver on the rough test terrain.

MEC-2	The suspension and frame shall ensure that the lunar rover is stable, can withstand the terrain, and protects the system from shock and vibrations.	Test	The suspension and frame will undergo test verification to ensure the components can withstand all loads and forces on the system. Further analysis and testing needs to be done so the rover has a strong and durable base. A physical model as well as CAD models will be needed for testing.	The suspension, chassis, and frame will undergo various test methods such as vibration testing, shock testing, and stress testing to analyze the loads and stability of the base. Analysis will also be performed in accordance with other components such as Finite Element Analysis (FEA) and simulations using ANSYS. Prototypes will be used and further testing will be done on fully integrated subsystems. The equipment needed is computer software such as FEA, ANSYS, Siemens NX, and vibration software. The expected result is that the suspension and frame will be able to withstand the predicted loads.
MEC-3	The goals of the scientific research or mission (science objectives) should be achievable using a Ground-Penetrating Radar and neutron spectrometer.	Inspection	Inspection methods will be used for all scientific instruments to ensure all components work properly and gather proper and accurate data. Visual examination of all scientific instruments is needed to ensure design features and end data are properly displayed. A physical model of the scientific instruments is needed for inspection.	Scientific instruments will be inspected to ensure they function properly on the lunar rover by using cameras, scales, and calipers to ensure the instruments are placed and display proper information. The equipment needed will be cameras, scales, calipers, and computer software. The expected result is that the instruments will work properly and display accurate information.

MEC-4	Structural component materials shall be chosen based on needed thermal properties, vehicle strength over rough terrain, instrument stability, and mass.	Analysis	Analysis will be conducted on all structural component materials to ensure materials and all properties meet the system needs including material strength, thermal requirements, force and loads, and mass. Mathematical models and simulations will be needed to analyze all properties. CAD models will be needed to perform analysis on the materials.	Finite Element Analysis (FEA) and simulations via ANSYS will be conducted on all material properties of the rover. FEA will be mainly conducted on the suspension, frame, and chassis to ensure the rover can undergo loads, shocks, and vibrations on the lunar surface. Computational Fluid Dynamics (CFD) may also be conducted to identify pressures that can affect the lunar rover. Radiative Heat transfer will be conducted to analyze thermal differences and transfers between surfaces. The equipment needed is computer software such as FEA, ANSYS, Siemens NX, and vibration software. The expected result is that the suspension and frame will be able to withstand the predicted loads.
MEC-5	The lunar rover will include a Guidance, Navigation, and Control (GNC) system that detects imbalances and helps the rover adapt to the terrain. This ensures the rover will be able to continuously maneuver on new terrain.	Demonstration	Demonstration will be conducted on all components of the GNC system. The GNC system needs to be able to demonstrate performance capabilities on the lunar surface and should be able to operate at all limits to ensure the rover is stable and can direct components accordingly. A physical model will be needed to perform a demonstration.	The GNC system will be demonstrated under similar conditions to the lunar surface. Rough terrain and uneven surfaces will be developed to test the IMU system and how the component will adjust to the imbalances. Sun sensors are demonstrated outside to determine the sun's position. They will work in accordance with the electric actuators and solar panels to ensure they function properly under extreme conditions. Equipment needed includes computer software to display position and properties. The expected result is that the GNC system will be able to properly send data to adjust components.

MEC-1.1	The wheels shall be able to conform to the terrain and provide traction and strength.	Demonstration	Demonstration will be conducted on the wheels to ensure that all wheels are able to conform and traverse over the terrain. This needs to be done through demonstration of a physical model and similar terrain to the lunar surface. A physical model will be needed to perform a demonstration.	The wheels will be demonstrated under similar conditions to the lunar surface. Rough terrain and uneven surfaces will be developed to test how the wheels will conform to the terrain and react to uneven terrain. They will work in accordance with electric motors and the overall system. Equipment environmental test chambers and computer software. The expected result is that the wheels rover will be able to maneuver on the rough test terrain and conform to surfaces properly.
MEC-1.2	There shall be an electric motor and gearbox that provides torque and power to the wheels to move.	Demonstration	Demonstration will be conducted on the electric motor and gearbox to confirm the component's performance capability to power the wheels. This needs to be done to ensure the lunar rover can maneuver properly under extreme conditions in the lunar environment. A physical model will be needed to perform a demonstration.	The electric motors and gearbox will be demonstrated under similar conditions to the lunar surface. Rough terrain and uneven surfaces will be developed to test how the electric motors perform and will monitor temperature and power consumption. They will work in accordance with the wheels. Analysis and tests will be conducted as well. Equipment environmental test chambers and computer software. The expected result is that the electric motors and gearbox will work properly under tested conditions.

MEC-2.1	The suspension must absorb all/ most energy and shocks.	Test	Testing will be conducted on the suspension system to verify performance and ensure the system has proper shock absorption, load, and force distribution under controlled conditions. Analysis may also need to be conducted with simulations. A physical model and CAD will be needed for testing.	The suspension will undergo various tests such as vibration testing, shock testing, and stress testing to analyze the loads and stability of the suspension system. Analysis will also be performed in accordance with other components such as Finite Element Analysis (FEA) and simulations using ANSYS. Prototypes will be used and further testing will be done on fully integrated subsystems. The equipment needed is computer software such as FEA, ANSYS, Siemens NX, and vibration software. The expected result is that the suspension will be able to withstand the predicted loads.
MEC-2.2	The suspension system shall keep the lunar rover in a balanced and stable position.	Test	Testing will be conducted on the suspension system to verify performance and ensure the system can keep the lunar rover balanced and stable under uncertain conditions on the lunar terrain. Analysis may also need to be conducted with simulations. A physical model and CAD will be needed for testing.	The suspension will undergo various tests such as vibration testing, shock testing, and stress testing to analyze the loads and stability of the suspension system. The suspension will also undergo demonstration on the overall system to ensure stability over rough terrain. Analysis will also be performed in accordance with other components such as Finite Element Analysis (FEA) and simulations using ANSYS. Prototypes will be used and further testing will be done on fully integrated subsystems. The equipment needed is computer software such as FEA, ANSYS, Siemens NX, and vibration software. The expected result is that the suspension will be able to withstand the predicted loads.

MEC-2.3	The suspension system will assist the wheels in maneuverability and keep the wheels in contact with the surface.	Test	Testing will be conducted on the suspension system to verify performance and ensure the system can keep the lunar rover balanced and stable as well as ensure the rover is maneuvering properly. Analysis may also need to be conducted with simulations. A physical model and CAD will be needed for testing.	The suspension will undergo various tests such as vibration testing, shock testing, and stress testing to analyze the loads and stability of the suspension system. The suspension will also undergo demonstration on the overall system to ensure stability over rough terrain. Analysis will also be performed in accordance with other components such as Finite Element Analysis (FEA) and simulations using ANSYS. Prototypes will be used and further testing will be done on fully integrated subsystems. Demonstrations will also be conducted in accordance with the wheels to ensure contact and stability are met. The equipment needed is computer software such as FEA, ANSYS, Siemens NX, and vibration software. The expected result is that the suspension will be able to withstand the predicted loads.
MEC-3.1	The lunar rover will hold and maneuver components such as power supply, instruments, communication devices, solar panels, thermal instruments, and lights.	Inspection	Inspection methods will be used to verify design features to be able to hold all components on the lunar rover for the system to function properly in all subsystems. Inspections will be made on all physical components, drawings, and documents to ensure all components are included on the final design.	The lunar rover will be inspected and analyzed to ensure that all components are mounted and connected properly. Scales, calipers, and optical lasers will be used to measure components' position for proper functionality and mass. The expected result is that the components will be mounted and fitted properly onto the lunar rover.

MEC-4.1	The chassis and frame will be designed from a material that is lightweight, strong, and cost-effective.	Analysis	Analysis will be conducted on the chassis, frames, and all materials properties to ensure components meet the system needs including material strength, thermal requirements, force and loads, and mass. Mathematical models, calculated data, and simulations will be needed to analyze all properties. CAD models will be needed to perform analysis on the materials.	Finite Element Analysis (FEA) will be conducted on all material properties of the rover. FEA will be mainly conducted on the suspension, frame, and chassis to ensure the rover can undergo loads, shocks, and vibrations on the lunar surface. Computational Fluid Dynamics (CFD) may also be conducted to identify pressures that can affect the lunar rover. Radiative Heat transfer will be conducted to analyze thermal differences and transfers between surfaces.
MEC-5.1	The system shall include sensors that shall be able to detect imbalances and adapt the rover's stability, acceleration, navigation, and sun direction based on changes in the terrain.	Demonstration	Demonstration will be conducted on all sensors. The IMU and sun sensors need to be able to demonstrate performance capabilities on the lunar surface such as ensuring the system can stay balanced, and stable, operate at the required speed, and direct solar panels properly. A physical model will be needed to perform a demonstration.	The IMU will be demonstrated under similar conditions to the lunar surface. Rough terrain and uneven surfaces will be developed to test the IMU system and how the component will adjust to the imbalances. Sun sensors may be demonstrated outside in order to correctly determine the position of the sun. They will work in accordance with the electric actuators and solar panels to ensure they function properly under extreme conditions. Equipment needed includes computer software to display position and properties. The expected result is that the sensors will be able to properly send data to adjust components.

2.1.2. Power Subsystem Overview

The power system, being one of the most important subsystems in the rover, is divided into three major categories: power generation, power storage, and power distribution. Each category serves a distinct purpose, addressing both the specific needs of the system and the overall mission objectives. This ensures the mission's success in both the short term, during active operation, and the long term when the vehicle returns to Earth and the collected data is extracted. To understand how the process works, it is essential to explore the tasks each category performs and how they work together to create a cohesive and reliable system.

Power Generation

The power generation system is the most crucial category within the entire system. It involves the use of both on-site components and the rover's hardware and software. In this stage, the rover utilizes a solar panel to harness energy from the sun. The solar panel's photovoltaic cells convert sunlight into electricity through the photovoltaic effect. This electricity is then transferred to the power storage section. The power generation system is designed to withstand various risks the vehicle may encounter, and all possible hazards were considered during its design. As the most important section, it ensures the proper functioning of all other internal systems and subsystems.

Power Storage

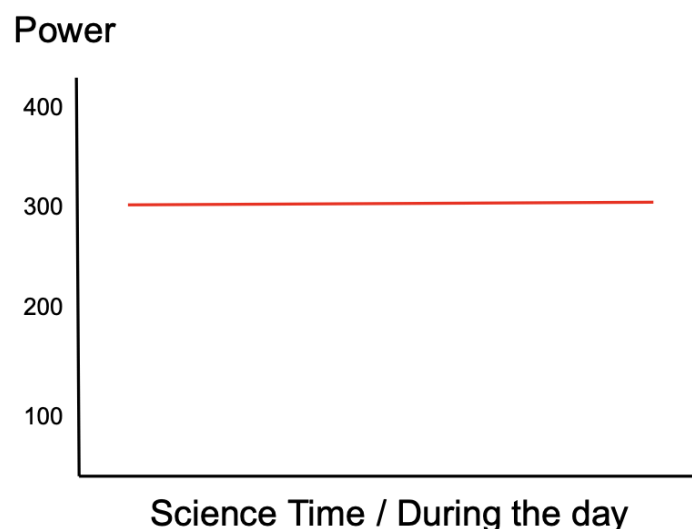
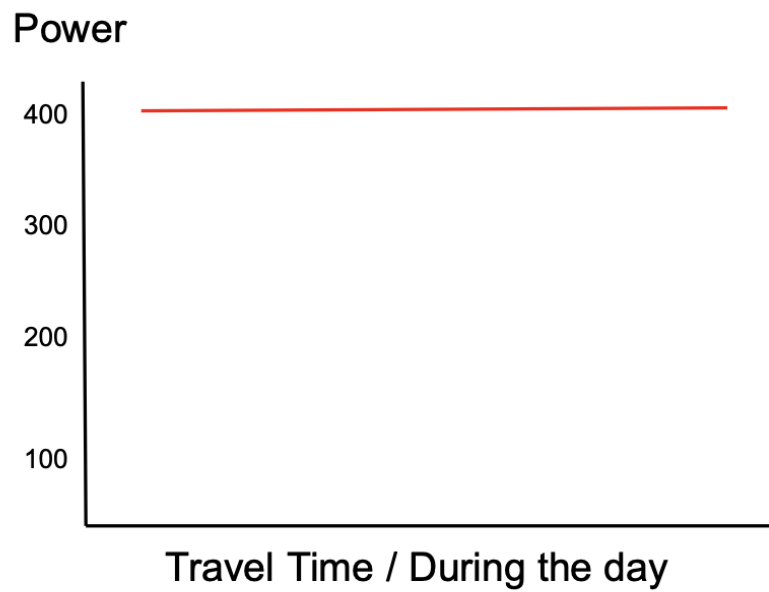
The second category in the power system is power storage. This section includes the battery pack, which consists of three batteries and one supercapacitor. The design of this system is influenced by several factors, including budget constraints and mass limitations. Additionally, the design focuses on efficiency during the different modes of the rover's operation. The hybrid system allows electricity generated in the power generation section to be stored in both components. This not only facilitates smooth transitions between modes but also extends the operational life of each component. By utilizing two components instead of one, the system reduces wear and tear, thereby decreasing the likelihood of major failures during the mission.

Power Distribution

After the generation and storage processes are complete, the next category in the power system is power distribution. This section contains the Power Management and Distribution Unit (PMDU). The PMDU utilizes a NASA-designed system that is compatible with hybrid systems like the one in the vehicle, as well as with all other

components in the system. This section is critical for ensuring that all subsystems function properly. It is responsible for distributing sufficient energy to each subsystem, as well as monitoring and addressing the vehicle's need to switch between its various modes.

Overall, the power system follows a carefully planned timeline to avoid any potential damage. The entire system works seamlessly together to make the necessary transitions during each phase of the mission. These phases are detailed in the Concept of Operations section, which outlines the step-by-step functioning of the rover.



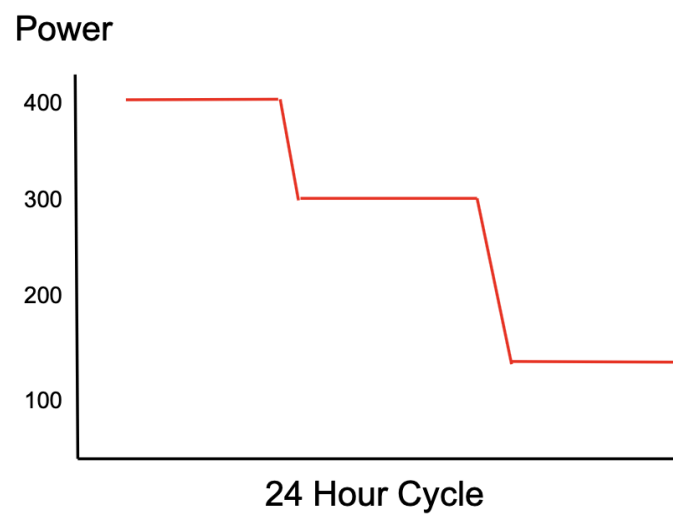
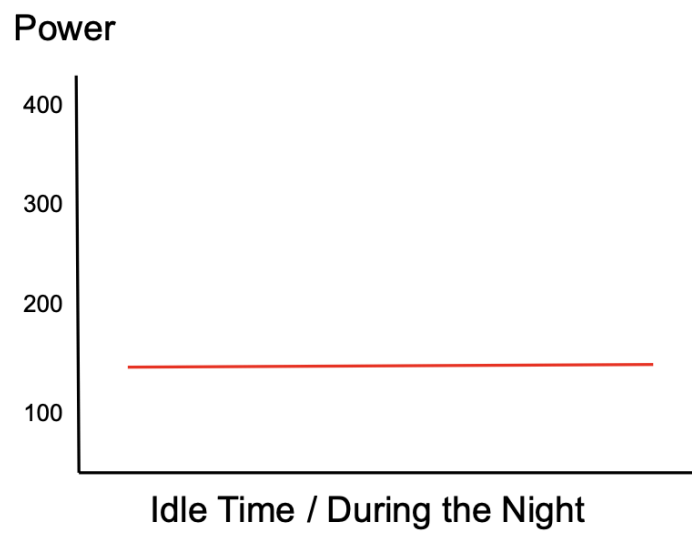


Figure 15. Power Vs. Time Graphs

2.1.2.1. Power Subsystem Requirements

Table 20. Power Subsystem Top-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Top Level Power Requirements							
POWER-1	The power system shall supply sufficient energy to maintain operating components for the duration of the mission.	The system requires power to operate all components properly and efficiently.	MR-1	POWER-2	Test	All	Met
POWER-2	The power system shall supply an approximate between 300W and 400W of power.	Components must be supplied with power to work properly.	POWER-1	POWER-1	Test	All	Met
POWER - 3	The electrical system and components shall survive extreme conditions such as microgravity, moon dust, and temperature drops, as well as make use of redundancy.	The system shall withstand the harsh environment to which it will be exposed.	MR-1, THERM-1	THER-2,THER-3, MEC-4	Test	Mechanical, Thermal	Met
POWER-4	The subsystem will have a power reservoir used to store excess energy.	Extra energy stored in the reservoir may be used during periods when the vehicle is idle.	POWER-1	POWER-2	Test	All	Met

Table 21. Power Subsystem Low-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Lower Level Power Requirements							
POWER 1.1	The PMDU is estimated to provide power during 24 hours for every day.	There will be at least one subsystem active within a 24-hour period.	POWER-1	POWER 1.2	Test	All	Met
POWER 1.2	The PMDU will have a consistent voltage regulation of +/- 5%	There must be a stable and reliable voltage supply.	POWER-1	POWER-2	Test	All	Met
POWER 1.3	The PMDU will only incur a minimum energy loss of less than 10%	Minimal energy loss is crucial for performance and reliability.	POWER-1	POWER 1.1	Test	All	Met
POWER 1.4	Will have a discharge efficiency of 90% or higher.	Conversion of energy must be optimized.	POWER-1	POWER 1.1	Test	All	Met
POWER 2.1	The solar panel to battery conversion shall be of at least 35% efficient.	A good conversion is required to optimize power usage.	POWER-2	POWER-2.2	Test	All	Met
POWER 2.2	Will distribute sufficient power to the rest of the subsystems based on priority; for example, mechanical and thermal systems	Some subsystems require more usage and	POWER-2	POWER-1.1	Test	All	Met

	will take precedence over communications.	higher power consumption.					
POWER 3.1	In case of failure, a second backup option will assume control in less than 10 seconds.	Limiting the loss of data and decreasing the risk of failure is crucial.	POWER-3	POWER-3.3	Test	Mechanical,Thermal	Met
POWER 3.2	All components will be lunar grade material.	Location of the rover is on the Moon.	POWER-3	POWER-3.2	Inspection	Mechanical,Thermal	Met
POWER 3.3	For every critical component, there will be two independent paths in case one fails to supply power.	Increases reliability and dependency while decreasing the risk of failure.	POWER-3	POWER-3.1	Test	Mechanical,Thermal	Met
POWER 3.4	Will contain mechanisms to prevent over charging and over discharging to help extend the batteries life.	Minimizes the percentage of failure.	POWER-3	POWER 3.2	Inspection	All	Met
POWER 3.5	Will operate at high performance regardless of the temperature, ranging from -40K to 220K.	Power must be supplied regardless of weather conditions.	POWER-3	POWER-3.2	Test	All	Met
POWER 4.1	The power reservoir shall have a minimum energy storage capacity of 20%	During idle periods, the vehicle can utilize the stored energy to maintain minimal operation of its subsystems.	POWER-4	POWER - 3.3	Test	N/A	Met

POWER 4.2	The power storage system shall support every charge-discharge at least 95% of its original capacity.	Shows that during the 14-day period, the vehicle will run efficiently.	POWER-4	POWER 1.1	Test	N/A	Met
-----------	--	--	---------	-----------	------	-----	-----

2.1.2.2. Power Sub-Assembly Overview

To ensure that all subsystems function properly, it is essential to understand why and how each component plays an important role. Each component is classified and used in a different section of the system, as explained in the following divisions:

Power Generation

Power generation includes the main component, the solar panels, which depend on situ resources to function properly. They are responsible for converting sunlight into electrical energy and operate by utilizing the long sunlight exposures to charge the entire vehicle. This component has a Technology Readiness Level (TRL) of 7, as it is a prototype designed for lunar endeavors and has yet to be tested.

Power Storage

Within power storage, the vehicle uses two main components along with wiring: the battery pack and the Battery Management System (BMS). Their function is to store the electricity produced by the solar panels. The batteries are used when the rover is no longer exposed to sunlight, such as during the night. Their purpose is to store the power generated and they are often chosen due to their high energy density and ability to function properly in extreme temperatures. Similarly, the BMS is used to monitor and control the charging and discharging of the batteries, ensuring there is no thermal runaway and that the batteries are not overexposed to long periods of operation that may damage them. The BMS works by tracking the state of charge, state of health, temperature, and voltage of the battery.

In addition, the power storage system includes a supercapacitor and a Supercapacitor Management System (SMS). The supercapacitor, similar to the battery, is used to store the energy generated by the solar panels. They are incredibly useful components for periods when the vehicle is in travel mode and experiences situations where it is required to use energy quickly. The SMS is used to balance and monitor the supercapacitor cells as well as control the flow of power. It ensures that the supercapacitor provides sufficient power when needed.

Both the BMS and SMS have a TRL of 8, as these systems have been used in previous lunar missions and have been tested in a space environment. The batteries and supercapacitors have a TRL of 7 because, although they have been tested in space conditions, they have not been tested in a hybrid mode.

Power Distribution

Power distribution, as its name implies, includes the Power Management and Distribution Unit (PMDU). The functionality of this component is to manage the distribution of power from the battery and supercapacitor. It serves as the central component of the entire power system. The PMDU operates by regulating voltage and current, ensuring each subsystem receives the correct amount of power. It is crucial for

ensuring that all other subsystems function properly; if one subsystem receives too much power, it may damage components and affect the entire vehicle. The PMDU protects against power surges and has the ability to prioritize power depending on the circumstances the vehicle may face, by prioritizing critical systems. This component has been carefully selected for its high reliability and redundancy features. For this reason, it has one of the highest TRLs, 8, as the specific model selected has been previously used by NASA, tested, and flight-qualified.

Additional Components

Main components cannot function without their smaller, yet equally important, counterparts. In this category, DC-DC converters, power connectors, cables, and charge controllers work together to ensure the major components function properly. Their purpose ranges from ensuring correct voltage conversion, transmission of electrical power, and regulating electricity flow. Although their operations differ, they are crucial to the system as they allow for a properly functioning overall system.

Each component of the power subsystem is crucial to the success of the mission. The system operates linearly, first collecting electricity using the solar panels, then storing it in the power storage division, and finally distributing it to the other subsystems. Most components have redundancy and fault tolerance designed to ensure that the vehicle can withstand all possible risks, such as the harsh environment of the Moon. Each component was carefully selected to ensure that the rover accomplishes its mission objectives.

2.1.2.3. Power Subsystem Recovery and Redundancy Plans

In the power subsystem, redundancy and recovery methods will be integrated to identify and mitigate points of failure. The primary subassembly incorporating redundancy will be the batteries, achieved by integrating a power reservoir using semiconductors. This approach addresses two main factors: the potential for battery damage upon arrival or during continuous usage leading to degradation, and the vehicle's periods of idle time. The reservoir will serve two primary purposes: firstly, to manage instances where the main battery pack fails, triggering the power management and distribution system to respond within 10 seconds or less; and secondly, during low power consumption phases of the vehicle. This power reservoir will allow for ample time for the system to diagnose and solve the issues plaguing the rover to keep the rover continually operational. Additionally, the power system and grid will be wired to ensure every critical component has redundant wiring paths, minimizing potential failure points and ensuring adequate power distribution.

While these redundancy methods mitigate key risks, the vehicle remains susceptible to single-point failures such as those in solar panels or the PMDU, where duplication or alternative integration is impractical due to constraints in mass, cost, and risk assessment. However, due to the design and reliability of the components that do not contain a backup the risks are mitigated, and fatal damage is unlikely to occur.

2.1.2.4. Power Subsystem Manufacturing and Procurement Plans

To ensure and maximize efficiency during manufacturing and shipping, each provider selected for the power subsystem is a company well-known for producing high-standard and quality products. These companies have had prior contracts with NASA and have demonstrated their products' ability to function and endure environments similar to those the vehicle will be exposed to. Additionally, some components will be purchased from the same manufacturer due to their specialization in specific components and their ability to offer integrated systems. This approach enhances reliability, reduces costs, and improves efficiency by minimizing extra labor.

Solar panels

Our supplier will be Pumpkin incorporated with an estimation of 26 to 52 weeks from production to shipping. Our backup is Rocket Lab which has a similar time estimate as to when the product will be finished; however, our backup is currently working on Artemis which could accelerate the production time by several weeks.

Battery Pack and BMS

Both components will be acquired via Eaglepitcher suppliers with a backup from A123 systems. Our main supplier provides an ecosystem that integrates both components and assembles the components. Both our main and backup have available options in stock which should allow for an estimated production time of three to six months.

Supercapacitor and SMS

The main supplier is Skeleton Technologies purchasing the SkelMod 51V supercapacitor or the BMOD0189 P051 B2A from Maxwell Technologies. Our main supplier would be acquired through a contractor while our backup can be directly purchased from. Since our company is partnered with Siemens the production costs are decreased as well as their production capabilities due to a new factory that opened recently. This leads to an estimate of production to shipping of around 2 to 4 weeks.

PMDU

The supplier is NASA directly which heavily reduces the time for production. This also applies to the backup, SpaceX, as both suppliers rely heavily on such components and are available. Lead time for these components is about 2 to 5 years due to it being a new space technology that is being currently developed.

DC-DC converters

The shipping time of such components ranges between 1 to 2 weeks since they can be acquired through suppliers that have the components in stock. The main supplier is Vicor power with a backup using Microchip.

Power connectors and cables

Powertrip is the main provider with TE technologies as the backup. Both are suppliers and the components are in stock which means shipping time should not exceed more than 4 weeks.

Charge controllers

The main supplier is Honeywell with EverExceed as a backup. Shipping time is expected to be less than 4 weeks since all components can be purchased directly from their website.

2.1.2.5. Power Subsystem Verification Plans

Since the power system uses testing as the primary method for verification, only the top-level requirements are used to develop the verification matrix. This approach is based on the reasoning that the lower-level requirements contain the same verification methods as the top-level ones.

Table 22. Power Subsystem Verification Matrix

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
POWER-1	Sufficient energy is supplied to the system	Test	If the system does not provide enough power the vehicle does not function	The vehicle will undergo a series of trials where it will be turned on and off in different environments to understand its power behavior and verify that it is adequate.
POWER-2	Correct amount of energy is supplied	Test	There is a minimum of energy the systems needs to function	The vehicle will be tested by creating a similar path as the one it will encounter on the Moon where it will be monitored and put to possible high risk scenarios
POWER-3	Components are lunar grade material	Test	The vehicle will be in an environment different to Earth	Using one of NASA's facilities, the vehicle will undergo a variety of tensile and strength tests, where not only individual components but also the entire vehicle will be tested.
POWER-4	System contains a redundancy plan	Test	Failure is minimized with redundancy methods	The vehicle will be purposely damaged to test the reaction time of the backup plan and how the vehicle handles the multiple risks it may face.

2.1.3. CDH Subsystem Overview

The Command, Data Handling, and Computing System (CDH) is the central nervous system of the spacecraft that coordinates interactions across all subsystems and relays telemetry data relevant to successful transfer of science data. It primarily interfaces with each subsystem by delivering commands and receiving telemetry and health status data at a rate of 1 Mbps. The CDH system receives commands from the Deep Space Network (DSN), aggregates and compresses data from subsystems, and uses redundancy protocols like Hamming code for error correction before transmission. This data is decrypted and decompressed in the ground station and is displayed in the mission control system, which is encrypted with AES-256: military grade security standards ([Kananda 2022](#)). The system requires a minimum data storage of 11.0 GB which accommodates all expected data acquired over 14 lunar days. Redundant systems and memory ensure continuous operations and guarantee mission success in anticipation of component failures. The following information on subsystems data is aggregated from the VALKYR engineering calculations.

A critical component of resource-intensive lunar operations is path finding. The Reactive Artificial Potential Field (RAPF) Algorithm is commonly used in lunar robotic missions for path planning and obstacle avoidance. It is effective for real-time decision-making due to its computational efficiency and simplicity (Li et al. 2021). The Monte Carlo Experiment demonstrated that the RAPF Algorithm achieved the same level of waypoints as traditional pathfinding algorithms like CCDP and outperforming A* planning times by 6 times with 200% higher success rates (Lamarre et al. 2024). A different paper written on Lunar Microrovers showed “200% higher success rate and 50% lower computing” (Manteaux 2024). A partial policy tree is developed at each waypoint to make decisions based on real-time conditions. It indicates the best nominal condition and corresponding risks and faults and recommends the optimal branches of behavior to reach the safe region. The system also combines autonomous and human-in-the-loop planning so the rover can be controlled dynamically (Lamarre et al. 2024). The Figure below demonstrates the effectiveness of risk-aware planning in reaching key waypoints to reach the target safe region, or the stable sunlit region of the lunar surface.

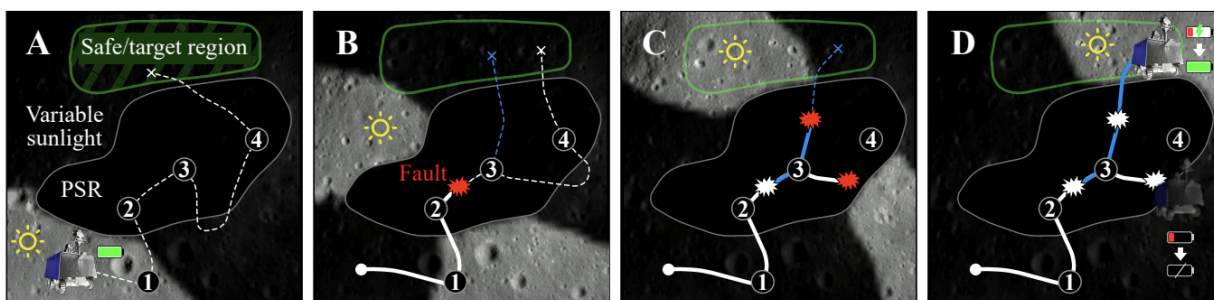


Figure 16. Risk-aware pathfinding algorithm shows the effectiveness of reaching safe conditions by evaluating the optimal path at each fault and waypoint (Lamarre et al. 2024)

Stochastic Faults from highly dynamic solar illumination demand pathfinding methodologies that take location and temporal factors into account. The algorithm works with a risk-aware planning structure with virtual forces that navigate the rover. The rover is attracted to the nominal (or ideal) path and repelled by obstacles (or faults), a system outlined in the Python simulation below. The trajectory is calculated at each node, providing a robust pathfinding system that adapts to each waypoint for semi-autonomous missions.

```
def attractive_potential(position, goal):
    return k_att * (goal - position)

def repulsive_potential(position, obstacles):
    force = np.zeros(2)
    for obs in obstacles:
        obs = np.array(obs, dtype=float)
        diff = position - obs
        dist = np.linalg.norm(diff)
        if dist < 1.0: # Influence distance of obstacles
            force += k_rep * (1.0 / dist - 1.0) * (diff / dist**3)
    return force

def compute_force(position, goal, obstacles):
    att_force = attractive_potential(position, goal)
    rep_force = repulsive_potential(position, obstacles)
    total_force = att_force + rep_force
    force_magnitude = np.linalg.norm(total_force)

    if force_magnitude > max_force:
        total_force = (total_force / force_magnitude) * max_force
```

```

    return total_force

# Simulation loop
trajectory = [position.copy()]
while np.linalg.norm(position - goal) > goal_threshold:
    force = compute_force(position, goal, obstacles)
    position += force
    trajectory.append(position.copy())

trajectory = np.array(trajectory)

```

Figure 17. Sample of the RAPF Algorithm in Python

Subsystems Data and Interfaces

The Mechanical Subsystem manages physical movement using aluminum structures, suspension systems, and harmonic drives. The gyroscope collects orientation and rotational data with an accuracy of 0.01 degrees per second to maintain the rover's balance. Solar Panel orientation data optimizes energy intake and Locomotion data monitors the rover's path.

The Electrical Power System generates and manages power through solar panels, converters, charge controllers, and supercapacitors. Power data such as generation, consumption levels, solar power, and distribution efficiency are collected as percentages and kWh. Critical power information such as emergency power levels are prioritized through a scheduling algorithm.

The Thermal Subsystem regulates temperature with MLI blankets, cryogenic radiators, and heating pipes. Given extreme temperature fluctuations, this subsystem combines passive and active control mechanisms. Thermal sensor data are collected from key points like the electronics bay and battery compartments.

Flight Software executes core mission operations, utilizing NASA's Open MCT for precise data handling. It runs with 32 GB of RAM and a robust UPS for reliable performance. It processes telemetry and science data collected from the rover and displays them on an intuitive mission control interface.

The Payload system contains two sets of instruments: the RIMFAX Ground Penetrating Radar (GPR) and the Neutron Spectrometer System (NSS). RIMFAX performs geophysical surveys and collects images at a resolution of <10cm and a depth of up to 10 meter, which is critical for detecting water-ice concentrations on the subsurface. The NSS conducts neutron spectroscopy measures hydrogen concentration at a sensitivity

of 1 part per million (ppm) to map volatile deposits.

The Telecomm (TT&C) Subsystem handles communication with Earth through S-Band and X-Band radios. It maintains uplink speeds of 500 kbps and downlink speeds of 1 Mbps. It acts as the primary interface for collecting commands and transmitting data. The LRO Satellite captures high-resolution data and communicates with the Earth Station, which processes and relays data to Earth using high-capacity transceivers and modems

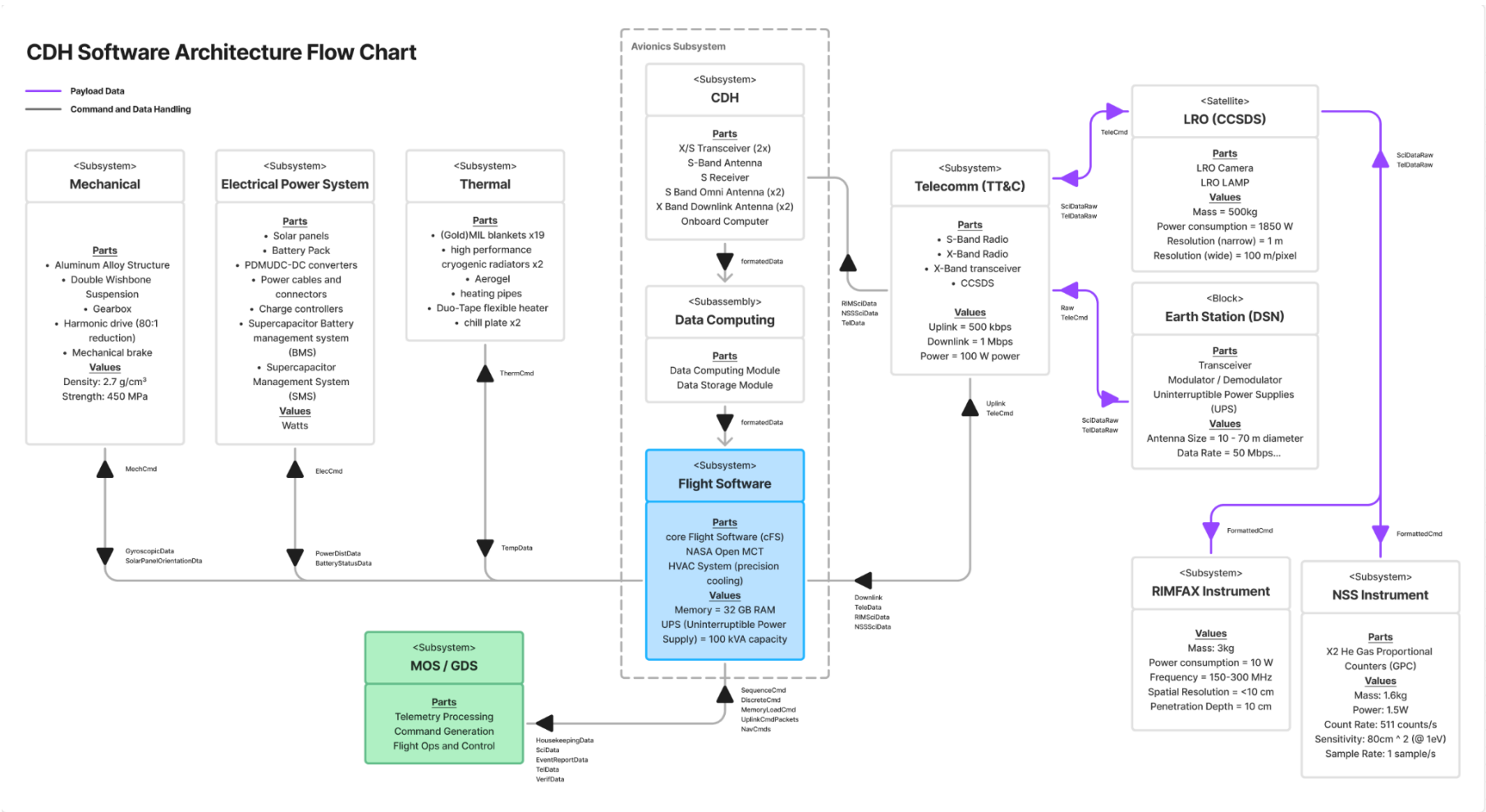
Software Architecture Flow Chart

Before developing the system architecture diagram, a comprehensive analysis of functional and nonfunctional requirements was conducted to delineate the primary input/output streams and the specific needs of each subsystem. Core interfaces and viewpoints—such as the User Interface viewpoint for the Ground Station and the Telemetry Viewpoint for communications—were identified and diagrammed to map the primary flow of information throughout the system. This exercise was essential in ensuring that each subsystem's role and data exchanges were clearly understood and aligned with mission objectives.

A modular architecture was adopted to capitalize on its advantages, including reduced costs, enhanced technology transferability, and minimized risk, which are expected to become increasingly prevalent in future mission designs (Shih et al. 2017). Subsystem integration, particularly concerning power management and inter-system compatibility, was rigorously evaluated to ensure seamless operation.

To further refine the system's design, a data communications flow chart was simulated, providing a high-level visualization of the data transfer processes within the concept of operations (refer to Figure 4). This modularity is critical in ensuring that the system remains robust, fault-tolerant, and capable of operating independently when necessary, thereby meeting the stringent requirements of space exploration.

Figure 18. CDH Software Architecture Flow Chart



Data Handling across the Concept of Operations

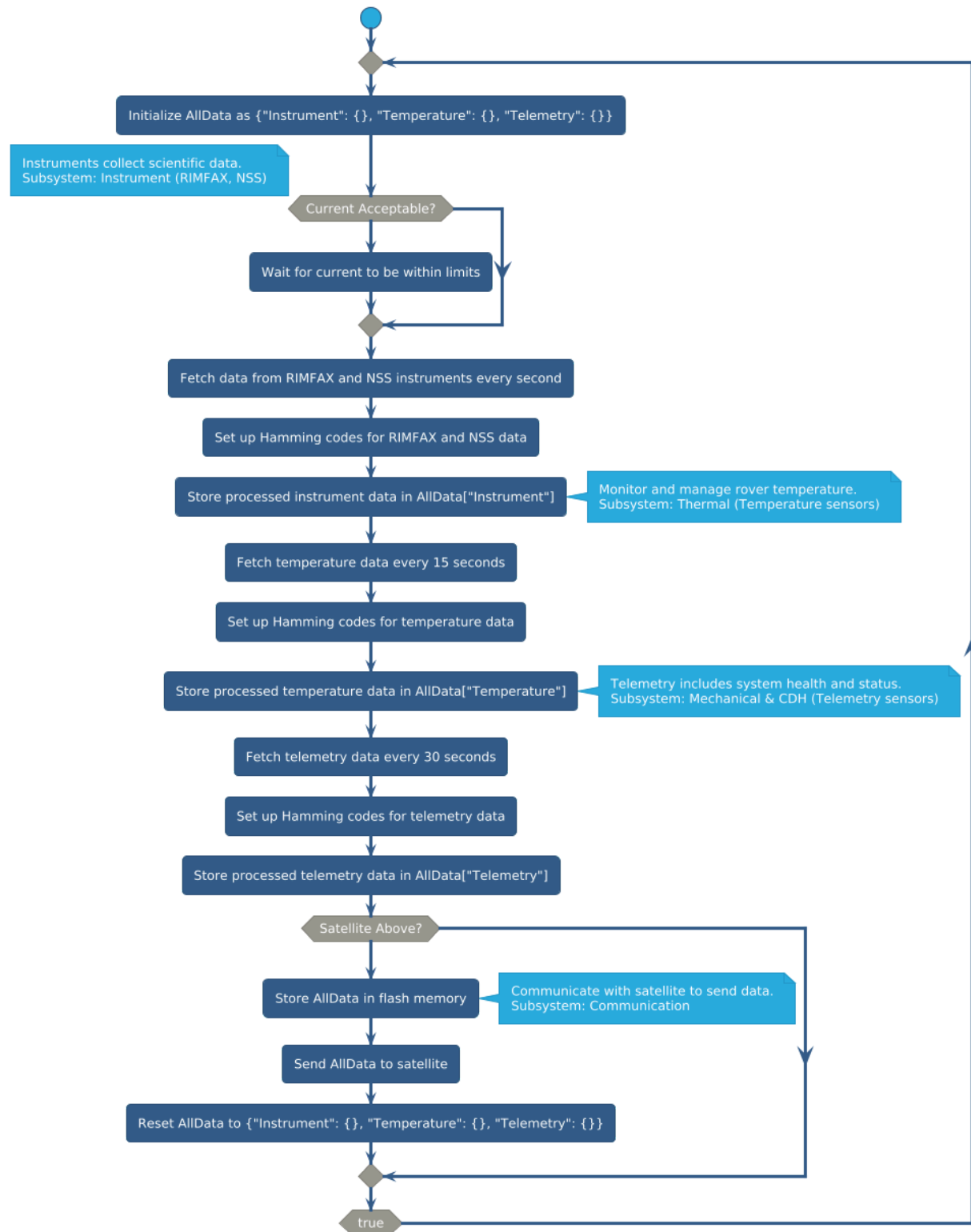
During the Traverse Phase of operations, the mechanical subsystems return gyroscopic and locomotion data while the electrical power system monitors power generation and returns this to the OBC.

During the Data Collection phase, The Payload system's RIMFAX and NSS instruments gather high-resolution subsurface data and neutron spectroscopy readings, which are crucial for detecting potential water-ice deposits.

During the Data Analysis and Relay Phase, data is aggregated, compressed, and error-corrected using redundancy protocols within the CDH system. This data is then prepared for transmission through the Telecomm Subsystem's S-Band and X-Band radios, which maintain high-speed communication with Earth. The Earth Station receives, decrypts, and decompresses the data, which is subsequently analyzed and displayed within the mission control system.

The data handling process involves a continuous loop that runs until the mission ends. During each loop cycle, data is collected and managed in a predetermined way. Instrument data is collected every second and stored in memory, temperature data is collected every 15 seconds and stored in memory, and telemetry data is collected every 30 seconds and stored in memory. After a 30 second loop, a check is performed to determine if the satellite is ready to receive data. If the satellite is ready, the data stored in memory to disk is copied, the data in memory is transmitted to the satellite, and the memory is cleared to prepare for the next cycle of data collection. This cycle repeats indefinitely, ensuring that all types of data are collected and transmitted efficiently, as long as the mission is ongoing and the satellite is available for communication. This process is shown in the *Data Handling Flow Chart* below.

Figure 19. Data Handling Flow Chart



2.1.3.1. CDH Subsystem Low-Level Requirements

Table 23. CDH Subsystem Low-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-1.1	The spacecraft shall receive and demodulate uplink commands from the Deep Space Network (DSN) and route them to the CDH subsystem.	This function is critical for managing and adjusting the spacecraft's activities as needed during the mission.	CDH-1	N/A	Test	CDH	Met
CDH-1.2	The spacecraft shall send housekeeping and science telemetry data from the CDH subsystem and modulate it onto a downlink carrier.	It is essential to monitor the spacecraft's health, status, and mission progress to ensure it is properly functioning.	CDH-1	N/A	Test	CDH	Met
CDH-1.3	The spacecraft communications system shall detect or provide modulation where the uplink and downlink carriers are phase modulated.	Phase modulation is robust and efficient, making it reliable for linking communication with Earth.	CDH-1	N/A	Test	CDH	Met
CDH-1.4	The spacecraft communications system shall include an omnidirectional antenna for tracking the relay spacecraft.	The relay satellite must be tracked every time it is within site of the spacecraft, which ensures effective data transmission.	CDH-1	N/A	Analysis	CDH	Met

CDH-1.5	The spacecraft communications system shall support a data rate of 30mbps.	The data rate is based on the volume of telemetry data expected within the duration of the mission.	CDH-1	N/A	Test	CDH	Met
CDH-1.6	The spacecraft shall collect telemetry data every 15 seconds and send the data during periods where the satellite is orbiting above the rover	Regular downlinks ensure mission control has up-to-date information on the spacecraft's status.	CDH-1	N/A	Analysis	CDH	Met
CDH-1.7	The link budget shall have a margin of at least 3 dB	A 3 dB margin is a common standard to ensure reliability of the communications system.	CDH-1	N/A	Test	CDH	Met
CDH-2.1	The subsystem shall include thermal management features to regulate operating temperatures within lunar temperatures of -233.15 C to -53.15 C.	Effective thermal management will prevent overheating or excessive cooling that can compromise performance and reliability.	CDH-2	N/A	Demonstration	CDH	Met
CDH-2.2	The subsystem must operate under low power consumption.	Minimized power consumption optimizes energy efficiency and reduces heat generation.	CDH-2	N/A	Demonstration	CDH	Met

CDH-2.3	The subsystem shall be radiation-hardened and must be able to withstand the space environment's radiation effects (TIDs, SEEs, and latch-ups)	The CDH subsystem must remain operational in the face of radiation that can induce sudden voltage or current sources or cause permanent faults in electronic components.	CDH-2	N/A	Demonstration	CDH	Met
CDH-2.4	The subsystem shall utilize conformal coatings on electronic components to enhance resistance against environmental hazards, such as moisture, dust, and temperature variations.	The CDH subsystem must be protected from short circuits, corrosion, or other damages to extend the lifespan and reliability of the subsystem.	CDH-2	N/A	Inspection	CDH	Met
CDH-3.1	The subsystem shall include Analog-to-Digital Converters (ADC) to convert analog signals into digital signals.	From the Nyquist Theorem, the given sampling rate ensures that all signals are accurately represented without loss of precision.	CDH-3	N/A	Test	CDH	Met
CDH-3.2	The subsystem shall provide a data storage capacity of at least 12 GB to accommodate for all expected telemetry and science data over the course of 14 lunar days.	Sufficient data storage capacity is necessary for storing, processing, and managing all data collected during the mission.	CDH-3	N/A	Inspection	CDH	Met
CDH-3.3	The Onboard Computer (OBC) shall have flash memory for storing critical operational and scientific data.	Flash memory allows the CDH subsystem to store operational and scientific data collected during the mission.	CDH-3	N/A	Inspection	CDH	Met
CDH-4.1	The subsystem shall include error-correction codes to protect data	The subsystem must be protected from SEUs.	CDH-4	N/A	Demonstration	CDH	Met

	transmission and storage.						
CDH-4.2	The subsystem must be able to detect high current flow through each subsystem and cycle power.	The subsystem must be protected from latch-up events.	CDH-4	N/A	Test	CDH	Met
CDH-4.3	The subsystem must have a redundant flash memory.	Since flash memory is susceptible to bit errors, adding redundancy ensures that the subsystem can perform routine updates and maintain reliability.	CDH-4	N/A	Inspection	CDH	Met
CDH-4.4	The subsystem must have a redundant Watchdog timer.	The subsystem must be protected from SEUs.	CDH-4	N/A	Inspection	CDH	Met
CDH-4.5	The subsystem must have a redundant communications payload.	The subsystem must guarantee continuous uplink commands and telemetry downlink data throughout the duration of the mission.	CDH-4	N/A	Inspection	CDH	Met
CDH-5.1	The subsystem shall monitor, record, and downlink the voltage and battery status data.	Monitoring power availability will prevent power-related failures during the mission.	CDH-5	N/A	Demonstration	CDH	Met

CDH-5.2	The subsystem shall monitor, record, and downlink all temperature sensor data.	Monitoring thermal conditions will prevent temperature-related failures.	CDH-5	N/A	Demonstration	CDH	Met
CDH-5.3	The subsystem shall monitor, record, and downlink attitude determination and positioning of the spacecraft.	Maintaining proper orientation and precise navigation will prevent the spacecraft from navigational errors, misalignment with the relay satellite, and inaccuracies in scientific data collection.	CDH-5	N/A	Demonstration	CDH	Met
CDH-5.4	The subsystem shall monitor, record, and downlink diagnostic data from onboard science instrumentation.	Quality science data is essential for mission success.	CDH-5	N/A	Demonstration	CDH	Met
CDH-5.5	The subsystem must activate power switches or deactivate components in response to critical errors or hazardous conditions.	The spacecraft must immediately respond to failures from potential damage.	CDH-5	N/A	Test	CDH	Met
CDH-6.1	The subsystem must be able to receive commands to enable semi-autonomous travel over the lunar surface.	Real-time driving cannot be achieved with a relay satellite under a circular polar orbit around the Moon.	CDH-6	N/A	Demonstration	CDH	Met

CDH-6.2	The subsystem must activate a hazard avoidance feature to prevent the spacecraft from traveling over steep slopes, large rocks, or other hazards.	The spacecraft must be safe from hazardous terrain.	CDH-6	N/A	Test	CDH	Met
CDH-6.3	The subsystem must perform power budget monitoring and management.	The spacecraft must ensure that the batteries are operating at its specified performance parameters.	CDH-6	N/A	Test	CDH	Met
CDH-6.4	The subsystem must deploy solar panels at optimal angles to maximize solar energy absorption for efficient battery charging.	Efficient battery charging supports long-term mission activities.	CDH-6	N/A	Test	CDH	Met
CDH-6.5	The subsystem must be able to turn on heaters or coolers to maintain components or subsystems within specific operational temperature ranges.	Temperature regulation is critical for preventing the spacecraft from experiencing thermal stress.	CDH-6	N/A	Test	CDH	Met
CDH-6.6	The subsystem shall activate payload instruments to collect science data after receiving commands or autonomously based on predefined parameters.	This capability supports the mission's science objectives.	CDH-6	N/A	Demonstration	CDH	Met

2.1.3.2. CDH Sub-Assembly Overview

The CDH Sub-Assembly Systems were identified and evaluated through a combination of trade studies, evaluations from analogous mission concepts, calculations from engineering, and subassemblies selected through the manufacturing and procurement modeling process (refer to the Manufacturing and Procurement Section).

Computing Subassemblies

The Onboard Computer serves as the brain of the system, handling data processing, command execution, and overall management. It has the highest TRL of 8, indicating its readiness for full-scale deployment and use in operational settings. Weighing 130 grams, the computer is compact with dimensions of 0.096 meters in length, 0.123 meters in width, and 0.017 meters in height, resulting in a total volume of 2.03E-04 cubic meters. The computer's power draw is 1.30 watts. This component is responsible for the operation of the entire system, ensuring that data is processed accurately and commands are executed correctly. This module encapsulates all computing functionality. ([satsearch](#), 2024)

The Guidance, Navigation, and Control System (GNC) is a critical component that operates in collaboration with the mechanical subsystem to maintain stability, orientation, and maneuverability. The system responds to environmental conditions by processing sensor data and sending commands to adjust movements in uneven terrain. The components of the GNC System, such as the Honeywell HG1700 IMU and the 2-Axis Coarse Sun Sensor have high TRL levels of 8-9. The GNC System is distributed across various components with the Honeywell component contributing 900 grams, reading to a total mass between 1 and 2 kilograms. The GNC system dimensions vary by component. The Inertial Measurement Unit (IMU) , for example, has dimensions of approximately 0.089 m x 0.089 m x 0.043 m. The IMU's volume is approximately 0.00032 cubic meters. The Honeywell system draws approximately 5 watts, leading to a combined maximum power draw between 10 to 15 watts. Refer to the Mechanical Subsystems Section for specific sources. This information is shown in a more organized way in the chart below.

Table 24. Computing Subassemblies Overview Chart

Computing Subassemblies Overview									
Subassembly	Description of Function	Requirement	TRL	Mass [g]	Length [m]	Width [m]	Height [m]	Total Volume [m ³]	Max Power Draw [W]
Onboard Computer	Responsible for data handling and processing, command execution, and overall system management	CDH-3, CDH-5, CDH 6	8	130	0.096	0.123	0.017	2.03E-04	1.30
Guidance, Navigation, and Control (GNC)	Responsible for the overall navigation of the rover.	CDH-2, CDH-6	-	900	0.089	0.089	0.043	3.41E-04	10

Table 25. Onboard Computer System Chart

Onboard Computer System (OBC)					
Criteria	Explanation	Grade	Weight	ICEPS Spacecraft System Core All-In-One	Berlin Space Technologies Command and Data Handling System (CDH)
Power & Performance	The OBC should be able to process data efficiently with minimum downtime	10 = high, 5 = medium 1 = low 0 = Fail	40%	10	10
Radiation Tolerance	The OBC should be tolerant against radiation events, such as SEEs, latch-ups, and TID effects	10 = high, 5 = medium 1 = low 0 = Fail	10%	0	9
Temperature	Must be able to operate under lunar temperatures	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	4
Memory & Storage	Must be able to transmit real-time data and store all relevant data aboard the rover and on earth	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	5
		TOTALS:	100%	78.00%	71.00%

Flight Software Subassemblies

The Core Flight Software is a crucial element of the data capture and analysis process. The Centralized Control Design Pattern is used to centralize all command and control under one global point of access, reducing the need to adopt various software subassemblies and encapsulating control logic ([J.S. Fant](#) et al. 2011)

VxWorks (RTOS) was selected for its real-time performance and context switch time of under 1 microsecond (“VxWorks” 2024). A more detailed trade study is conducted in figure #. The Core Flight System (cFS) is the industry standard for its modular architecture and minimal memory overhead as low as 50 KB RAM (NASA 2024). The Power Distribution Unit (PDU) was selected for its conservative power consumption at only 8 Watts, as demonstrated in systems used in the Mars Curiosity Rover (NASA 2024). The Mission Operations System (MOS) and Ground Data System (GDS) support planning, command, and data analysis with capacities up to 30 Mbps (NASA 2024). Finally, the Uninterruptible Power Supply (UPS) is crucial in supporting continuous operations, providing 20 Watts of backup power (NASA 2024).

Table 26. Flight Software Subassemblies Overview Chart

Flight Software Subassemblies Overview									
Subassembly	Description of Function	Requirement	TRL	Mass [g]	Length [m]	Width [m]	Height [m]	Total Volume [m³]	Max Power Draw [W]
VxWorks Real-time operating system (RTOS)	Infrastructure for managing hardware	CDH-1.6, CDH-2.3	8	600	0.16	0.12	0.06	0.00115	6
Core Flight System (cFS)	Flight software framework	CDH-6.1	8	1200	0.25	0.20	0.15	0.0075	10
Power Distribution Unit (PDU)	Monitors and controls power distribution	CDH-6.3	8	1000	0.25	0.20	0.15	0.0075	8
Mission Operations System (MOS)	Supports Flight planning and command	CDH-1.1	8	800	0.20	0.15	0.10	0.003	6
Ground Data System (GDS)	Manages and analyzes data	CDH-1.2	7	1500	0.30	0.25	0.15	0.01125	10
Uninterruptible Power Supply (UPS)	Provides continuous power supply	CDH-6.5	9	2000	0.30	0.25	0.20	0.015	20

A trade study was conducted over the Core Flight Software to evaluate the Given the asymmetric importance of reliability and performance in a lunar environment and the ability of the roger to operate autonomously with robust fault-tolerance systems, VxWorks was determined at the optimal provider (refer to Figure #). VxWorks has been used in multiple NASA missions such as the Mars Science Laboratory (Curiosity Rover) where it demonstrated high reliability and extensive fault-tolerant features. Its deterministic architecture is built on priority-based scheduling and multi-core processors that enable parallel processing and efficient data management ([Windriver](#) 2024). State-of-the-art Memory Management Units (MMU) and security certifications like ARINC 653 ensures the system meets rigorous safety requirements. This combination of data protection and efficient processing makes the VxWorks RTOS system the optimal foundation for the software interface ([Mistral](#) 2024).

Table 27. Core Flight System Trade Study

Core Flight System (cFS)						
Criteria	Explanation	Grade	Weight	NASA Core Flight Executive (cFE)	FreeRTOS	VxWorks (RTOS)
Power & Performance	The system must efficiently process data with minimal downtime and operate under low power conditions (CDH-2.2).	10 = high, 5 = medium 1 = low 0 = Fail	30%	7	9	8
Reliability and Fault Tolerance	The software interface must incorporate redundancy features (CDH-4.1 to CDH-4.5) to ensure continuous operations and resist against Single Event Effects (SEEs).	10 = high, 5 = medium 1 = low 0 = Fail	40%	9	7	10
Ease of Integration	The software system must integrate smoothly with hardware interfaces to monitor power budget (CDH-6.3) and various subsystem performance (CDH-5.1).	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	9	8
Memory & Storage	While the Onboard Computer (OBC) holds the majority of data storage capacity, the software system must provide sufficient memory capacity (CDH-3.2) and integrate redundant systems for error correction (CDH-4.1).	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	9	8

Scalability and Flexibility	The system must scale to adapt to different missions to reduce costs. This system should allow for semi-autonomous travel (CDH-6.1) and effectively perform commands without human input (CDH-6.6).	10 = high, 5 = medium 1 = low 0 = Fail	5%	9	7	8
		TOTALS:	100%	80.50%	81.00%	88.00%

Telemetry Systems Subassemblies

The chart below presents a summary of telemetry system subassemblies used for satellite communications. Each subassembly is listed along with its description, the relevant requirement, Technology Readiness Level (TRL), mass, dimensions (length, width, height), total volume, and maximum power draw.

The X/S Transceiver is a critical component of the system designed for both uplink and downlink communications. Utilizing the EWC27 and OPT27-SRX technologies, it facilitates uplink via the S band and downlink through the X band. This ensures reliable communication between the spacecraft and ground stations. With a Technology Readiness Level (TRL) of 6, the transceiver is well-advanced in its development and has been tested in relevant environments. The transceiver has a mass of 320 grams, and its compact design measures 0.096 meters in length, 0.090 meters in width, and 0.039 meters in height, occupying a total volume of 3.37E-04 cubic meters. It requires a maximum power draw of 3.98 watts. ([satcatalog](#), 2024)

The S-Band Antenna is engineered for tracking relay satellites, ensuring continuous communication links. With a TRL of 7, this component is highly mature and has been proven in operational environments. Weighing 100 grams, the antenna is designed with a length of 0.051 meters and width and height of 0.051 meters and 0.000 meters, respectively, indicating a flat profile. Its volume is minimal, at 2.60E-08 cubic meters, and it has an extremely low power draw of 0.002 watts. ([AAC-Clydespace](#), 2024)

The S Receiver plays a pivotal role in the system by receiving signals for relay tracking. It shares a TRL of 7, indicating its high reliability and performance in realistic conditions. The receiver is heavier than the antenna, with a mass of 200 grams. Its dimensions are 0.135 meters in length, 0.050 meters in width, and 0.025 meters in height, resulting in a volume of 1.69E-04 cubic meters. The receiver operates with a maximum power draw of 1.50 watts. ([satcatalog](#), 2024)

Designed for uplink commands, the S Band Omni Antenna is crucial for sending instructions to the spacecraft. With a TRL of 6, the component is in the advanced stages of development, suitable for operational use. Each antenna weighs 280 grams and has compact dimensions of 0.020 meters in length, width, and height, with a total volume of 8.00E-06 cubic meters. Its maximum power draw is a minimal 0.003 watts. ([satsearch](#), 2024)

The X Band Downlink Antenna is essential for the downlink of science and telemetry data, facilitating the transmission of valuable information from the spacecraft to ground stations. With a TRL of 7, the antenna is well-proven in its capabilities. It has a mass of 140 grams and larger dimensions compared to other antennas, measuring 0.200 meters

in length, width, and height, with a volume of 5.20E-03 cubic meters. The antenna requires 0.07 watts. ([anywaves](#), 2024)

Table 28. Telemetry Subassemblies Overview Table

Telemetry Subassemblies Overview									
Subassembly	Description of Function	Requirement	TRL	Mass [g]	Length [m]	Width [m]	Height [m]	Total Volume [m ³]	Max Power Draw [W]
X/S Transceiver (2x)	EWC27 + OPT27-SRX; Uplink S band and downlink X band	CDH-1, CDH-4	6	320	0.096	0.090	0.039	3.37E-04	3.98
S-Band Antenna	Track relay satellite	MR-8	7	100	0.051	0.051	0.000	2.60E-08	0.002
S Receiver	Receiver for relay tracking	MR-8	7	200	0.135	0.050	0.025	1.69E-04	1.50
S Band Omni Antenna (x2)	For uplink commands	CDH-1, CDH-4	6	280	0.020	0.020	0.020	8.00E-06	0.003
X Band Downlink Antenna (x2)	For downlink of science and telemetry data	CDH-1, CDH-4	7	140	0.200	0.200	0.130	5.20E-03	0.07

A trade study was conducted to evaluate the X/S transceiver due to its criticality in ensuring the smooth transition of data throughout the mission lifecycle. Given the critical need for compact design, power efficiency, and proven reliability in the space environment, the Syrlinks EWC27+OPT27-SRX was selected as the optimal choice (refer to Figure #). The Syrlinks transceiver has been successfully deployed in NASA missions, particularly those with stringent power and mass constraints. Its dual telemetry and telecommand (TT&C) capabilities makes it reliable for lunar environments (Smith et al. 2022). It leverages a state-of-the-art low-power design that balances performance with energy efficiency. It was used in the European Space Agency's (ESA) CubeSat missions where it maintained high data integrity under extreme conditions (Jones & Harris 2023).

Table 29. X/S Transceiver Antenna Trade Study

X/S Transceiver Antenna						
Criteria	Explanation	Grade	Weight	Syrlinks EWC27+OPT27-SRX	Continental Electronics (CEC)	Cobham SATCOM SAILOR 100 GX
Power Efficiency	The transceiver must minimize power consumption while maintaining data throughput under low-power conditions (CDH-2.2).	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	7	6
Reliability and Fault Tolerance	The transceiver must incorporate redundancy to ensure continuous operation, even during single event upsets (SEEs) (CDH-4.1 to CDH-4.5).	10 = high, 5 = medium 1 = low 0 = Fail	40%	8	9	9
Ease of Integration	The transceiver must integrate smoothly with the CDH system, ensuring effective communication with minimal hardware modifications (CDH-5.1 and CDH-6.3).	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	8	8
Mass & Size Constraints	The transceiver must be compact and lightweight to minimize the impact on the spacecraft's overall mass and volume budget (CDH-1.2).	10 = high, 5 = medium 1 = low 0 = Fail	10%	9	8	7
Technology Readiness Level (TRL)	The transceiver should be mature and proven in operational environments to reduce risk (CDH-7.1).	10 = high, 5 = medium 1 = low 0 = Fail	5%	7	9	10
		TOTALS:	100%	82.00%	81.50%	78.00%

2.1.3.3. CDH Subsystem Recovery and Redundancy Plans

A survey on fault-tolerance and recovery techniques conducted by the National Center for Supercomputing Applications (NCSA) suggested that checkpointing and replication were the two most effective methods for large-scale cluster computing. Checkpointing and Rollback Recovery calibrates systems with multiple states to fall back on in case of failure. Replication is the process of a second machine copying all inputs from primary nodes and independently generating them onto an “identical system running its own copy of all necessary software” ([Treaster](#) 2005). These processes are reflected in the recovery systems in the CDH subsystem.

Software Recovery and Redundancy

The CDH system will incorporate software-level bit error correction with Hamming codes to protect data transmission and storage from radiation. This software-level redundancy feature works by utilizing a very small amount of extra storage to encode additional parity bits that enable the detection and correction of single-bit errors within data blocks. This ensures that the location of corrupted bits can be identified and corrected to maintain the integrity of the transmitted and stored data. ([3Blue1Brown](#), 2021)

The code for the hamming code implementation is provided in Python below. ([GeeksForGeeks](#), 2022)

```
def calcRedundantBits(m):
    """
    Determines the number of redundant bits 'r' needed for Hamming Code given 'm' data
    bits.

    Returns: int: Number of redundant bits required.
    """
    for i in range(m):
        if(2**i >= m + i + 1):
            return i
```

```
def posRedundantBits(data, r):
    """
    Inserts redundant bits at positions that are powers of two in the data sequence.

    Returns: str: Bit sequence with placeholders for redundant bits.
    """
    j = 0
    k = 1
    m = len(data)
```

```

res = ''
for i in range(1, m + r+1):
    if(i == 2**j):
        res = res + '0'
        j += 1
    else:
        res = res + data[-1 * k]
        k += 1
return res[::-1]

```

```

def calcParityBits(arr, r):
    """
    Computes and inserts parity bits at their respective redundant positions in the
    sequence.

    Returns: str: Bit sequence with calculated parity bits in place.
    """
    n = len(arr)
    for i in range(r):
        val = 0
        for j in range(1, n + 1):
            if(j & (2**i) == (2**i)):
                val = val ^ int(arr[-1 * j])
        arr = arr[:n-(2**i)] + str(val) + arr[n-(2**i)+1:]
    return arr

```

```

def detectError(arr, nr):
    """
    Identifies the position of a single-bit error in the received Hamming Code
    sequence.

    Returns: int: Position of the error (0 if no error is detected).
    """
    n = len(arr)
    res = 0
    for i in range(nr):
        val = 0
        for j in range(1, n + 1):
            if(j & (2**i) == (2**i)):
                val = val ^ int(arr[-1 * j])
        res = res + val*(10**i)
    return int(str(res), 2)

```

A sample setup function for this process is provided below

```
def setupHamming(data):
    """
    Initializes the Hamming Code sequence with redundant bits and parity bits.

    Returns: str: The Hamming Code sequence.
    """
    m = len(data)
    r = calcRedundantBits(m)
    arr = posRedundantBits(data, r)
    arr = calcParityBits(arr, r)
    return arr
```

Figure 20. Software Recovery And Redunancy

The mission control software architecture ensures that data is processed efficiently and to minimize downtime in the event of a failure. The Backend Server is designed on a Kubernetes Architecture which groups functionalities into individual pods, or microservices, that operate independently of each other. As opposed to traditional centralized Cloud Systems, Kubernetes is ideal for complex computing tasks with large databases and processing intervals. This distributed processing enables resilient disaster recovery through pod replication that prevents Single Point of Failures ([\[x\]cube LABS](#) 2024). Persistent storage supports data restoration in the event of failure. Kafka Services such as the Ingress Gateway routes large data traffic efficiently to appropriate destinations. Based on an experiment modeling performance based on resource management capabilities, single containers were deployed in less than a second up to three seconds, with termination time approximating in the order of a tenth of a second. However, there are still interferences from resource contention and high network latency which can have substantial impacts on its architecture ([V. Medel](#) 2018). The network performance and pod lifecycle will be continuously monitored by the team to regulate performance. Refer to Figure # for a sample of the architecture.

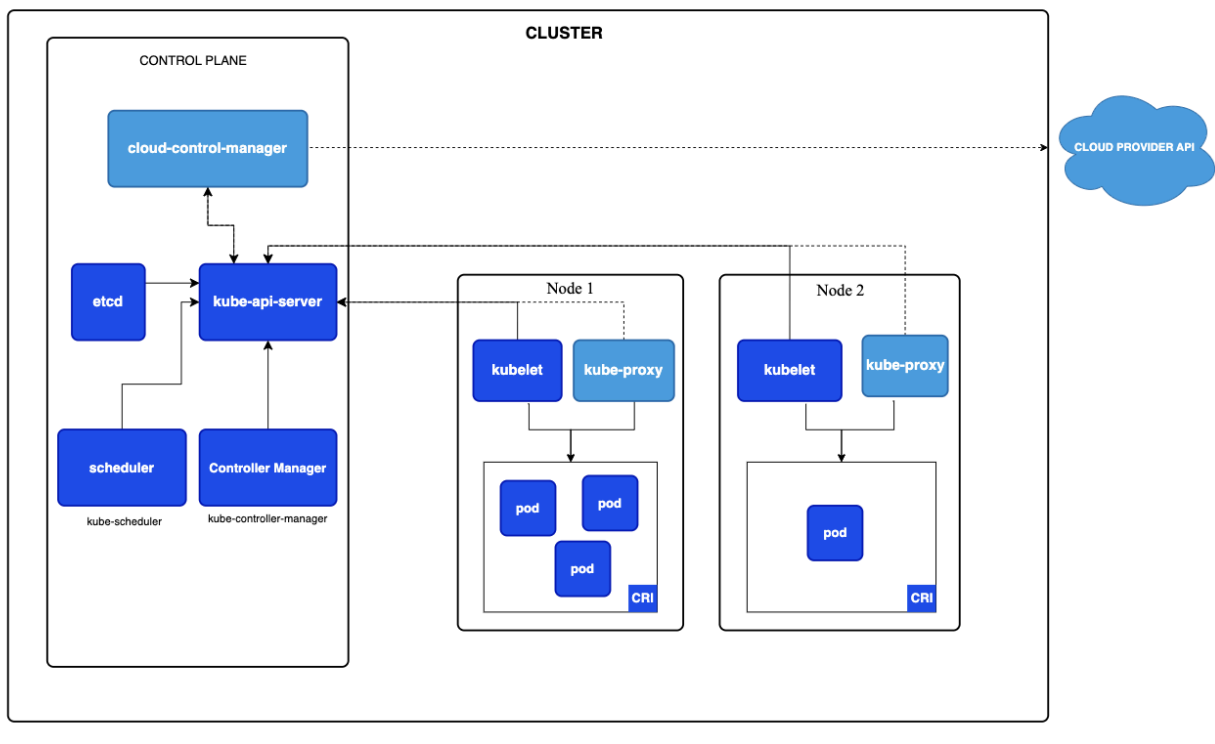


Figure 21. Kubernetes Architecture for a redundant backend architecture ([kubernetes 2023](#))

Hardware Recovery and Redundancy

The Onboard Computer (OBC) has several built-in redundancy systems such as fault-tolerant design which leverages advanced techniques to protect data. For example, the Triple-Modular Redundancy (TMR) System runs three identical processes in parallel and uses majority voting to determine the optimal output to enhance fault tolerance and selects the highest quality piece of data ([AAC Clyde Space](#)). This is consistent with the Replication Approach endorsed by the NCSA Survey and has proven effective for protecting systems against single-event upsets (SEUs). The OBC also contains redundant flash storage in the event of data loss to preserve any data we have previously collected.

Consistent with the NCSA Survey, the CDH system also contains a checkpointing system that saves the system's state at regular intervals, which enables "high reliability ensuring data integrity and continuity of operations" with only a "2-5% performance overhead" in space mission switch low computational resources and high cost of failure (Elnozahy 2004).

Autonomous Failover Timing will be implemented to take over a functionality in the event of a failure, without human intervention. This is crucial during Blackout Periods

when operators cannot communicate with the CDH system. Two timer systems are present: 1) Cold and Hot Spares and 2) A watchdog timer. Hot spares can immediately replace a function in the event of a failure while cold spares perform after manual activation. Hot spares with autonomous failover can achieve “switchover times as low as 10 milliseconds” ensuring that the switch causes minimal disruptions (Johnson, B. W. 1989). A watchdog timer prevents system lockups by detecting errors and automatically resets the system. This ensures that, should a software or hardware component fail or begin producing repeatable errors, the system will be able to recover from these errors and return to proper functionality. This will not only assure that the CDH components are in full working order, but all of the systems which are connected to CDH. A watchdog timer is defined as: A specialized timer that resets the system if a fault is detected. The timer expects regular signals from the software indicating normal operation. If the signal is not received within a predefined time frame, the watchdog assumes a fault and initiates a system reset. (embedded.com, 2001). The OBC contains a unit that detects high current flow through each subsystem and power cycle if necessary to ensure no electronic components are short-circuited and receive more than the recommended wattage.

2.1.3.4. CDH Subsystem Manufacturing and Procurement Plans

Mission VALKYR's Command and Data-Handling (CDH) Subsystem components are primarily sourced from Syrlinks, AAC Clyde Space, Continental Electronics, Anywaves, SpaceQuest, and PlaneWaves. The Manufacturing Strategy for this system is developed based on the NASA Supply Chain Management Framework ([Galluzi et al 2006](#)). This process emphasizes collaborative vendor management and a top-level analysis of the supply chain. Suppliers such as CEC and Syrlinks were selected based on historic experiences with NASA missions, such as the Perseverance Rover ([Lain 2013](#)). Previous experiences initiate strong relationships across suppliers and encourages collaborative approaches during the supply chain lifecycle, reducing lead times and increasing material compatibility under the "Collaborative planning, forecasting, and replenishment" (CPFR) Framework.

Training a Predictive Model to Optimize Supplier Selection

Selection of optimal suppliers involves evaluating multiple factors while complying with NASA's policy of non-competition with the private sector, as stated in NPD 1370.1. To conduct initial forecasting of the supply chain, simulations were run to test supply chain configurations against future scenarios to enable more dynamic performance through early and rapid risk identification and mitigation ([Tannock et al. 2007](#)). Mission VALKYR took a comprehensive approach to optimizing the supplier selection process for the CDH subsystem by leveraging predictive modeling techniques, consistent with the model simulation procedures of the SCM framework. By leveraging historical data from NASA's Procurement and Data View (NPVD), the team determined the most efficient and reliable suppliers by training a model on the data to predict and craft robust manufacturing and procurement plans ([Charlton 2022](#)).

Data was sourced from NASA's NPVD, which includes a 2129-sized sample set from the 2024 Fiscal Year. The primary parameters in consideration are price, lead time, and quality based on the SCM model which evaluates suppliers on "efficient, agile, and cost-effective" standards (AIAA 2006).

Relevant features were extracted, encoded, and normalized to prepare for use in the predictive model. Due to limited access to direct quotes from suppliers, an analogous calculation approach was used based on the dimensions and volume data to estimate the pricing of each component. Award Value determines the reliability of each supplier, and a time parameter is calculated as the difference between Award Date and Completion Date. Several assumptions were made to streamline the decision-making process, including the following:

- All items are in stock
- All items are compatible with other systems

- All items are of acceptable quality
- All items adhere to high performance standards
- No significant delays that could cancel operations

```
def create_feature_vector(suppliers_info, preprocessor):
    """
    Create a feature vector aligned with the model's input features.
    """
    vectors = []
    for item in suppliers_info:
        for supplier in item['suppliers']:
            data = {
                'Total Award Value': supplier['total_award_value'],
                'Lead Time': supplier['lead_time'],
                'Place of Performance State': supplier['location']
            }
            data_df = pd.DataFrame([data])
            processed_data = preprocessor.transform(data_df)
            vectors.append((supplier['supplier'], processed_data[0]))
    return vectors

def select_best_supplier(suppliers_info, model, preprocessor):
    """
    Select the best supplier based on the model's prediction.
    """
    best_suppliers = []

    for component in suppliers_info:
        best_supplier = None
        best_value = -np.inf # Initialize with negative infinity
        feature_vectors = create_feature_vector([component], preprocessor)
        for supplier_info, vector in zip(component['suppliers'], feature_vectors):
            score = model.predict([vector[1]])[0] # Get the first (and only) prediction
            if score > best_value:
                best_value = score
                best_supplier = {
                    'component': component['component'],
                    'supplier': supplier_info['supplier'],
                    'location': supplier_info['location'],
                    'score': score
                }
        best_suppliers.append(best_supplier)

    return best_suppliers
```

Figure 22. Code block for selecting the optimal supplier by scoring the vector aggregation of lead time, total award value, and location of the manufacturing site.

A Random Forest Regressor Model was chosen for its “high prediction accuracy across a variable range of data” and reduced prediction error due to Out-of-Bag Error

Estimates that enable internal error evaluations of the same test sets ([Segal 2003](#)). The model was trained using a 80/20 split, consistent with industry standards. Hyperparameter sizing with the Grid Search Algorithm was used to standardize the data and increase reliability (Figure #)

```
def tune_model(X_train, y_train) :
    """
    Hyperparameter
    """
    param_grid = {
        'n_estimators': [100, 200, 3000], # calibrate number of trees
        'max_depth': [10, 20, 30, 40, 50], # calibrate max depth of trees
        'min_samples_split': [2, 5, 10], # calibrate min samples to split a node
        'min_samples_leaf': [1, 2, 4], # calibrate min samples in a leaf node
        'bootstrap': [True, False] # randomly sample original dataset
    }
    rf = RandomForestRegressor(random_state=42)
    grid_search = GridSearchCV(estimator = rf, param_grid = param_grid,
                               cv = 3, n_jobs = -1, verbose = 2)
    grid_search.fit(X_train, y_train)

    return grid_search.best_params_

def train_model(data, random_state, test_size, preprocessor):
    """
    Train a Random Forest Regressor model to predict the total award value.
    """

    features = preprocessor.transform(data)

    scaler = StandardScaler()
    normalized_features = scaler.fit_transform(features)

    X_train, X_test, y_train, y_test = train_test_split(normalized_features, data['Total
Award Value'], test_size=test_size, random_state=random_state)
    model = tune_model(X_train, y_train) # tune the model
    model.fit(X_train, y_train) # fit the model to the training data

    return model, X_test, y_test
```

Figure 23. Code blocks for hyperparameter sizing the model with Grid Search and training the model with the Random Forest Regressor

After this procedure, Continental Electronics, Anywaves, Spacequest, L3 Harris Technologies, and MicroChip Technology Inc were identified as the primary contenders. Each supplier scored between the range of 9.155e+09 and 9.299e+09 calculated by calibrating scores across three dimensions (Lead times, Cost, and Location).

The trained model was then used to simulate the flow of resources and identify inefficiencies and potential bottlenecks in the CDH supply chain ([Lupton and Allwood 2017](#)). The diagram shows the flow and dependencies of components across various suppliers and manufacturing facilities to their final location. The starting nodes are the selected suppliers derived from

Component Supplier Flow

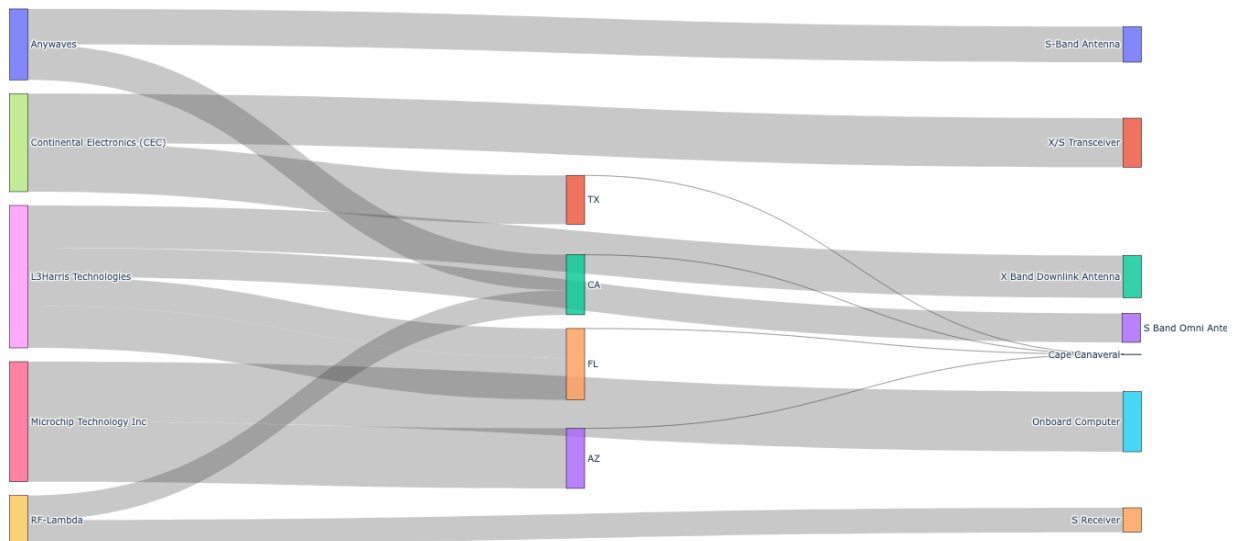


Figure 24: Sankey Diagram Visualization of the CDH supply chain with nodes: component, manufacturing facilities, supplier, and the final destination.

The Random Forest Regression outline above, while robust in theory, acknowledges that it is not entirely accurate and may oversimplify the complexities inherent in supply chain operations. Factors such as real-time supplier performance variations, unforeseen logistical challenges, and the dynamic nature of market demands are not fully captured in this model. However, predictive modeling techniques provide a practical framework for initial assessments based on analogous missions and historic NASA suppliers and identify major bottlenecks on resources early on. This enables informed decision-making aligned with NASA industry standards while minimizing resource expenditures. In the future, scenario-based event simulation techniques will be favored for increased accuracy and more realistic behavior predictions. Specialized models for inventory management, transportation, and supplier performance will be developed and combined in an ensemble approach to provide more holistic optimization ([Tannock et al. 2007](#)).

S-Band and X-Band Antennas

L3Harris has sustained a six-decade partnership for electronic technologies, dating from Apollo to the International Space Station missions. Based on the Nancy Grace Roman Space Telescope which sourced its antenna components from L3Harris, the average lead time extends around 12 to 16 weeks (L3Harris, 2024). They will supply the S-Band and X-Band Antennas which have a history of supplying critical communication systems for NASA's Tracking and Data Relay Satellite since the program's inception (L3Harris 2024).

Onboard Computer

AAC Clydespace is a global leader in space satellite manufacturing, with historic partnerships with lunar missions such as the Nova-C Lander of NASA's Commercial Lunar Payload Services (CLPS), to supply efficient and adaptable power for wide-range satellite communications (Clydespace 2024). Lead times range from 12 to 14 weeks for CubeSat structures and battery systems due to extensive testing periods for reliable integration (AAC Clyde Space 2024). They will supply the Onboard Computer which has historically been used in NASA missions, holds advanced memory scrubbing, fault tolerance systems, and error detection critical for sensitive space environments where robust error handling systems are critical.

X/S Transceiver

Continental Electronics (CEC) will supply the X/S transceiver for the VALKYR mission. Continental Electronics has a lead time of 14 to 18 weeks. They were chosen because of their extensive experience with NASA, which attests to their reliability and high quality. CEC will provide high-quality and reliable transceivers that have been successfully utilized in previous NASA missions, ensuring they meet the rigorous demands of deep space communications. (CEC 2017).

S Receiver

RF Lambda will supply the S Receivers for the VALKYR Radio-Frequency (RF) Communications System. RF Lambda specializes in high-end RF components, modules, and systems for various aerospace applications to support efficient communication. NASA's Small Spacecraft Technology (SST) program previously funded projects to advance RF communication systems ([NASA](#) 2024). With a lead time of 12-16 weeks, RF Lambda is the optimal choice to supply the S-Receiver.

Alternative Suppliers

Mission VALKYR is equipped with alternative partnership scenarios to prepare for unexpected cancellations and lead times from primary contractors, which is especially poignant due to importing externally from Clydespace and the frequent delays of

L3Harris. VALKYR has selected a viable candidate for alternative procurement options: Anywaves.

Anywaves, with a lead time of 10 to 14 weeks, was selected as a backup due to its established track record with NASA, underscoring its reliability and high-quality standards. Their antennas have been proven in previous NASA missions, ensuring dependable performance. As a result, Anywaves will deliver high-quality and reliable antennas that meet the stringent requirements of space missions (Anywaves 2024).

Table 30. CDH Subsystem Alternate And Primary Suppliers

Component	Primary Supplier	Alternative Supplier	Est. Lead Times
X/S Transceiver (2x)	Continental Electronics (CEC) - extensively used by NASA for deep space communications. Specialize in X-band and S-band transmitters	Syrlinks - The Syrlinks EWC27+OPT27-SRX is an X/S transceiver designed for small satellites, offering both telemetry and telecommand (TT&C). Designed for 2-year missions. Used by NASA in the past	Syrlinks: 12-16 weeks CEC: 14-18 weeks
S-Band Antenna	Anywaves - Offers high performance S-band antennas that are specifically designed for telemetry, tracking, and command (TT&C). Have been successfully deployed in numerous space missions by NASA	AAC Clyde Space - considered a global leader in manufacturing solutions for small satellite missions and have been used by NASA in the past. The PULSAR-SANT-A and PULSAR-SANT C S-Band patch antennas are designed to be mounted on the nadir facing side of a 3U CubeSat. A wide beamwidth ensures satellite communication through a wide range of elevation angles.	AAC Clyde Space: 8-12 weeks Anywaves: 10-14 weeks
S Receiver	RF-Lambda - Provides a variety of proven, low-noise receivers and have been used by NASA in the past.	SpaceQuest - a satellite communications and data manufacturer that has been used by NASA in the past. The RX 2000 is an efficient space qualified FM S Band receiver for microsats and small satellites. The RX 2000 is an efficient space qualified FM S Band receiver for microsats and small satellites.	SpaceQuest: 10-14 weeks RF-Lambda: 12-16 weeks

S Band Omni Antenna (x2)	L3Harris Technologies - has a current S Band Omni Antenna (AS-48915 Series Omnidirectional Conical Spiral Antenna) designed for S Band telemetry that has been used in several NASA missions	PlaneWave - provides high-quality telescopes and optical systems for astronomical and space communication workloads. Used by NASA in the past. The PW2020-000 is a high-performance uplink antenna designed for TT&C applications in harsh space environments. It features excellent axial ratio over the entire frequency band, making it ideal for demanding and reliable space communication links.	PlaneWave: 12-16 weeks L3Harris: 14-18 weeks
X Band Downlink Antenna (x2)	L3Harris Technologies - Known by NASA to provide robust downlink antenna, including X-Band, and has been used in the past by NASA	Anywaves - Offer high performance X-band antennas specifically designed for downlink and have been used in the past by NASA. Anywaves' High Gain X-Band antenna is used for the payload telemetry subsystem. It downlinks the relevant data from the payload to the ground station and provides high gain in order to enable a high data rate link.	Anywaves: 10-14 weeks L3Harris: 12-16 weeks
Onboard Computer	AAC Clyde Space - Used in various NASA missions in the past and considered a global manufacturing leader by NASA. The Sirius TCM LEON3FT has advanced error detection and correction in its design. The real-time operating system runs on a LEON3FT fault-tolerant soft processor, compliant to IEEE 1754 SPARC v8, and fault tolerance is secured by using triple-modular redundancy on FPGA and memory scrubbing.	Microchip Technology Inc - selected by NASA's Jet Propulsion Lab to develop an HSPC processor specifically for lunar missions.	AAC Clyde Space: 8-12 weeks Microchip: 12-16 weeks

Procurement Plans and Integration Testing

Mission VALKYR adheres to the International Traffic in Arms regulations (ITAR) and favors domestic partners for component manufacturing. Due to its proximity to the Kennedy Space Center (KSC) and Cape Canaveral, the Florida Space Coast is identified as the primary location for CDH Component manufacturing. Geographic proximity facilitates consistent collaboration throughout the manufacturing and integration lifecycle. The Space Coast supports infrastructure for rigorous testing and launch operations with limited travel costs. In addition, VALKYR facilitates collaborative approaches across suppliers to increase the effectiveness of systems integration.

Suppliers are also selected based on proximity to the Kennedy Space Center (KSC) to reduce travel times and encourage an incremental testing approach.

Integration will adhere to the incremental integration approach with continuous testing and verification. Quality Assurance personnel will be introduced to ensure reproducibility of results through verification testing and demonstration experiments (refer to the following section). An additional 13 technician personnel will be hired with a base salary of \$60,000 to assist with increasing manufacturing demands. Specialized manufacturing procedures may be necessary for the On-Board Computer system due to heavy dependencies of external subsystems on this unit. Extra radiation-hardened components and specialized shielding materials will be necessary to withstand the harsh lunar environment. Special sealing and coating techniques are also requested from manufacturing partners. Specialized training required of personnel justifies the significant increase in technician personnel for a diverse palette of technical expertise.

2.1.3.5. CDH System Verification Plans

Two primary verification methods are applied: Testing and Demonstration. Simulation testing and parallel processing has demonstrated high performance for preventing data bottlenecks for large-scale, electromagnetic simulations ([Wiley et al. 2002](#)).

Testing

The Mission adheres to several NASA standards for integration testing to ensure the highest quality materials. The System Integration Testing Methodology (SIT). This procedure involves an incremental testing approach that encourages consistent testing and simulations using code stubs to avoid integration all-at-once. The Hardware-in-the-loop (HIL) simulation technique enables real-time unit testing of embedded system elements by synthetically generating input signals, reducing costs and increasing reproducibility of results ([Ledin 1999](#)). The Systems Under Test Framework (SUT) will be used to develop real-time simulation models of operational environments with I/O interfaces for synthetic RIMFAX data, for example with stub programs. The Adams-Bashforth Second Order Algorithm with fixed-time step sizes is most suitable for real time continuous system simulations due to the reduction in truncation errors and ability to predict the next state of the system based on the current state (Ledin 1999).

Performance verification techniques will be conducted through parallelization of computational cycles through unstructured mesh generations, which will create more accurate graphical representations of the complex lunar subsurface geometries from raw sensor and image data (Eiley et al. 2002). The NASA JIGSAW(GEO) will be used to produce high-quality Delaunay triangulations and measure the quality of data collection, storage, and processing ([Engwirda et al. 2017](#)). To enhance testing efficiency, computational domains will be partitioned into sub-domains that distribute tasks across different processors to manage and evaluate computations effectively (Wiley et al. 2002). This enhances the scalability of the CDH system by enabling it to handle increasingly larger datasets effectively. Algorithm efficiency will be measured based on the speed-up to processor ratio, which measures ability to handle a larger number of elements and tasks efficiently with limited additional computing power.

Demonstration

Tolerance of the spacecraft to extreme vacuum and space conditions must be experimentally validated before flight, in alignment with the NASA-STD-7002 standards “Payload Test Requirements” ([NASA 2023](#)). Thermal vacuum testing will be the primary approach to demonstrating environmental resilience and component stability through computer controlled cooling and thermal cycling systems ([J. Kousal et al. 2019](#)). The

demonstration has a modest cost with 700 euros (765.17 USD) for all system components and 2000 euros (or 2186.19 USD) for 120 liters of nitrogen and hot air for testing, amounting to 10,000 euros (10,930.95 USD) in total. The temperature control system is manipulated by interchanging liquid nitrogen with hot air through a metal one-way valve system ([J. Kousal et al.](#) 2019). The CDH system will endure 10 temperature cycles between +70°C and -70°C with various operations tested including data acquisition, data handling, data management, error handling, and communication across subsystems. This procedure will endure until all potential failures are identified and accounted for. Referred to Figure # for more detailed verification experiments for each core CDH requirement.

Table 31. CDH Subsystem Verification Matrix

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
CDH-1	The spacecraft shall receive uplink commands from Earth and downlink telemetry data via a relay satellite	Test	An end-to-end laboratory-based satellite simulator will replicate the entire communication chain from the spacecraft to the ground station. This reduces the cost of running a real simulation while accurately representing the data flow.	The simulation will be run through an artificial environment with a satellite simulator like the SIMSAT system to represent the CDH and communication subsystems. The simulation will be processed with real-time data and command execution. Deliberate environmental anomalies like extreme temperatures and signal interference will also be implemented to induce error handling for extreme conditions.
CDH-2	The subsystem shall operate reliably in the lunar environment for 14 lunar days.	Test	A Thermal Vacuum environment will be induced to simulate to accurately replicate the extreme temperature fluctuations and vacuum conditions on the lunar surface. This is the industry-standard for qualifying spacecraft components for environments.	The test will be performed over an extended period of time to verify long-term performance. The CDH system will be subjected to stress testing including simulations of thermal cycling and extreme vacuum conditions. After the simulation, potential failures like material degradation and electronic component failure will be identified and mitigation strategies developed.
CDH-3	The subsystem shall collect, manage, and store analog and digital data.	Demonstration	A multidisciplinary approach with thermal-electrical simulation and computer modeling of the data flow provides a comprehensive simulation of data performance in different environments that can be used to predict system responses to different temperature variations	A Thermal Analysis Model will be applied to a series of quasi data points to predict the impact on data management with different temperature variations. An electrical performance simulation will measure electronic performance under various thermal conditions. Spectral Analysis will be conducted to compare the effects of the simulation to potential temperature errors and actual solar radiation sources for a more well-rounded comparative analysis.

CDH-4	The subsystem shall have recovery and redundancy features to ensure continuous operation and mission success.	Demonstration	Parity Bit Calculation and Syndrome Decoding will be used due to its simplicity and cost-effectiveness for error detection and handling. This also provides a high degree of reliability for detecting and correcting single-bit errors, which are the most common type of error induced from the harsh lunar environment.	A series of hamming codes and parity bits will be calculated for a simulated database. Upon encoding the data, parity bits will be recalculated. A syndrome will be created to compare the recalculated parity bits with the received ones. Error locations are identified and corrected by flipping the bit locations. This operation will be continued until all data is correctly transferred between source and final destination.
CDH-5	The subsystem shall monitor and support the mechanical, thermal, power, and payload subsystems.	Test	End-to-end System Testing will be induced to measure the system's capability to monitor and manage other subsystems in a simulated environment under realistic operational conditions. This is an industry standard method used by the LRO, Curiosity Rover, and Perseverance Rover CDH systems during testing.	The CDH system will be placed under extreme stress and its ability to interact with other systems such as power and scientific instruments will be measured. All systems will be connected and operational and environmental simulations will be simulated in a thermal vacuum chamber to measure the CDH systems ability to manage data under stress. Simulated faults in the system such as data corruption will test the system's ability to identify and correct issues.
CDH-6	The subsystem shall execute necessary commands when prompted and perform onboard autonomous functions.	Demonstration	The Real-Time Mission Execution Integrity (RMEI) Verification Method will be used to measure the CDH system's ability to receive and execute commands in real-time environments. It provides a comprehensive test of execution under a chain of command and leverages the mission control system for testing.	The CDH system will be measured relative to timely execution of tasks. Control flow, timing, and command execution will be measured. Policy-Based Attestation provides a framework to customize and execute specific commands based on the operator's input. Specific attributes of the system will also be measured to evaluate the authorization policies before executing commands.

2.1.4. Thermal Control Subsystem Overview

The rover's thermal control system is critical to preventing mission failure by maintaining operational temperatures and protecting its components from extreme environmental conditions. The system includes key elements such as cooling plates, radiators, and aerogel insulation, all of which work together to regulate the rover's internal temperature and ensure its functionality throughout the mission.

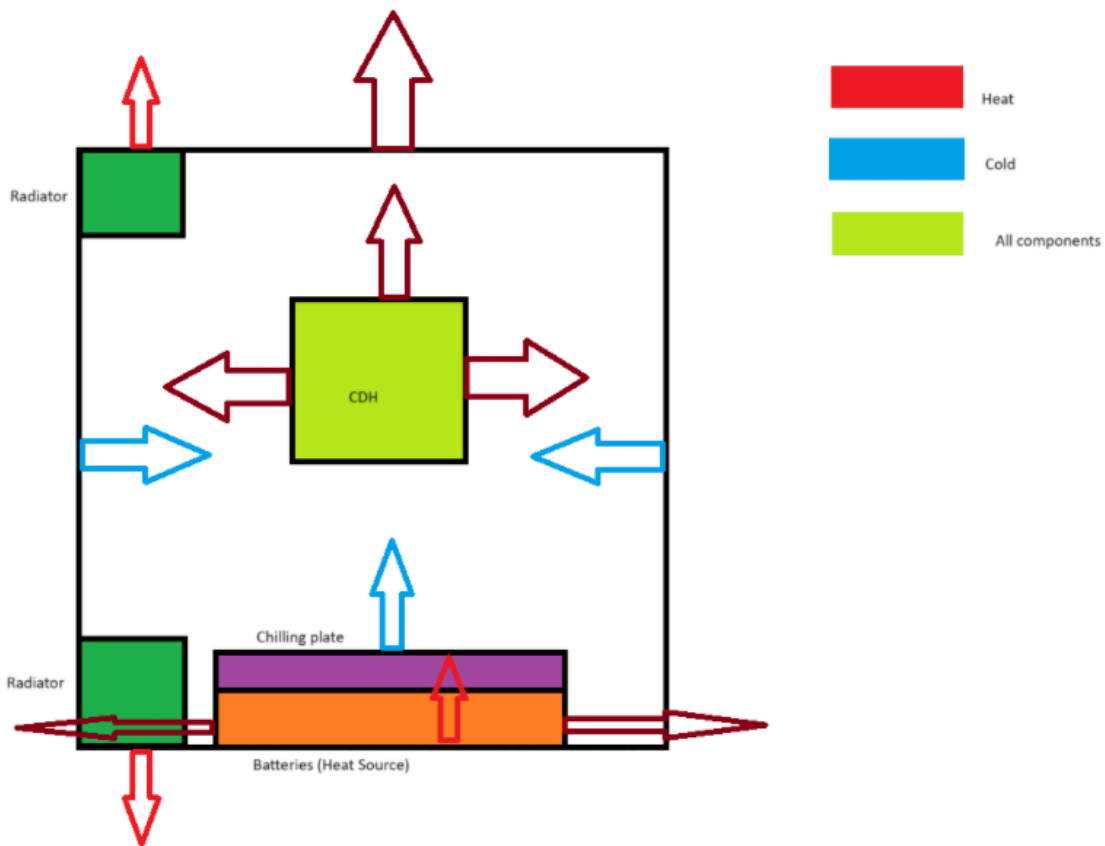
Radiators play a significant role in dissipating excess heat generated by the rover's systems, thus preventing overheating. The multilayer insulation (MLI) blankets, which are passive components, further enhance thermal regulation by minimizing heat transfer without requiring active cooling. These blankets are effective in maintaining the internal temperature by reflecting radiant heat, with the cold side reaching temperatures as low as -150°C and the hot side up to 120°C .

The rover's batteries, which are vital for powering all components, have a functional temperature range of -20°C to $+60^{\circ}\text{C}$. Their performance directly impacts the efficiency and longevity of the mission. Additionally, the radiators must operate effectively within a thermal range of -173°C to 120°C to ensure that the rover remains within safe operational limits. Cooling plates, which are active thermal management components, function within a temperature range of -120°C to 40°C , providing targeted cooling to critical systems.

Aerogel, with its exceptional insulating properties, supports the thermal control system by maintaining temperatures as low as -270°C on the cold side and up to 650°C on the hot side. As a passive component, aerogel does not generate additional heat, making it an ideal material for thermal management in the harsh conditions of space.

Each component of the thermal control system is designed to manage the heat generated by both active and passive systems within the rover. The mechanical components, in particular, are significant heat producers and require precise thermal regulation to maintain the rover's operational integrity throughout the mission. The interplay of these components ensures that the rover can continue its mission without thermal-related failures, thereby supporting the successful extraction and transmission of data.

Figure 25. Heat Flow Maps



The heat flow map of the rover details the thermal interactions within the system, focusing on the impact of active components such as radiators, batteries, and other essential elements. These components generate heat, which is managed by the thermal control system to prevent internal overheating and maintain operational efficiency. The cooling components are strategically placed to dissipate heat from the interior of the rover, ensuring that each subsystem remains within its designated temperature range. This cooling process is crucial for the rover's survival in the harsh conditions of space, where it must endure both external and internal thermal challenges. Radiation pathways, which include both external environmental radiation and internally generated heat, are managed to prevent the buildup of excess heat within the rover. The batteries, a significant source of heat due to their high voltage and power output, contribute to the overall thermal load, necessitating careful management. The rover's aluminum structure plays a vital role in thermoregulation by providing a conductive pathway for heat dissipation. This structure is designed to deflect and manage heat, ensuring that the rover's interior remains protected from external thermal extremes.

2.1.4.1. Thermal Control Subsystem Requirements

The purpose of the thermal subsystem is to ensure the rover's structural integrity and the proper functioning of its electronics throughout the mission. Maintaining the rover's safety and condition is the top priority, with a focus on sustaining consistent and efficient thermal properties. Proper management of thermal stresses is crucial to prevent material fatigue, deformation, or failure, which informs the selection of materials and cooling requirements within the system. The cooling systems are designed to provide the necessary thermal regulation to ensure mission success.

The rover will encounter a wide range of temperatures in space, requiring continuous monitoring of thermal conditions. The Command and Data Handling (CDH) system will play a critical role in monitoring and adjusting the rover's thermal environment, enabling confident navigation through varying conditions. This capability is essential for the thermal subsystem, as it allows the rover to gather and relay information about internal temperatures, facilitating necessary adjustments for optimal performance.

Active components, such as radiators, will be employed to extract heat from the rover, while passive components, like MLI blankets, will prevent excessive heat buildup. These elements are vital for protecting the rover from the harsh space environment. Chill plates will be used to prevent overheating of critical components by providing targeted cooling. Additionally, heating tape and heating pipes will distribute heat throughout the rover to prevent freezing, particularly in areas where chill plates and radiators might otherwise cause excessive cooling.

The lunar rover must function effectively on the moon's surface, maintaining stable conditions even when exposed to lunar dust. The mechanical subsystems are critical to the mission's success, making their preservation a priority. The rover must be capable of maneuvering and responding to both expected and unforeseen terrain conditions. To achieve this, the thermal subsystem will include devices designed to maintain constant internal temperatures, ensuring the rover can traverse various terrains while maintaining operational integrity.

The thermal subsystem is configured to provide optimal cooling and heating performance, ensuring the rover's sustainability throughout the mission. Active systems will protect the rover from lunar dust, which poses a significant threat to the internal components. An efficient and robust seal will be implemented to prevent dust infiltration, as contamination could compromise the rover's functionality. Ensuring the rover is protected from lunar dust is a priority to ensure the successful completion of its mission objectives.

Table 32. Thermal Subsystem Top-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Thermal Requirements							
THER-1	The system shall be able to survive and operate in the conditions of Lunar space travel	Ensures the system and components and frame dont break during travel due to the technology inside of the rover	MEC-2	THER-2	Test	Thermal, Mechanical	Met
THER-2	The system shall be able to withstand and operate under low lunar surface temperatures of TBD °C to TBD °C and withstand thermal cycling.	Ensures the system and components work to not malfunction under extreme temperatures.	MR-1, MEC-4	THER-3	Test	All	Met
THER-3	The insulation must withstand the mechanical stresses of landing and launch..	All components of the rover shall withstand a soft landing on the lunar surface.	Customer	TBD	Test	Thermal, Mechanical	Met

Table 33. Thermal Subsystem Low-Level Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Lower Level Power Requirements							
THER-4	The thermal subsystem shall efficiently conduct heat within the chassis to ensure that all components operate within their specified temperature ranges		THER-2	THER-8	Test	Thermal, mechanical	Met
THER-5	The system must use the right color and amount of MLI to ensure the subsystem is cool during lunar day and warm during cold lunar nights.		THER-2	THER-10	Test	Thermal	Met
THER-6	The system must prevent batteries from overheating and catching on fire.		THER-2	THER-8	Test	Thermal, Mechanical, Electrical	Met
THER-7	The system shall survive the lunar dust and prevent it from getting in the system and withstand potential micrometeoroid impacts without degradation	Ensures the system doesn't get any dust inside so components don't break during travel.	THER-1	THER-3	Test	Thermal, Mechanical	Met
THER-8	The thermal insulation materials shall retain their insulating properties after exposure to mechanical stresses		THER-1	ThER-2	Test	Thermal, Mechanical	Met

	encountered during launch and landing.						
THER-9	The thermal management system shall maintain operational efficiency at lunar surface temperatures ranging from -233.15 °C to -53.15 °C.	Ensures the system operates efficiently under extreme lunar surface temperatures	THER-2	THER-3	Test	Thermal	Met
THER-10	The thermal insulation shall maintain integrity and thermal resistance after being subjected to landing shock loads up to 3 g.	Ensures that insulation remains intact and effective after the landing impact	THER-3	THER-2	Test	THERMAL,Mechanical	Met

2.1.4.2. Thermal Control Sub-Assembly Overview

The thermal dynamics system in a space mission plays a critical role in maintaining the mandatory ranges that the rover has to maintain to operate in space. While it's important to maintain the operational temperatures in space, it's mandatory to manage the components' durability and purpose in the rover. This is something the rover depends on while it has active components there are many passive components that affect the rover in many ways. This system is composed of several key components and subassemblies. In each component in the rover there will be an explanation on how it works, what is needed to make the rover efficient in space and Technology Readiness Levels. This is essential as the rover needs to overcome obstacles that make it difficult for any rover to operate in space and keep it as efficient as possible. Keeping the rover efficient and maintaining a well diagram rover will make it easier in the mission to get the needed data for the mission.

Radiators are crucial for removing the unwanted heat that is produced in the rover or accumulated by the space temperatures. These devices make it easier for the rover to function in the long run, and keep the rover maintain a good tolerance. The radiators work by getting the heat produced from the interior of the rover and releasing it to the exterior of the rover into the deep parts of space. These ideas are needed for the rover to succeed as the rover will be producing a lot of heat and removing that heat from the rover will be ideal in the mission of maintaining a good overall system. Keeping the rover from melting or burning inside will help all the other components function as the other components would not have to worry about melting or circuitizing from the heat of space. The TRL of the radiator will be a 6 as the components will need to be tested many times. The rover will have a custom radiator which will affect the rovers TRL because the radiator will have to be tested many times and make sure the rover has the efficient amount of heat getting removed from the rover. If the radiators fail the TRL will go to a 4 as there will be changes to the components to remove the heat inside the rover and go through many testings and changes.

The heating pipes of the rover have an essential part of the rover as it is used to remove heat from one side of the rover to the other side if needed. These are important because they keep the rover monitored and make sure the components don't freeze. Using all the exterior materials will make it difficult to get heat in the rover, and even though space is hot the rover will exceed cold temperatures while there is no sunlight. The rover will exceed numbers and there will have to be a component that will release heat and make it possible to get heat in the components that need warming. The rover will utilize these components and produce the ideal temperatures around the rover and manage it from side to side as the heating pipes have sensors to manage the heat. The

heating pipes TRL will be a 9 as they are used in many missions, making them reliable and something the rover will utilize. The rover will be dependent on the TRL and make it easier to confirm that the components in the rover will work and keep the rover from freezing or overheating. The issue that would come from this would be if the rover has custom heat pipes with angles in different directions.

Thermal insulation materials, such as aerogels, play a critical role in minimizing heat loss and gain. Aerogels are known for making it difficult for heat to reach the interior of the rover and making it manageable. The Aerogel will be used to prevent the rover from heating up too much and making it impossible for the electronics to work. The TRL of the aerogel is a 9 as the rover will be using enough to make it possible to keep the area needed manageable. The company that will be used is trusted by NASA as it's been used many times and keeps their different spacecraft protected. There will not be much testing for the rover as it's fairly simple to see the heat transfer of the rover and the amount needed to protect the interior.

Cold plates are used to manage the temperature of high-power electronics by providing a conductive path for heat to be transferred to the radiators. The cold plates will help to produce a cooling temperature for parts that could possibly start to burn or heat up too much. This is essential for the mission as the parts will need to be cooled from a source if things get too hot and the cold plates will make sure that's possible. The cold plates will be placed on the bottom of the rover so the whole rover gets the management needed for a successful mission. The TRL for cold plates will be a 6 as the cold plates will be custom made by a trusted company that NASA trusts and used in the past missions. The reason for the pick of the company was the fact that NASA used the company in the past but their products work with the rovers dimensions and components. The cold plates can go to certain parts of the rover which is essential in the mission

PCMs are used to absorb and store thermal energy during periods of excess heat and release it when temperatures drop. These components will help the rover manage and keep it running when there are little to no heat options available. These components will be scattered on the corner of the rover to make sure they are not obstructing a needed area and giving them space to be effective around the rover. The TRL for the rover's PCM is a 8 as for the most part the standard PCM that NASA use are used and trusted for there effectiveness. These numbers can change for the TRL as the rover can or may use different materials for the PCMs throughout the mission.

Thermal sensors are essential for the mission as the rover will have to be monitoring each component and what heat or temperatures are going on while in space. These sensors must be highly reliable, as they operate in harsh space environments. The TRL

for thermal sensors is typically high, around 7 as they are reliable for the missions and NASA has used them in past missions with effectiveness. These sensors will be scattered around the rover monitoring the heat of the rover with CDH components and making sure everything is monitored. The components will still have to be tested for effectiveness and making sure the rover has correct measurements. Having the rover read wrong data can ruin a mission so making sure getting high quality thermal sensors will be needed to give the rover the best chances of success.

MLI blankets are a passive component that will be placed around the rover making it very difficult for the rover to get affected by moon dust and the space heat. The Material is used in many missions from NASA making it one of the most efficient components in the rover giving the system the best chances for success. The Material will be an essential passive component in the rover as it has one of the most efficient effects on the rover and that would be keeping it from overheating. The company that will be providing the MLI blankets are trusted by NASA as the company has been used in the past for different missions. The TRL of the MLI Blankets will be a 9 as the component is trusted for many reasons but the biggest part is its reliability in past NASA missions. The product will be essential for a successful mission.

The thermal dynamics system is essential for a successful mission in space for each subsystem as each has its specific role in maintaining thermal balance. The TRL of the system will be a crucial part for preparing the rover for a successful mission. Understanding the purpose and how the rover will be functioning will be needed to prevent failures. The more information gathered from the TRL will be better for the future of the rovers as there will be an option and space for change in materials or changing the rovers functions. There can be more options of what needs to be added for the rover to succeed.

2.1.4.3. Thermal Control Subsystem Recovery and Redundancy Plans

In the thermal system there will be incorporated radiative cooling surfaces to dissipate heat into space. This is crucial as the rover needs to survive in all types of temperatures and conditions. There will be heaters and cooling systems to maintain consistent temperatures and make sure the systems are within operational conditions. This is crucial as the system will have times where it gets too hot, while the system is in operation so cooling will be needed. The system will use thermal switches and valves to redirect heat flow as needed when traveling and landing on the targeted area. These systems will be built with reasonable headroom to accommodate extreme temperature conditions within the lunar environment, assuring that the rover is always in operational ranges. When some components get too hot there will be an active system which will help maintain constant and efficient temperatures for the rover to be at operating levels. The rover will be able to gain information with CDH and be able to tell whether it needs cooling for heating for the components to maintain a well rounded temperature. The Radiators and the cooling pad are placed in areas that make the components the option to change and maintain a well rounded temperature. The components will help the rover last for the entire mission and maintain the temps needed to operate. The cooling will happen with the cooling mats which will be on the bottom to cool every component at once, or in certain locations if needed. The cooling will be needed as the rover will get hot from the insides. The cooling will be needed and to monitor if it gets too hot, there will be sensors in the rover which will send a signal to a computer to activate the cooling mats where needed. If the whole rover is under stress all the coolers will activate to preserve the rover and give it a chance of lasting.

The sensors will monitor temperature gradients and component temperatures. The moon will have a lot of space dust which could affect the durability of the rover so having different thermal components could save the mission from failure. The rover will have to go through tests beforehand so conducting thermal vacuum tests to simulate space environment conditions and verify system performance is appropriate and no issues can be found. The materials with high thermal conductivity and heat capacity to absorb and distribute excess heat will be needed when landing on the landing target. Preparing for the actual landing will be needed for thermal as the ground team will get a better understanding of what stress the rover will go through when landing. The ground team will validate redundant systems through rigorous testing and simulations. The material that will be chosen will be aluminum as the base as it maintains a well rounded condition in space and maintains the thermal conductivity for space. The price is another reason why the rover will be using aluminum as it is very price efficient and durable. The rover will be using aerogel as well as it maintains good temperatures and heat resistance throughout the mission. The price of aerogel can give the rover a well rounded amount of aerogel for the rover to maintain the temperatures needed to travel

through the moon. The Aerogel will also be used to prevent moondust from getting into the components of the rover and the heat changes. The materials are a passive component that needs zero power but will need a component to check the temperature of the metal and the durability the rover is in when it's on the moon.

2.1.4.4. Thermal Control Subsystem Manufacturing and Procurement Plans

Aerogel

The manufacturer will be Aerogel Technologies. The alternative material the rover will use will be fiberglass insulation. The rover will use Aerogel as insulation because the thermal components will provide efficiency and durability. It will take 3-5 business days to get the aerogel to the facility. On the other hand, using fiberglass is as efficient for the rover as it is light in weight, and the cost is adequate to protect the rover. To ensure the aerogel works effectively in the mission it will go through many thermal chambers which will help it determine if it's efficient for the mission. The durability of the material will be efficient enough to withstand the temperatures of space and the moon. The durability of the material is strong and price-efficient over many other materials. The aerogel will be efficient in weight and in the thermal chamber as the material was used in past missions with NASA and using the material in the rover will be efficient because of the price and effectiveness.

(Gold)MLI blanket

The primary component will protect the rover from the sun's waves. The supplier will be cs hyde. The alternative supplier, MLI blankets, will be purchased from Thermal Space Ltd, which has made products for NASA and has been successful in the mission. The MLI blankets will be used and chosen because they are sustainable and efficient enough to withstand the sun's rays. The company Cshyde was chosen because NASA has used this company in past missions. The components needed are crucial for the mission as it is a passive component that will provide the rover the needed protection needed to manage to function.

High-performance cryogenic radiators

The radiators will be made in-house, and there will be 2 for the whole rover. This will be because the rover needs custom-made radiators, and the team knows what is required and what is price-efficient. As an alternative, Boeing will buy and customize the rover, as NASA has used its products in past missions. The delivery process from the company to headquarters will take 5-7 business days to be in the rover. The source was chosen by NASA's past collaboration with CS Hyde. Their parts are up to spec for the mission. The price effectiveness is essential to make the rover possible to travel and put money somewhere else.

Heating pipes

The components will be bought from Argtec, a trustworthy company that has helped NASA complete missions. The supplier shall make enough heating pipe as needed to have the rover as efficient as possible. The manufacturer has many heating pipes in stock, which must be custom-made to fit the rover. It will take around 1-3 business days to get the components delivered to the NASA headquarters. An alternate purchase could be made from Thermaltake Technology Co., Ltd as they have very good quality graded products and could be used as a backup in the system. The rover will go through many temperature changes and the rover will have to put heating components and transport it around the rover.

Duo-Tape flexible heaChillDuo-Tape- fine strand resistance wire, 37 to 40 gauge, covered with a minimum of 2 layers of high-temperature braided AMOX yarn. This will be purchased from Tempco. The tape will wrap around components, which will heat the system if it gets too cold. The supplier has enough in stock and can custom-make if needed. It will take 3-5 business days by foot to get these parts delivered. An Alternate company can be bought from Minco Products, Inc., as they make products that could heat the rover, manage the temperatures, and monitor them. These picks are because NASA has used them in past missions and were price-efficient for the rover. The rover uses the needed tape to make sure it has the heat components that are needed to provide the rover so they don't freeze.

Chill plate

The chilling plates will be built in-house as the rover will have a custom made to fit in the rover, cool down certain parts of the rover, and focus on one area more than another. The chill plates will have to be custom-made for the systems around the rover, and the necessary machines can be custom-made. An alternate company will be API Heat Transfer, which offers high-quality cooling plates and can manage the subsystems in the rover. This pick would be because NASA has recommended and used API Heat Transfer in the past and has proven that it is efficient for missions. The Rover will have in-house chill plates that should take around 4-6 weeks in total. The design process will take 1-2 weeks, material selection will take 1-2 days, machining and fabrication will take 1-2 weeks, assembly will take 3-4 days, and testing will take 1-2 weeks. The materials the chill plate will need are in stock and will take a week to arrive at the facility to be machined. The rover will go through many phases and this will make sure the rover stays at the temperature needed for the mission.

Manufacturing high-performance cryogenic radiators typically spans several months. Initially, the design phase involves detailed thermal modeling and simulations to meet the specifications needed to go to space. Once the design is finalized, specialized materials like aluminum will be chosen. The machining process, which includes CNC milling, ensures the radiator meets precise specifications. After the fabrication of the radiators, there will be a testing process where the radiators will be put under pressure and tested multiple times. This entire process can take approximately 6 - 7 months. All the materials have already been bought in-house. The rover will function in the needed environment with the radiators so the rover will be able to function throughout the mission.

2.1.4.5. Thermal Control Subsystem Verification Plans

To ensure the electrical components in the rover will stay safe in space the rover will have components to keep a constant temperature. The limits will be reached in the rover as the systems of the rover for the thermal will keep the rover at a distinct and constant temperature. The two most important components of the rover will be the heating and cooling components that will keep the rover in stable conditions throughout the mission. The rover will be able to complete all the tasks that are needed as long as the thermal components keep the rover together, and keep it safe from the temperatures of space. The requirements of the rover will make the rover capable of withstanding the temperatures in space. The past documents talk over how the components will affect the rover in the long run and how it helps protect the rover in space. The components and subsystems will keep the rover in a well rounded condition throughout the mission. The rover will go through many testing processes to make sure the rover is ideal and able to go into space with these conditions and boundaries made for the mission.

The rover's behavior in space will be efficient as the thermal components will keep it at an effective condition. The rover will be prepared to survive throughout the mission and make sure to protect all the subsystems in the rover and keep it at a comfortable temperature. The passive components of the rover will be ideal in space as it prevents the rover from using too many active components that would make the rover incapable of working without some sort of electronics. The purpose of the passive components would be making the rover able to perform and work on its own in space. The MLI blankets and aerogel will keep the rover at an ideal condition. The testing components will be the trade studies where the materials and other components will be determined which one would be better than the other. There will be a testing system such as a thermal vacuum test that will make sure the rover is ideal for the conditions of space and make sure the electronics stay safe in space. The rover will be expected to stay safe and have a constant temperature in space with all the components that are put into the rover to keep it stable. The results will be kept at a constant where the rover will be put in a position where it will be expected to survive in space for the needed days for the mission. The components of the rover will be successful in the mission as the certain components will keep the oven at an ideal temperature.

The testing of the thermal systems for the lunar rover will take place at an in-house facility equipped to simulate the environmental conditions the rover will encounter during its mission. This facility is critical for evaluating the rover's performance under the harsh conditions of space. The testing process will include the use of vacuum chambers, which provide the most realistic simulation of space by replicating the vacuum and extreme temperature variations the rover will face (Smith, Johnson, and Lee 2019).

The primary objective of these tests is to ensure that the rover's components, particularly the electronics and structural frame, can withstand the thermal stresses of space. As noted by Cheng and Williams (2021), effective thermal management is crucial for the survival of electronic components in the extreme environments of space. The criteria for success will be based on the ability of these components to survive and function effectively after exposure to the simulated conditions. Of particular importance is the testing of the active thermal management components, which must demonstrate their ability to maintain the rover at an optimal temperature as it experiences significant temperature fluctuations (Doe, Thompson, and Walker 2020).

Components that fail initial testing will undergo additional stress testing to identify weaknesses and determine necessary modifications. Identifying and mitigating risks is essential for ensuring the rover's success during its mission (Nguyen and Roberts 2018). This thorough testing process, which will span two months, is intentionally paced to minimize errors and ensure that any issues are addressed in a controlled environment before the rover is deployed.

The testing process will be meticulously documented, with data on temperature fluctuations and component performance being tracked and analyzed. These reports will be reviewed by the team to determine if any adjustments are needed to enhance the rover's reliability and operational efficiency in space (Smith, Johnson, and Lee 2019). Meeting all system requirements is crucial to ensure that the rover is fully prepared to survive and operate independently during its mission. These requirements will be validated before the rover's departure, ensuring it is capable of enduring the challenges of space travel (Cheng and Williams 2021).

2.1.5. Payload Subsystem Overview

The NASA RIMFAX and NASA NSS systems will be utilized to analyze the water-ice abundance and elemental composition of de Gerlache -Kocher Massif. These two instruments were chosen due to their capabilities surpassing alternative instruments (refer to Science Team Trade Studies). The NASA NSS system had a lower TRL percentage of 86.5% in comparison to the NASA RIMFAX system of 88%. However, the capabilities of both instruments will enhance the success of the mission.

The NASA RIMFAX ground penetrating radar (GPR) is a Frequency Modulated Continuous Wave (FMCW) radar that covers the ranges of 150-300 MHz (S.E., Hamran et al., 2020). This frequency range enables imaging down to 10m (NASA RIMFAX) of subsurface structure and composition. The radar sends electromagnetic waves through the surface creating changes in subsurface dielectric properties that create a refracted wave that returns back to the antenna producing imagery of the subsurface (S.E., Hamran, et. al., 2020). The wave velocity of the reflection can be calculated by: $d=vt/2$ (v =wave velocity in the subsurface, t = two way travel time) (S.E., Hamran et al., 2020). This information provides ground penetrating measurements which helps to create a 2D image of the subsurface referred to as a radargram (S.E., Hamran et al., 2020). Measurements can also be collected from the RIMFAX while stationary in correspondence to the diurnal cycle which allows studies of subsurface changes over time (S.E., Hamran et al., 2020). This information is imperative to understand diurnal reactions occurring that would enhance our knowledge base of the environment overall.

Table 34. NSA RIMFAX Specifications

Parameter	Specification
Dimensions (Volume)	196 x 120 x 66mm
Mass	3kg
Power Consumption	10 W
Frequency Range	150-300 MHz
Penetration Depth	10m
Vertical Resolution	15-30 cm

(NASA RIMFAX)

There have been issues with ambiguous waveforms in GPR systems, however the FMCW waveform proves to be energy efficient and provides a filter that removes deeper reflections to eliminate ambiguity (S.E., Hamran et al., 2020). Another constraint of the RIMFAX instrument is the thermal gradient that is created due to the location of its respective subsystems. The electronics unit is in a thermally controlled environment while the antenna is in a heated location of the instrument and faces the cold ground (S.E., Hamran et al., 2020). However, with the low power consumption the maximum

temperatures do not seem problematic with data reporting circuit boards only 2-6°Celsius above the maximum temperature of the instrument (S.E., Hamran et al., 2020).

The maximum time needed for the RIMFAX unit to send back information is recorded at 100ms (S.E., Hamran et al., 2020). There are three operational modes of surface mode, shallow mode, and deep mode. The surface mode is where the antenna reflection is in the receive window and the very upper subsurface information is received. Meanwhile the shallow mode does not have the antenna reflection in the window and measures the surface reflection and the shallow subsurface. The deep mode removes both the antenna and surface reflection from the receiver window and measures reflection of the upper subsurface (S.E., Hamran et al., 2020). Utilizing all ranges is imperative as there are tradeoffs to be considered with data volume and penetration depth (S.E., Hamran et al., 2020). This system can collect radar data every 10 cm while traversing and is suitable for use in various temperatures from glacier/permafrost conditions/desert conditions thereby making it applicable for this mission set.

The NASA Neutron Spectrometer System (NSS) measures neutrons within subsurface locations to estimate enhanced hydrogen content for .5 wt% water equivalent hydrogen (WEH, Peplowski et. al., 2023). The NSS has two gas proportional counter (GPC) sensors that lose all of their kinetic energy when they detect a neutron which produced a signal for the spectra (Peplowski et. al., 2023). Analyzed spectra can provide information regarding the thermal and epithermal neutron fluxes of the environment (Peplowski et. al., 2023). Furthermore, the detection of hydrogen can indicate water or hydrated minerals in the subsurface.

Table 35. NSA NSS Specifications

Parameter	Specification
Manufacturer	NASA Ames Research Center, Lockheed Martin Advanced Technologies Center
Sensors	X2 He Gas Proportional Counters (GPC)
Mass	1.6 kg
Dimensions (Sensor Module)	21.3 x 32.1 x 6.8 cm
Dimensions (Data Processing Module)	13.9 x 18 x 3 cm
Power Consumption	1.5 W
Count Rate Range	≤ 511 counts/s
Sensitivity	80cm ² (@ 1eV)

Field of View	4 TT Steradian
Operating Voltage Range	28±6 VDC
Sampling Rate	1 sample/s

(NASA RIMFAX)

The NSS can measure up to three feet below the surface (NASA, 2019). Overall, given its prior deployment, testing, and success in the 2020 Mars mission, the RIMFAX has a TRL of 9. It is proven to be successful in space on a surface similar to the Moon's and was able to accurately map the subsurface of Mars. The NSS is less proven as it has only been tested in training environments that mimic lunar conditions, however, NASA has successfully deployed neutron spectrometers in the Lunar Prospector Mission and the Mars Odyssey Mission, so it is a technology that is tested and ready for field use. For that reason, the NSS scores a 6-7 on the TRL scale.

2.1.5.1. Science Instrumentation Requirements

The RIMFAX Ground Penetrating Radar system detects water-ice layers of the lunar regolith through subsurface imaging. The parent performance requirements, derived from the Science Traceability Matrix, include operating within a frequency range of 150-300 MHz to balance depth penetration and resolution, collecting data continuously to avoid gaps in subsurface profiles, maintaining high sensitivity to detect subtle changes in dielectric properties, and achieving a spatial resolution of less than 10 cm for detailed imaging (S.E., Hamran et al., 2020). The RIMFAX antenna must be mounted on the rover's undercarriage at a height not exceeding 0.5 meters above the lunar surface. This placement ensures optimal ground penetration and minimizes interference which are important for detecting fine structures and layers within the regolith. The system must include active thermal management to maintain operational temperatures between -150°C to $+50^{\circ}\text{C}$ (S.E., Hamran et al., 2020). Continuous data collection requires stable thermal conditions to avoid overheating or freezing. The power subsystem must provide a continuous 10 W power supply to the RIMFAX system. Stable power is needed for maintaining the system's high sensitivity, allowing it to detect subtle changes in dielectric properties within the regolith. A reliable power supply ensures that the radar can operate continuously and effectively during the mission. Lastly, the system must have dust-resistant enclosures to prevent lunar dust from interfering with radar signals or causing damage to the system. The lunar environment is known for its fine, abrasive dust, which can interfere with the radar signals and affect system performance. Dust protection measures are necessary to maintain the system's ability to operate effectively within its frequency range of 150-300 MHz.

The Neutron Spectrometer System is designed to detect hydrogen and other elements within the lunar regolith. The parent performance requirements from the STM include measuring thermal and epithermal neutron flux to detect hydrogen concentrations, an integration time of 1 second to allow for quick and accurate neutron detection, sensitivity to detect hydrogen concentrations as low as 0.5 wt% water-equivalent hydrogen, and a spatial resolution of less than 1 meter to accurately detect variations in neutron flux. The neutron detectors must be mounted on the rover with a clear line of sight to the lunar surface. This placement ensures that the detectors have optimal exposure to the lunar surface, allowing them to achieve the required spatial resolution of less than 1 meter and accurately detect neutron flux and hydrogen concentration. Additionally, the system must include both passive and active thermal control mechanisms to maintain operational temperatures between -150°C to $+50^{\circ}\text{C}$ (S.E. Hamran et al., 2020). Consistent thermal conditions are essential to ensure the detectors operate efficiently within the specified 1-second integration time. The NSS must also integrate with the rover's communication subsystem, capable of transmitting data packets of up to 1 MB every second to onboard storage. Efficient data transmission is important for handling

the high-sensitivity measurements of hydrogen concentration. Lastly, the system must include radiation shielding to protect sensitive components from cosmic radiation and solar wind particles. This shielding is necessary to prevent interference, ensuring the system maintains its high sensitivity and accurate measurement of thermal and epithermal neutron flux. These detailed payload requirements ensure that both the RIMFAX and NSS systems can operate effectively and reliably in the harsh lunar environment, fulfilling their respective science objectives.

2.1.5.2. Payload Subsystem Recovery and Redundancy Plans

Radiation interference from cosmic rays is a risk for both the RIMFAX and NSS systems. Cosmic rays are high-energy particles from outer space that impact the lunar surface. The moon lacks a protective atmosphere and magnetic field, making its surface vulnerable to this radiation. For the RIMFAX GPR, cosmic rays can create noise in the radar signals, leading to distorted or unclear subsurface images. This noise makes it difficult to detect and map water-ice deposits and geological structures, as the radar reflections may be altered by the radiation interference. Also, exposure to cosmic rays over time can degrade the electronic components of the RIMFAX, potentially leading to malfunctions or reduced operational lifespan. The NSS is also affected by cosmic ray radiation. It is designed to detect thermal and epithermal neutrons to measure hydrogen content in the lunar regolith. Cosmic rays can interfere with these measurements by generating secondary neutrons upon striking the lunar surface, which can be detected by the NSS as false positives. This interference can lead to inaccurate readings of hydrogen levels, compromising the mission's objectives of mapping water-ice distribution. Furthermore, cosmic rays can damage the delicate neutron detectors and other electronic components of the NSS, leading to data loss or system failures. Radiation shielding by the use of covering the instruments with aluminum along with a 3-d printed shields will be utilized to mitigate these risks and ensure the accurate functioning of both instruments on the moon. This provides for redundancy within protective measures. The redundancy of utilizing both systems also helps to validate redundancy of data collection as the data through both instruments gives a wholesome perspective of the data collected.

Extreme temperatures on the moon pose another serious risk for both the RIMFAX and NSS systems. The lunar temperature of the de Gerlache-Kocher Massif ranges from 40 K in permanently shadowed regions to 220 K in sunlit regions. For the RIMFAX GPR, these temperature extremes can cause thermal expansion and contraction of materials, potentially leading to mechanical failure. Cold temperatures can reduce the efficiency of electronic circuits and batteries, while high temperatures can cause overheating and thermal damage to sensitive electronics. Effective thermal management systems will maintain the RIMFAX's operational temperature range without decreased performance. The NSS also needs to adjust based on these temperature extremes to function correctly. Low temperatures can affect the operation of neutron detectors, making them less sensitive or causing them to malfunction. High temperatures can lead to overheating, resulting in data loss or damage to the spectrometer's components. Maintaining the NSS within its optimal temperature range of -150°C to +50°C is crucial to ensure accurate measurement of thermal and epithermal neutron fluxes. Without proper thermal control, the NSS may fail to provide reliable data on hydrogen content in the lunar regolith. The active and passive thermal control systems will help to mitigate

overheating. Passive thermal controls will be multi-layer thermal control systems, special paint coatings, thermal washers, and mirrors (Gilmore 2002). Should these methods not prove fully effective, active thermal control systems with thermoelectric coolers can be utilized operating by the Peltier effect which passes electric current through junctions of dissimilar metals to enable localized cooling (NASA, 2024).

2.1.5.3. Payload Subsystem Manufacturing and Procurement Plans

RIMFAX

The RIMFAX GPR will be supplied by the Norwegian Defence Research Establishment. This company is known for its expertise and experience in developing radar technology for both scientific and defense applications. The organization has a proven track record, having developed the RIMFAX for NASA's Mars 2020 mission (Norwegian Defence Research Establishment 2015). This previous success demonstrates FFI's capability to produce reliable and high-performance radar systems suitable for harsh environments like those on Mars and the Moon. The estimated lead time for manufacturing and delivering the RIMFAX system is approximately 12 months. This timeline includes the necessary customization and testing to ensure compatibility with our mission requirements.

In the event that the Norwegian Defence Research Establishment is unable to produce the RIMFAX on time, Lockheed Martin Corporation has been chosen as a backup supplier. Lockheed Martin has plenty of experience in developing advanced radar and imaging systems for defense and space applications. Their manufacturing and design capabilities allow for an alternative, high-quality radar system to be produced if necessary. The estimated lead time with Lockheed Martin is around 14 months, which accounts for potential modifications and testing.

While in house manufacturing was considered for the RIMFAX, at the NASA Jet propulsion Laboratory in Southern California, it was determined that relying on established commercial entities would be more efficient and align with NASA's policy of not competing with the private sector. Utilizing the expertise and existing infrastructure of the chosen suppliers ensures that the payload instruments will be delivered on time and meet all mission specifications. The RIMFAX has ambiguous waveforms along with a thermal gradient that is created due to environmental extreme locations of subsystems. The electronics unit is located in a thermally controlled environment while the antenna is in a headed location facing the ground. The RIMFAX also has risks in environments such as power supply malfunctions, mechanical failures, signal penetration and interpretation. There could also be issues with calibration and alignment, data handling and storage, software communication, dust/debris and the length of use in the mission. The baseline assumption is that this system will be effective as its prior deployment was in a 2020 Mars mission. The development timeline for full integration of this system could be up to four years (Ansari et. al., 2018).

Neutron Spectrometer

The Neutron Spectrometer System will be produced by NASA's Jet Propulsion Laboratory. JPL has a long history of developing and deploying neutron spectrometers

for space missions, including the Lunar Prospector and Mars Odyssey missions. This extensive experience will ensure that the NSS will meet all the mission's scientific objectives and be able to operate effectively in the lunar environment. The estimated lead time for manufacturing and delivery of the NSS is approximately 18 months, which allows time for customization, integration with the rover, and thorough testing and calibration of the system (NASA, 2024).

Southwest Research Institute (SwRI) has been selected as the backup supplier. SwRI has developed many neutron spectrometers and similar scientific instruments for other space missions, making them a viable option if JPL cannot deliver the NSS on schedule. The lead time with SwRI is estimated to be around 20 months, accounting for the need for customization and testing (Southwest Research Institute 2016).

In-house manufacturing through JPL was chosen for the NSS due to several key benefits. JPL's direct involvement creates seamless integration with other NASA systems and subsystems, ensuring compatibility and reducing the risk of prolonged time scales due to manufacturers being on different schedules. Additionally, JPL's proximity to other NASA facilities allows for easy collaboration, testing, and troubleshooting during the production process. Producing in-house also allows greater quality control and labor standards during every step of production leading to quicker implementation of the NSS system into the rover. JPL's experience and infrastructure allow the NSS to be delivered on time and meet all mission specifications. Potential risks with this system could be exposure, environmental conditions, mechanical failures, calibration changes, data interpretation, software/data handling issues, power supply and comms issues. This system is ready for field use due to testing in training environments that mimicked lunar conditions along with successful deployment in Lunar Prospector Mission and Mars Odyssey missions. The development time for full integration of this system could be up to six years (NASA, 2023).

2.1.5.4. Payload Subsystem Verification Plans

The purpose of the Verification and Validation Plan is to ensure both the RIMFAX and NSS activities will comply with the requirements (verification) and ensure the system will meet the expectations (validation) (NASA, 2023). The science team will be responsible for the maintenance plan with the Chief Scientist seeking final approval of any changes through coordination with the Lead SE and PM.

Verification and validation plans are as follows:

Table 55. Payload Subsystem Verification Matrix

Verification Matrix											
RIMFAX											
Requirement #	Document	Paragraph	Shall Statement	Verification success Criteria	Verification Method	Facility or Lab	Phase	Acceptance Requirement	Preflight Acceptance	Performing Organization	Results
1	Artemis III	Goal 2a	Shall detect the depth of subsurface reflections from water-ice layers 1 km ² area	Frequency Range: 150-300MHz	Prior deployment in 2020 Mars Mission	Norwegian Defence Research Establishment	8	Yes	Yes	NASA	Same as Success Criteria.
2	Artemis III	Goal 2c	Shall detect changes in the reflected radar signals corresponding to different materials in	Continuous Integration time High Sensitivity <10cm Spatial Resolution							

			a 2-3 km ² area								
NSS											
3	Artemis III	Goal 2a	Shall detect hydrogen peaks in the thermal (<0.3 eV) and epithermal (0.3 e to 1keV) neutron flux range in lunar regolith samples.	Neutron Flux Range Thermal and Epithermal 1s Integration Time 0.5wt%H Sensitivity	Prior deployment in Lunar Prospector and Mars Odyssey Missions	NASA Jet Propulsion Laboratory	8	Yes	Yes	NASA JPL	Same as Success Criteria.
4	Artemis III	Goal 2c	Shall detect variations in energy and frequency with a (10 ² to 10 ⁴ neutrons/s/cm ²) intensity	<1m Spatial Resolution							

2.2. Interface Control

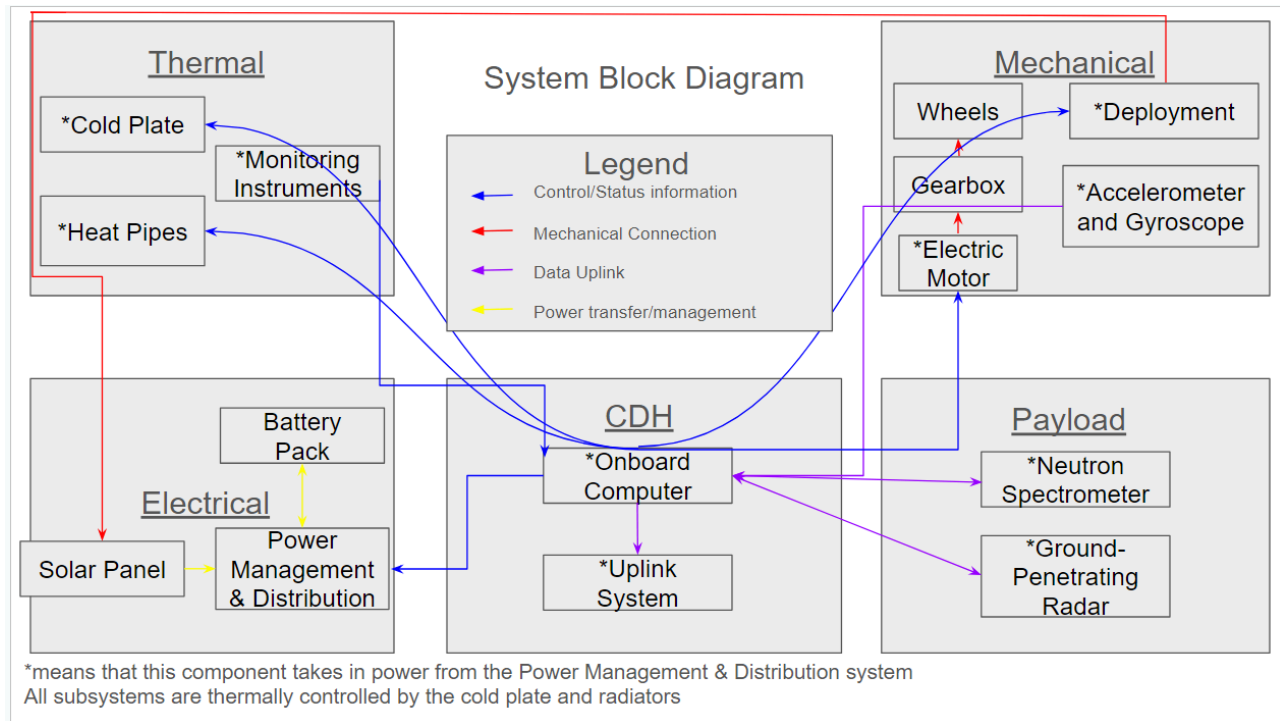


Figure 26. System Block Diagram



Figure 27. N2 Chart

For the many different interfacing systems, an in depth look at how transmittal is occurring can be seen from the system block diagram, though that view doesn't particularly describe what is being transmitted between the different systems. The N² chart on the other hand is able to describe what is traveling from one subsystem to another.

The power system is able to provide power for almost every component in the system. This will be done through a power cable. The electrical system does acquire thermal control from the thermal subsystem, panel deployment from the mechanical system and

controls from the command and data handling subsystem based on what power is needed and where.

The thermal subsystem delivers thermal control to every subsystem, through its usage of a cold plate and heat pipes. This thermal control will be delivered through vents and along the thermal systems own water cooling system in regards to the heat pipes and chill plate. This subsystem will also be controlled by the command and data handling subsystem. Particularly, the thermal subsystem will be using insulation in order to thermally isolate the payload instruments, particularly the RIMFAX, to ensure that they are working properly throughout the entire workcycle.

The mechanical subsystem will deploy the solar panel, and it will also provide command and data handling with data from their guidance, navigation, and control sensors. This subsystem will have deployment and locomotive control from the command and data handling subsystem as well.

Next, the payload subsystem will provide instrumentation data and status to the command and data handling subsystem which will provide back controls for data collection.

Finally, the interaction between the command and data handling subsystem and the ground system is facilitated by the lunar orbiter that is utilized for all telemetry purposes as a middle ground between the ground station and the on board command and data handling system. Communications between these two systems involve all telemetry and uplink going to the ground station, as well as information on the overall system health and status, as well as system-wide commands coming from the ground station to the onboard computer.

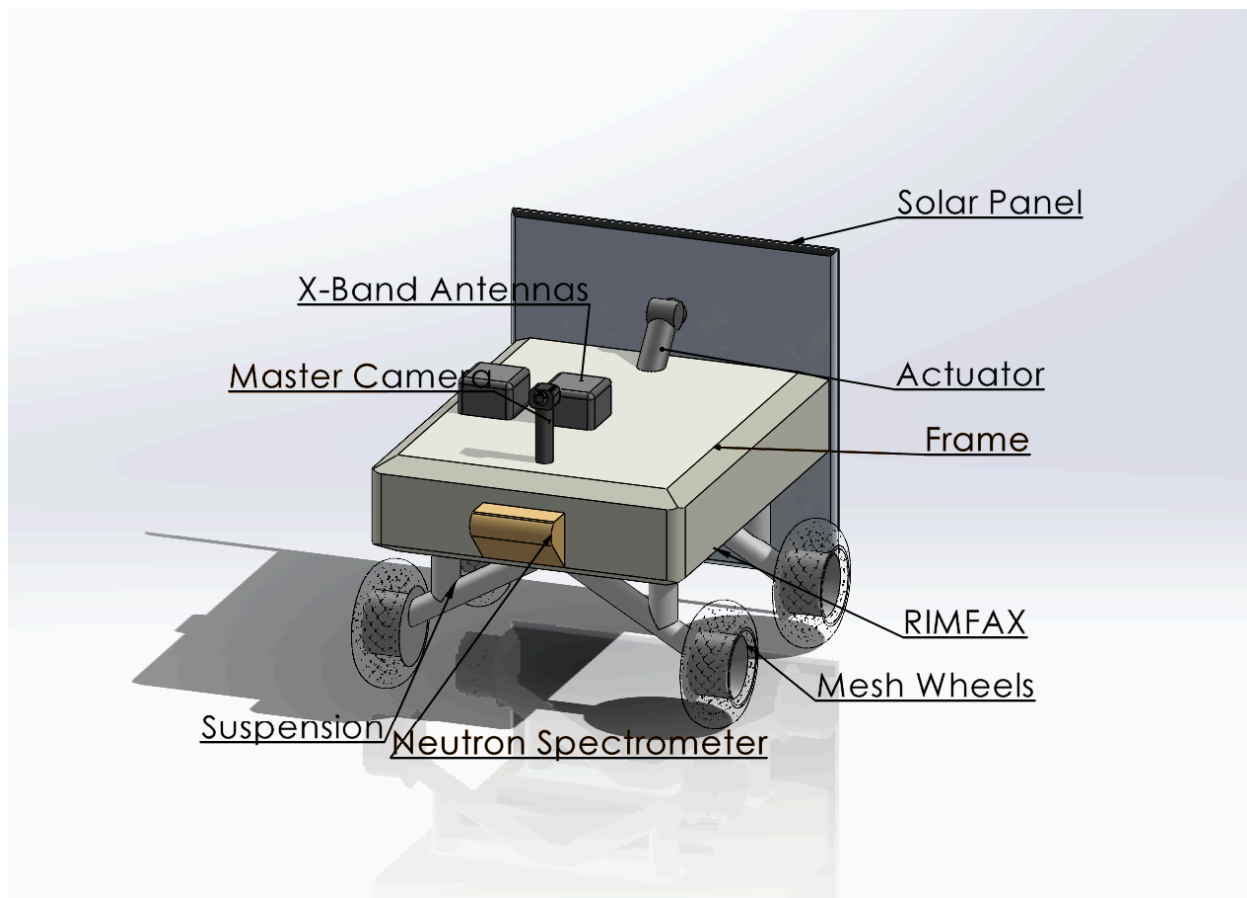


Figure 28. Lunar Rover CAD Labeled Components

3. Science Mission Plan

3.1. Science Objectives

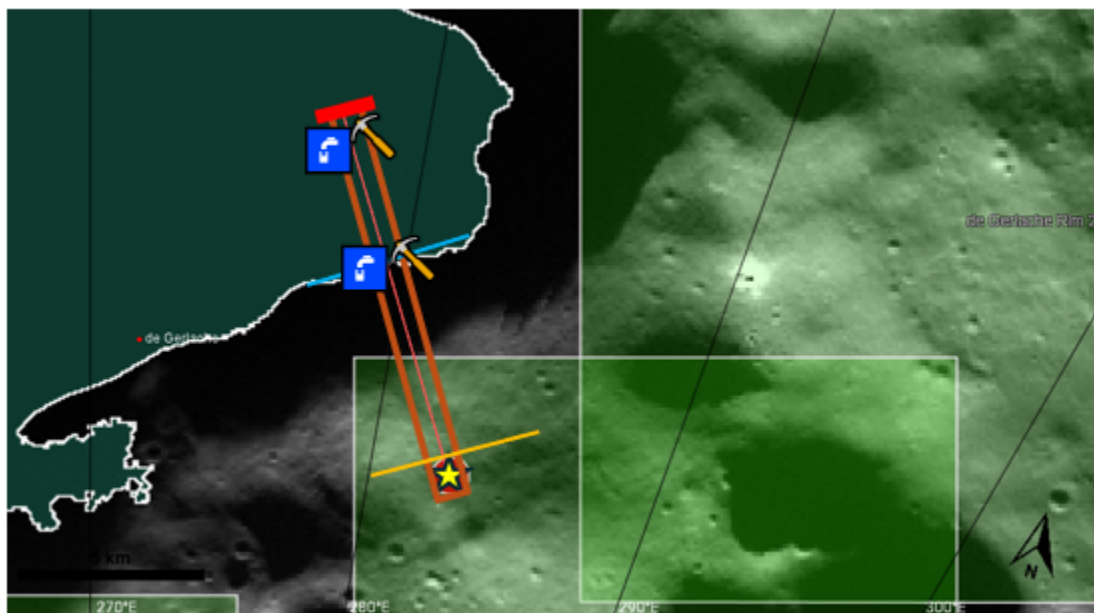
The primary objective of the mission is to determine the water-ice abundance of the de Gerlache- Kocher massif region within the top 1 meter of regolith to at least a +/-5% accuracy. The secondary objective is to determine the elemental composition of the lunar regolith to measure the phase and distribution with a +/- 10% accuracy as a function of time. Our primary objective supports Artemis III Goal 2a of determining the compositional state and composition of the volatile component in lunar polar regions. The objective focuses on identifying the subsurface layers to detect water and ice as well as the hydrogen concentrations in the lunar regolith. Observables will be to detect the depth of subsurface reflections for the water -ice layers over a 1 km^2 area as well as detecting hydrogen peaks in the thermal $<0.3\text{eV}$ and epithermal (0.3 eV to 1 keV) neutron flux range in the lunar regolith samples (NASA 2024). The water and ice abundance of our landing site within 1 meter of the regolith to at least +/- 5% accuracy will be determined. Our secondary objective supports Artemis III Goal 2c of understanding the transport, retention, alteration, and loss processes that operate on volatile materials near and at permanently shaded lunar regions. This objective determines the dielectric properties of subsurface layers and abundance and distribution of hydrogen and other volatile compounds within the lunar regolith. Focused observables are to detect changes in the reflected radar signals corresponding to different material in a $2\text{-}3 \text{ km}^2$ area along with variations in energy and frequency with a 10^2 to 10^4 neutron s/s/cm^2 intensity. The elemental composition of the lunar regolith will measure the phase state and distribution with a +/- 5-10% accuracy. The NASA RIMFAX will allow for imagery down to 10m of subsurface structure and composition which could target both objectives. However, this would be implied data regarding the water data and would not be as definitive as the NSS. The NSS can measure neutrons within the subsurface locations to estimate detection of hydrogen which would indicate water or hydrated minerals in the subsurface. Overall, the combined technical capacity of the RIMFAX and NSS instruments will ensure mission success.

3.2. Experimental Logic, Approach, and Method of Investigation

The scientific payload will have 177 days to determine the water-ice abundance of the de Gerlache- Kocher massif region within the top 1 meter of regolith to at least a $\pm 5\%$ accuracy and determine the elemental composition of the lunar regolith to measure the phase and distribution with a $\pm 10\%$ accuracy as a function of time. Upon arrival to the landing point -88.571°N , 282.866°E , both the RIMFAX and the NSS will be calibrated to ensure they are fully functioning prior to beginning to traverse towards the first water, ice, and sample of elemental composition located 5km into the permanently shadowed region at -88.393°N , 279.408°E and again at the 9 km turn around point at -88.273°N , 277.436°E . The NASA RIMFAX will help get a general idea of the subsurface structure and composition while the NASA NSS will detail that water is present to overcome any ambiguous waveforms from the RIMFAX system. Both components will work in conjunction to generate data that will share a full picture of the lunar regolith.

The experimental plan is to complete the mission in phases. Starting with Phase 0 systems will be tested at the landing point. Phase 1 will begin the traverse out while Phase 2 will be the beginning of collection of Science Operations. Scientific exploration will not go beyond point -88.273°N , 277.436°E as there is a confirmed slope at this location peaking up to 13.5° (traversing path and further explanation of this slope can be found in the JMAR images located in 1.3 Summary of the mission location) . The following imagery depicts the various sites of interest for this mission:

Figure 29. Sites Of Interest



	Proposed Landing Point @ -88.571°N, 282.866°E
	Candidate region for Artemis III
	Traverse Path
	Transversible Regions (1km either direction from planned path)
Sampling Points	
	Water and ice detection @ -88.393°N, 279.408°E & -88.273°N, 277.436°E
	Sample elemental composition at 9km turn around point @ -88.393°N, 279.408°E & -88.273°N, 277.436°E
Phase Lines	
	Phase 0: Systems Up (T+29.5 days*) @ -88.571°N, 282.866°E
	Phase 1: Traverse Phase Out (T+ 29.5-88.5 days) @ -88.555°N, 282.484°E
	Phase 2: Science Operations (T+ 88.5 – 147.5 days) @ -88.273°N, 277.436°E
	Do not go beyond point @ -88.273°N, 277.436°E
	Phase 3: Exit and EOL (T+147.5-177days) @ -88.571°N, 282.866°E
*1 lunar day = 29.5 earth days	

The procedure for collecting data will be for the power shifting from the super capacitor to the batteries for a steady power supply. The RIMFAX can collect subsurface radar data through GPR images on the move. The RIMFAX will be located 60 cm above the surface and can attain an estimate of the surface reflection measuring the distance from the lunar surface to the air through signal transmission of radio waves into the ground. Once the surface signal reflection strength is measured the permittivity of the subsurface will be estimated thereby giving the density measurement for data recording of the radargrams giving visual representations of the subsurface layers. Continuous signal transmission, signal reflection, data recording, and scanning will occur repetitively. When the RIMFAX is in a stationary position upon first landing after testing calibration and at the final 9km turn around point time lapse soundings can be collected gathering information utilizing this same method. However, this data will focus on the diurnal cycle to study changes in the surface reflection coefficient over time as interactions of the atmosphere may change the lunar regolith. Variations in permittivity and dielectric loss can be identified to consider the interactions of water vapor, the atmosphere, and the lunar surface (Hamran 2020).

The NSS will then be deployed to collect neutron data for evidence of hydrogen by measuring the amount of hydrogen bearing materials and determining the bulk composition of the regolith. This instrument conducts neutron detections of the local

thermal and epithermal neutron flux to determine hydrogen content by capturing cosmic rays striking the surface of the lunar regolith. Neutrons with energy under .3eV are absorbed to measure epithermal neutrons and when this measurement is subtracted from the initial atmospheric pressure the thermal neutron flux is given (NASA,2024). These neutron emissions are continuously recorded. Data analysis alone with mapping and interpretation will help to infer the composition of the lunar surface once transmitted back to earth for analysis.

The rover will collect additional samples through automatic sensor detection. The rover on board computer (OBC) will then store the RIMFAX and NSS data and conduct verification checks to confirm the data is accurate. There will be a downlink that occurs every 59.1 minutes and the OBC will compile telemetry and sensor data into data packets. The data will be compressed and transmitted to the Lunar Reconnaissance Orbiter. During visibility periods the rover will transfer data multiple times to the ground station. Travel speeds of the rover are at speeds of .36 km/h to .72 km/h for 9km. The master camera continuously collects imaging from the environment and there will be a constant power check. Should the battery fall below 30% the rover will be automatically shifted into night mode. Command uplinks will be sent if hazards are sensed. There will be autonomous travel to and from the landing site as power will be directed to the mechanical system during these times. During solar panel deployment the rover and actuators will reorient to capture the energy from the sunlight and the rover will maintain operating temperatures.

3.3. Payload Success Criteria

The NASA RIMFAX and NSS will be considered successful if they gather good quality and quantity of data, meet the scientific goals for mapping the subsurface structures, operationally perform, integrate their data together, and overall effectiveness to the mission.

Quality data for the NASA RIMFAX would be the ability to have resolution and detail of 10 meters down into the lunar surface and with the quantity ranging about every 4 inches of measurement intervals (NASA 2024). Operational performance would be considered successful with the RIMFAX if it was able to procure a data return of 5 to 10 kilobytes per sounding location without excessive power consumption of 5 to 10 watts (NASA 2024). The NASA RIMFAX staying within the following threshold target specifications for range, depth, and resolution would be beneficial (NASA 2024) :

Parameter	Specification
Dimensions (Volume)	196 x 120 x 66 mm
Mass	3 kg
Power Consumption	10 W
Frequency Range	150-300 MHz
Penetration Depth	10 m
Vertical Resolution	15-30 cm

Figure 30. RIMFAX Specifications

The NSS would be considered successful by being able to identify the chemicals of the rocks and soils along with the make of their atoms and molecules (NASA 2024). Maintaining a calibration target of 3 centimeters with a data return of 4.2 megabits per day or 15.5 megabits per experiment with a power consumption of 17.9 watts would be ideal (NASA 2024). Production of gamma-ray-induced signals in the ^3He gas is in a favorable threshold of channels less than 7 (Peplowski 2023). Analysis recommends 1600V bias voltage with no greater than 1700V as the higher place neutron capture peak in over load channel (channel 31) compromising measurements (Peplowski 2023). Staying within the following threshold target specifications for power consumption, range, sensitivity, field of view, and sampling rate is desired:

Parameter	Specification
Manufacturer	NASA Ames Research Center, Lockheed Martin Advanced Technologies Center
Sensors	x2 He Gas Proportional Counters (GPC)
Mass	1.6 kg
Dimensions (Sensor Module)	21.3 x 32.1 x 6.8 cm
Dimensions (Data Processing Module)	13.9 x 18 x 3 cm
Power Consumption	1.5 W
Count Rate Range	≤ 511 counts/s
Sensitivity	80 cm ² (@ 1eV)
Field of View	4 π steradian
Operating Voltage Range	28 $\pm$ 6 VDC
Sampling Rate	1 sample/s

Figure 31. NSS Specifications

Integration of the NASA RIMFAX and NSS data to create a better understanding of the lunar regolith overall would demonstrate overall effectiveness of the mission. Furthermore, the instrumentation's ability to integrate and not affect the overall mobility of the rover is imperative to a successful mission.

The real time hydrogen concentrations provided by the NSS measurements can provide data to support potential extraction activities (Peplowski 2023). Local thermal and epithermal neutron fluxes can also provide information on subsurface hydrogen content within the environment (Peplowski 2023). The RIMFAX's ability to provide imagery of the subsurface layers in conjunction with the specified hydrogen concentrations will develop more definitive evidence in data as to what is occurring in the lunar regolith region in question.

3.4. Testing and Calibration Measurements

RIMFAX:

The RIMFAX ground penetrating radar has a built in system utilized for the express purpose of calibrating the RIMFAX's FMCW signal. There is a calibration cable that is shorted at one end allowing the signal to reflect at the end and allowing the RIMFAX to measure gain variations in the transmitter and receiver. This allows the device to report when measurements are becoming affected by temperature and other environmental concerns. On previous Mars missions, including Perseverance mission, the RIMFAX calibrated during traversal and while stationary, however, for the purpose of this mission the RIMFAX will calibrate during the stationary periods only because that is the only time that our payload will be gathering science data. This calibration will occur every hour during the stationary mode of the rover to ensure that the calibration is accounting for temporal variations like temperature and dust accumulation. The nominal gain variation is a control variable that would be utilized and can be determined through testing and experimentation on earth and compared to the lunar data. The data will be accurate if the reflected data is matching the received data during the calibration section of the rover's process.

NSS:

In order for the Neutron Spectrometer System to get proper readings, the NSS must be properly calibrated to the current lunar temperature. This calibration process begins at the moment that the rover begins its traversal, the thermometers from the thermal subsystem will record the highest temperature and the lowest temperature and record the readings at those extremes. Using the gain shift from the NSS at those extreme temperatures the NSS can properly calibrate for the entire range of temperatures in order to ensure that a proper reading is being gathered throughout the entire process of data collection.

3.5. Precision and Accuracy of Instrumentation

The RIMFAX system operates in the frequency range of 150-300 MHz, which is optimal for balancing penetration depth and resolution. The higher end of the frequency range (300 MHz) provides better resolution for detecting fine subsurface structures, while the lower end (150 MHz) ensures effective depth penetration. RIMFAX penetrates up to 10 meters into the lunar regolith, making it suitable for detecting subsurface features such as water-ice layers within the top 10 meters. This depth is suitable for the derived science objective. Given that our objective focuses only on the top one meter of regolith, this extra depth is unneeded.

The data collection method also plays a significant role in instrument selection. RIMFAX collects continuous profiles as the rover moves. This continuous data collection allows for uninterrupted mapping of the subsurface (Hamran 2020). The RIMFAX has a proven track record from its successful deployment on the Mars 2020 Perseverance rover (Perseverance Science Instruments 2020). This experience proves its reliability and effectiveness for lunar missions.

Table 36. RIMFAX Trade Study

Criteria	Explanation	Grade	Weight	RIMFAX
Resolution and Detail	System's capability to create detailed imaging of the top 1m of subsurface and be able to distinguish between small details and layers within the regolith	10 = high, 5 = medium 1 = low 0 = Fail	35%	9
Range	Depth of range (m) that the system can survey as well as level of accuracy	10 = high, 5 = medium 1 = low 0 = Fail	15%	9
Power Consumption	Watts (W) required to power the instrument	10 = high, 5 = medium 1 = low 0 = Fail	20%	8
Integration/Mobility	How easily the system can be integrated into the rover: mass (kg), size (m)	10 = high, 5 = medium 1 = low 0 = Fail	30%	9

		TOTALS:	100%	88.00%
--	--	----------------	-------------	---------------

The neutron spectrometer can detect subsurface hydrogen and water-ice. The primary science objective of the mission is to determine the water-ice abundance and the elemental composition of the lunar regolith, especially within permanently shadowed regions (PSRs). Neutron spectrometers are most promising for this mission because they can directly detect hydrogen. Neutron spectrometers work by measuring the flux of neutrons emitted from the lunar surface. The presence of hydrogen in the regolith slows down these neutrons, creating a change in neutron flux that is then detected by the neutron spectrometer. This makes neutron spectrometers highly sensitive to the presence of water and ice (Peplowski 2023). The NSS has greater sensitivity to hydrogen detection, with an ability to measure hydrogen concentrations as low as 0.5 wt% water-equivalent hydrogen (WEH). Additionally, the NSS measures thermal and epithermal neutron flux, providing a detailed analysis of hydrogen distribution, which is essential for achieving the mission's science objectives. Its integration time of 1 second allows for quick and accurate measurements (Peplowski 2023). Furthermore, the NSS has proven operational reliability in previous planetary missions, ensuring its performance in the lunar environment. This combination of high sensitivity, detailed subsurface measurement capability, efficient integration time, and proven reliability made the NSS the optimal choice for the mission.

Table 37. Neutron Spectrometer Trade Study

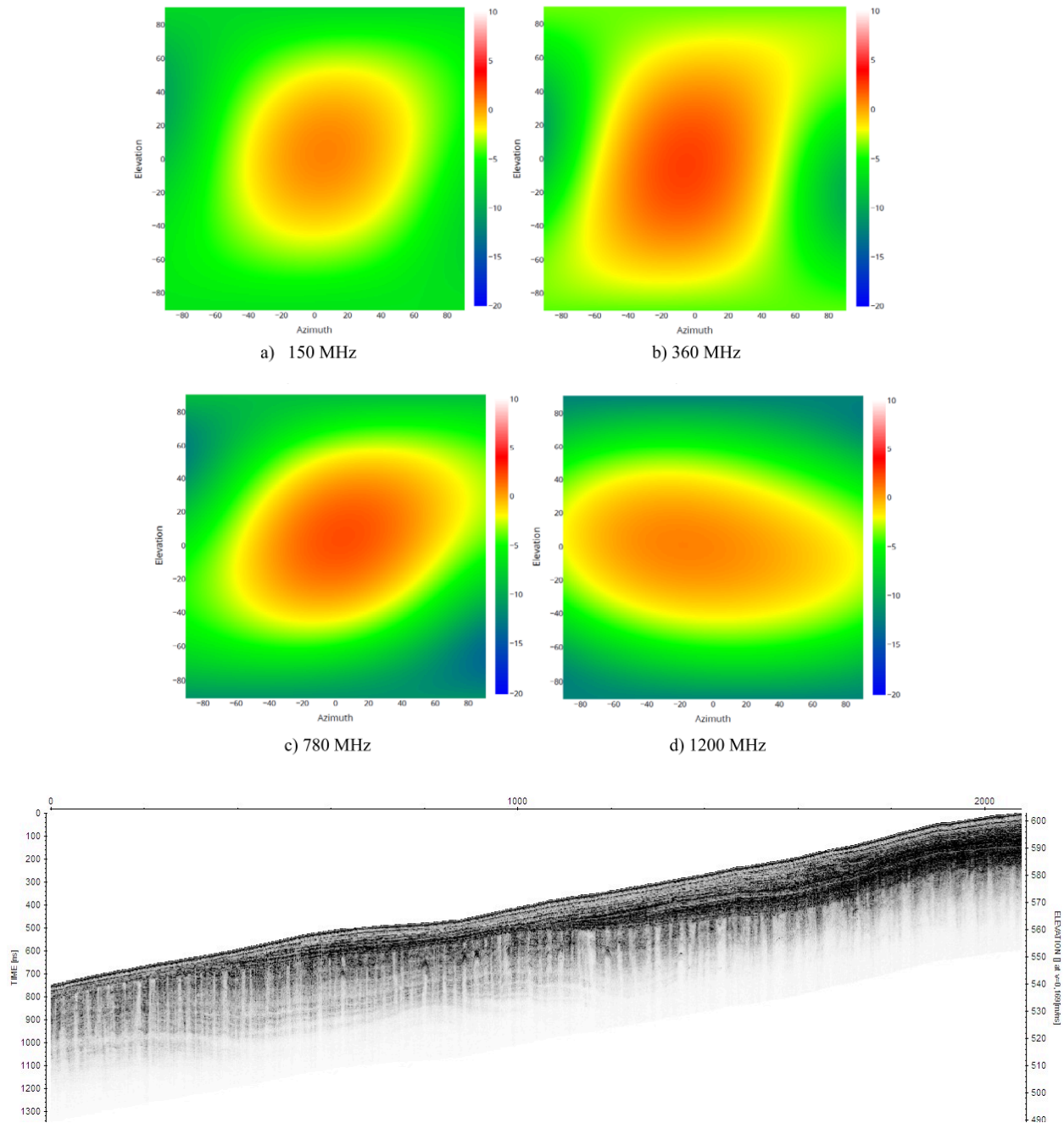
Criteria	Explanation	Grade	Weight	Neutron Spectrometer
Element Detection Accuracy	System's capability to accurately detect different elements within the top meter of regolith	10 = high, 5 = medium 1 = low 0 = Fail	35%	9
Hydrogen Sensitivity	Sensitivity to hydrogen (important for detecting water or ice), often measured in hydrogen concentration ex. ppm or % wt H)	10 = high, 5 = medium 1 = low 0 = Fail	15%	10
Penetration Depth	How deep (m) each instrument can penetrate into the lunar surface and how accurate it is at greater depths	10 = high, 5 = medium 1 = low 0 = Fail	20%	8

Suitability/Integration	Mass (kg), size (m), power (W)	10 = high, 5 = medium 1 = low 0 = Fail	30%	8
		TOTALS:	100%	86.50%

3.6. Expected Data & Analysis

Different operational modes of RIMFAX can optimize data collection in various subsurface conditions. Removal of reflections can increase the dynamic range of detection of weaker reflections. There are three modes: surface, shallow, and deep mode shown in the following diagrams:

Figure 32. RIMFAX Operational Modes



(Hamran 2020 ; NASA 2015).

The surface mode will capture the antenna reflection in the receiver window thereby allowing upper subsurface reflection measurements. The shallow mode removes the antenna reflection in the receive window and is able to measure the shallow subsurface. In the deep mode the receiver window does not have the antenna or surface reflections and can measure reflections of up to 1 meter depth (Hamran 2020). Measurements can be optimized by choosing frequency ranges and sweet time of the waveform (Hamran 2020). The Blackman Window Algorithm is ideal for complex pattern recognition and digital signal processing tasks, and acts as the initial noise filter to smooth data. It has an approximate 1.7542 bandwidth which is superior to the Hamming and Hanning windows with less side lobes that could reduce the accuracy of data (P. Podder et al. 2014). The following code shows signal processing of the RIMFAX reflection amplitude for spectral analysis with the Blackman Window Function for data collected in the "Surface" Mode.

```
data = np.array(lunar_mission_data['rimfax']['reflection_amplitude']['surface'])
def noise_filter(data):
    """
        noise filtering with Blackman-Harris Window Function for signal processing and
        spectral analysis.
    """

    window = np.blackman(len(data))
    plt.figure()

    A = fft(window, 2048) / 25.5
    mag = np.abs(fftshift(A))
    freq = np.linspace(-0.5, 0.5, len(A))
    response = 20 * np.log10(mag)
    response = np.clip(response, -100, 100)

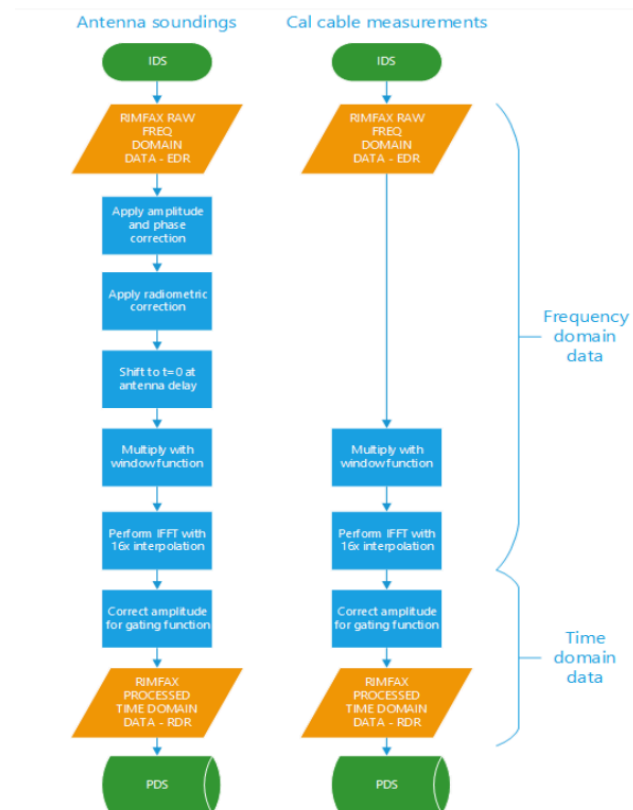
    plt.plot(freq, response)
    plt.title("Frequency response of Blackman window")
    plt.ylabel("Magnitude [dB]")
    plt.xlabel("Normalized frequency [cycles per sample]")
    plt.axis('tight')
    plt.show()

noise_filter(data)
```

Figure 33. MATLAB simulation of a sample RIMFAX dataset for the reflection amplitude using the Blackman Window Function

Once the subsurface profiles are collected by the RIMFAX, data will be analyzed by preprocessing. This is a process where noise must be filtered out to correct any distortions thereby improving the clarity of the radargrams. The radar reflections will be compared to geological models to identify subsurface structures and layers. MATLAB or geophysical software can be utilized to help with further detailed analysis and visualization of the data. The subsurface composition can further be analyzed by comparing the found data to existing geological data of other locations (Russell & Sullivan 2021).

Figure 34. Process of transcribing Raw data from JPL's Instrument data system into their Planetary data system.



The Raw data is processed first to the frequency domain and then into the time domain. To account for the antenna delay in the Fourier domain the data must be shifted to the “time zero” (=0ns) (Russell & Sullivan 2021). Side lobe levels are reduced by applying a Blackman-Harris (TBC) window function where the window function is multiplied to the last step of the data prior to the transformation into the time domain (Russell & Sullivan 2021).

The NSS procures results such as the following figure:

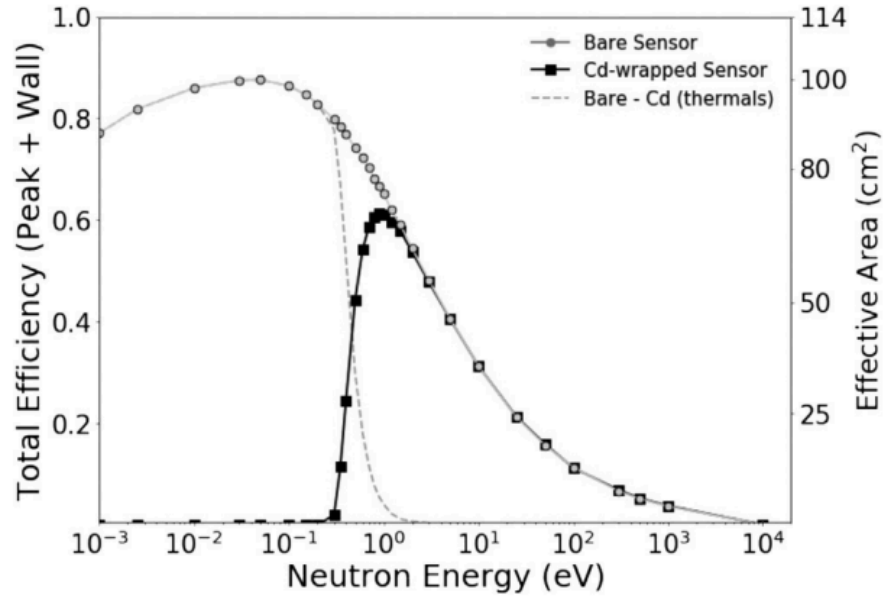


Figure 35. Total Efficiency Vs. Neutron Energy (Peplowski 2023)

The neutron detection efficiency is calculated from Figure 35, with the following equation:

$$A(E_n, \theta) = \frac{N(E_n, \theta)}{\Phi_n}$$

and has units of cm².

The efficiency of detection is measured by the variation of pulse-height channel ranges utilized during range analysis of the detector (Pelowski 2023). With distinctive interpretations of this data derived recommendations for operation on the lunar surface can be formulated. Two parameters that can be changed are the lower - level discriminator (threshold) and high voltage bias (Peplowski 2023). Screening out the lower level pulses that are out of selected ranges can help limit the analysis of the radiation generated pulses to windows that will allow counting pulses, pulse height analysis, and pulse shape analysis (duration). Counting the pulses will provide exposure rate, dose rate, dose equivalent rate, and activity of a source. Pulse height will differentiate the amount of energy displaced into the detector and help to designate a spectrum of gamma or alpha. Furthermore, understanding the shape can help to understand various types of radiation. Ultimately the ability to distinguish the pulse shapes is imperative as overlapping pulses can cause misinterpretation, which is called

a, “pile-up rejection” (U.S NRC 2011). Clarifying these differences in the data will provide more clarity of the data and a thorough analysis.

4. Mission Risk Management

4.1. Safety and Hazard Overview

Mission Valkyr adheres to a rigorous and precise criteria for risk identification, management, and mitigation. The Risk Assurance Team has compiled a comprehensive framework combining NASA-standard review processes, such as the Risk Informed Decision Making Method (RIDM), with collaborative functions cross-team to strategically tackle interdependent processes. Under this standard process, the Deputy Project Manager sets quality benchmarks such as percentage likelihood and frequency. These benchmarks are used for continuous assessment through the stages of risk identification, analysis, mitigation, and revision.

The Risk Identification Methodology is built on subject-level expertise, including all engineering and science subteam members to contribute to risk. The procedure follows the NASA-standard Continuous Risk Management Process (CRM) where risks are evaluated against analogous risk alternatives. During the design lifecycle, frequent surveys are conducted across teams to acquire data on subsystem-specific risks, and as an accessible way to collect risks at low costs. These responses are iteratively compiled by the mission assurance team after each major benchmark of Phase A, such as for systems architecture design, trade studies, and subsystem modeling.

The Risk Analysis and Prioritization procedure is built on the Cost-Risk Analysis Framework that integrates financial and resources considerations into the risk management process ([NASA](#) 2024). The compiled responses are organized based on criticality and shipped directly to the Deputy Project Manager and FMEA team for review and approval. Risks that are identified with a probability (p) within the $0.60 < p < 0.80$ range (where p represents the likelihood of occurrence) will undergo cross-analysis against the Risk Likelihood Criteria (NASA, 2017) to determine the Criticality level of the risk. This evaluation involves benchmarking against the Impact Horizon Definition, which measures the progression of the risk over a select time frame.

The Risk Management Strategy is built on the Failure Modes and Effect Analysis Model (FMEA) which involves a bottom-up, inductive analysis to postulate potential failure modes (scenarios where environmental or internal conditions induce a failure in the system) and the associated context behind the failure on various levels such as component and subsystem. Identified failures are measured across levels of severity, capturing the immediate causes and effects propagating through the system hierarchy. Relevant risk scenarios are selected and managed through the Probabilistic Risk Assessment (PRA), quantifying the cross-section of Likelihood (L) x Probability (P) of each scenario.

Many of the identified risks are preventable, such as calculation errors by engineers and ensuring the structural integrity of the space object. However, some risks stem from unpredictable events, like meteorite impacts. CDH risks are primarily associated with external factors, including radiation and signal loss, making effective shielding critical due to the high severity of these risks. Power-related risks, such as miscalculating energy requirements, are of high severity but low likelihood, as testing can readily identify issues. Instrumentation risks, driven by environmental factors, present high risk and high severity, necessitating robust protection. Thermal risks, such as material misreading heat distribution, are low risk but high severity. Mechanical risks, such as enduring shock waves, are high risk but low severity, focusing on the system's resilience.

Planetary Protection is an equally critical risk due to forward and backward contamination of microbes that could interfere with science data and pose a threat to the earths' biosphere ([Harris](#) 2024). To address this, VALKYR will employ a comprehensive planetary protection strategy that includes categorization of the planetary body, defining stringent sterilization procedures pre-launch, and containment of sample returns. Lunar dust poses the largest risks due to fineness, jagged edges, and electrostatic charge that could impair movement ([Pohlen](#) et al. 2022). VALKYR will adhere to the CRM methodology throughout the mission to identify and mitigate granular issues.

4.1.1. Risk Analysis

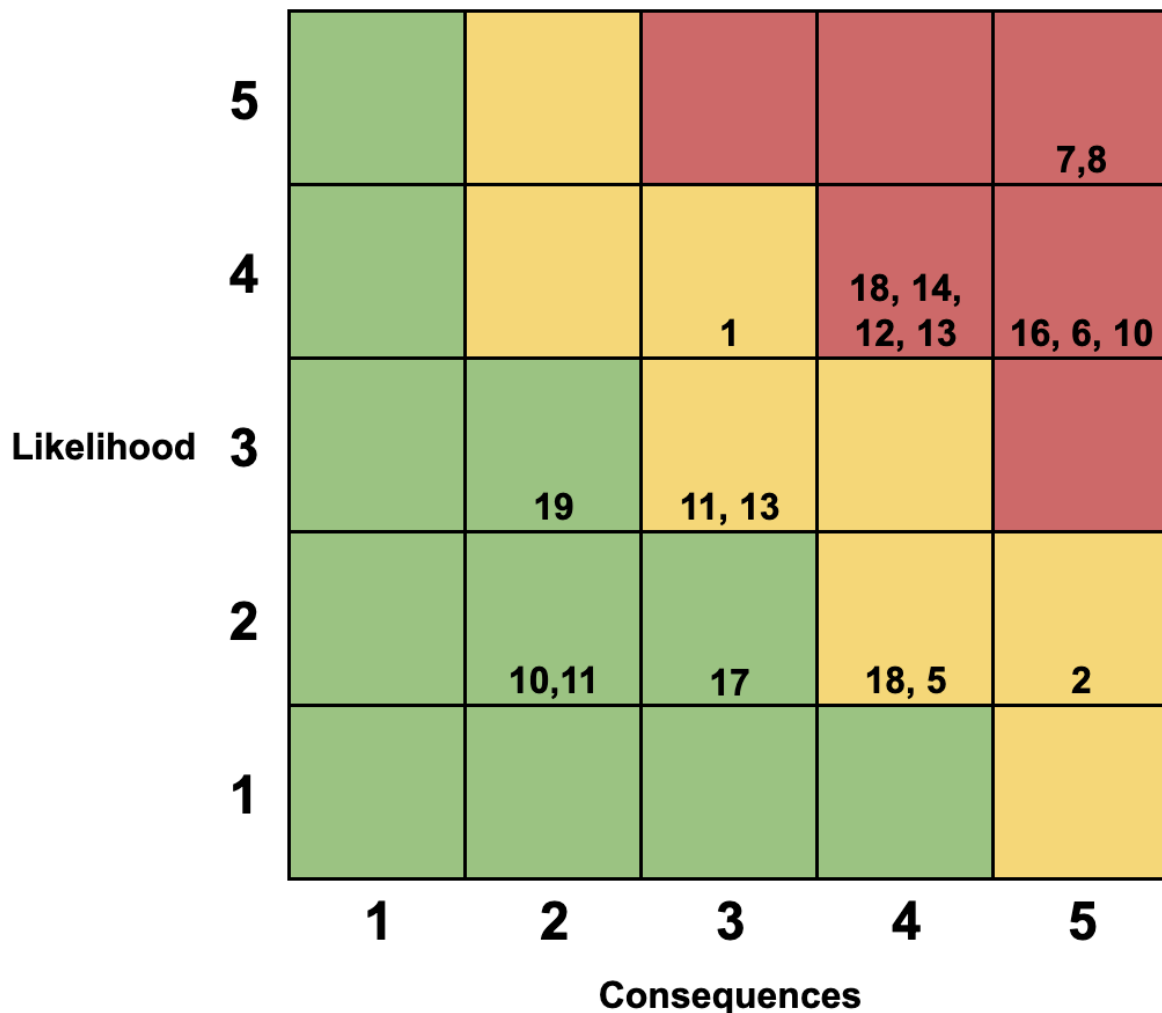


Figure 36. Risk Analysis Block Chart

VALKYR's Risk Analysis Procedure aligns with the NASA Risk-Informed Decision Making Handbook (RIDM). Stakeholder Expectations are first characterized. Risks are extracted according to their impact on these expectations. An alternative selection process normalizes risks to create more thorough risk profiles. Trade studies aid with this process by identifying alternative routes leveraging the RIDM graded approach selects risks based on their stakes and complexity of the decision, to ensure that low impact risks are not considered first. A sample trade study of the Power Management System can be found below. This evaluated three primary power suppliers based on the following criteria: Power Generation, Battery Capacity, Environmental Resilience, Failure Control, and Power Management. This criteria provides an objective measurement that can be weighted to deduce the most effective power supply given

budgeting limitations. Due to client limitations for Fuel Cells and Radioactive components, the Solar Panels were selected. This decision also yields lower consequences, given backup power suppliers and the Onboard Computer's ability to stabilize power supplies and manage load. Additional pathfinding algorithms like RAPF reduce likelihood of power outages by optimizing pathfinding against solar oscillations (refer to the CDH subsystem section).

Table 38. Power Management System Risks

Power Management System Risks						
Criteria	Explanation	Grade	Weight	Solar Panels	Fuel Cells	Radioisotope Power System
Power Generation	The Power System should be able to generate a consistent supply of power of at least 300W to 400W of power and contain systems to maintain a consistent power supply.	10 = Low Risk 5 = Medium Risk 1 = Major Risk 0 = Fail	40%	8	5	9
Battery Capacity	The battery must withstand extreme degradation and have power available during peak demands or unforeseen loss of power.	10 = Low Risk 5 = Medium Risk 1 = Major Risk 0 = Fail	20%	3	7	8
Environmental Resilience	The Power System must withstand harsh lunar environments including dust and extreme temperatures	10 = Low Risk 5 = Medium Risk 1 = Major Risk 0 = Fail	25%	4	7	9
Failure Control	The Power System must contain fault-tolerant and/or redundant mechanisms to mitigate unforeseen risks.	10 = Low Risk 5 = Medium Risk 1 = Major Risk 0 = Fail	10%	5	6	8
Power Management	The Power System must properly distribute and manage voltage supplies when systems fail with autonomous power management capabilities.	10 = Low Risk 5 = Medium Risk 1 = Major Risk 0 = Fail	5%	6	6	9
		TOTALS:	100%	85.50%	91.00%	132.50%

Table 39. Power Management Risks Reasoning

Explanation and Reasoning				
Criteria	Reason for rating	Solar Panels	Fuel Cells	RPS
Power Generation	All Rover Subsystems cannot operate without sufficient power supply	consistent solar supply other than during lunar night	Depend on fuel storage, fixed power supply	Consistent power due to radioactive lunar environment and not affected by lunar day-night cycles
Battery Capacity	Battery performance is essential for fault tolerance and peak demands	High degradation risk due to dependency on large, lithium-ion batteries	Risk from storage efficiency	Reliable with advanced batteries for long missions, offering high density and minimal capacity degradation.
Environmental Resilience	Battery must be sustained in spite of environmental risks.	Susceptible to dust and extreme temperatures due to exposed exterior	Same as Solar Panels	Suitable for harsh lunar conditions due to built-in thermal management, enclosed nature, and radiation resistance
Failure Control	Fault-tolerant systems to mitigate unforeseen risks	Solar panels require added redundant units to handle failures	Same as Solar Panels	Multiple layers of redundancy (ex: multiple power conversion units) and proven reliability from multiple missions
Power Management	Proper voltage distribution is essential for sufficient power for all systems.	Require advanced power management systems to handle variability.	Same as Solar Panels	Consistent power supplies without power fluctuations and autonomous power management
Final Rationale: Fuel cells are outside of the scope duration of the mission. Radioactive instruments are not allowed, as requested by the client.				

The following table presents an overarching risk assessment for various subsystems involved in Mission VALKYR. Each entry identifies a specific risk, detailing the system affected, the level of risk, the likelihood and consequence of the risk occurring, and the trend of the risk over time. The likelihood and consequence are both rated on a scale from 1 to 5, where higher values indicate a greater probability of occurrence or a more severe impact.

The risks are categorized into levels, with "Major" and "Minor" designations based on the potential impact on the mission. For example, several major risks involve critical systems such as Comms and Data Handling (CDH), power, and the mechanical subsystems. These risks range from the potential damage to electrical components due to radiation exposure, which could lead to loss of mission-critical data, to the possibility of power system failures due to improper insulation, which could cause overheating or total system failure.

This table also tracks the trend of each risk, which indicates whether the situation is improving, worsening, or remaining stable. Several risks are worsening, particularly those related to power, thermal, and mechanical systems. For example, inadequate insulation and exposure to extreme temperatures are significant threats to the rover's stability and functionality.

Each risk is actively monitored, with an approach to manage it. Depending on the severity and nature of the risk, the approach might involve acceptance, where the risk is acknowledged and planned for; mitigation, where steps are taken to reduce the likelihood or impact of the risk; or monitoring, where the situation is closely observed to detect any changes.

This provides a structured framework for identifying and managing risks that could impact the success of Mission VALKYR. By understanding the potential risks and their trends, the team can prioritize actions to mitigate the most severe threats and ensure mission success, through the FMEA Analysis framework in the following section.

Table 40. Risks Table

Likelihood (L)	Consequence (C)	L x C Trend	Approach
1 - Not Likely	1 - Low Consequence	↑ - Increasing	A - Accept
		→ - Unchanged	M - Mitigate
5 - Extremely Likely	5 - High Consequence	↓ - Decreasing	W - Watch
		NEW - recent	R - Research

Table 41. High Criticality Risks

High Criticality Risks							
ID	System	L	C	Trend	Approach	Risk Statement	Status
1	CDH	4	3	↑	R	Given that electrical components of the CDH subsystem are sensitive to radiation events, there is a possibility of radiation damage or accumulation of charge, resulting in temporary or permanent damage to electrical components, thus failing to use error-correction codes and shielding leads to potential loss of mission-critical data and command.	Mitigation in Progress
2	Thermal	2	5	↑	W	Given that multilayer insulation has the ability to distribute heat equally when traveling in space, not using enough insulation can cause the spaceship to burn up, causing loss of parts and functionality	Active monitoring
3	Power	4	5	↑	W	Given that power has the ability to provide electricity to subsystems and ensure functionality while on the moon, due to exposed wires on the rover interface the rover might fail to generate 150-200 kW of power when it hits rough lunar terrain	Active monitoring
4	Mechanical	4	4	↑	M	Given the moon is filled with particles like regolith and lunar dust, while exploring the moon, lunar dust might get into the rover's systems due to loose/not tightened enough systems causing it to break down temporarily and causing a loss of functionality and data collection (Pohlen et al. 2022)	Mitigation in Progress

5	Instrumentation	2	4	↑	A	Given that the moon can reach below freezing temperatures, the rover's instrumentation while exploring polar shadowed regions with extreme temperatures can become brittle, causing loss of functionality and data will not be collected	Mitigation in Progress
6	CDH	4	5	↑	R	Given that the communication system can be exposed to potential signal interference, there is a possibility of signal loss or distortion, resulting in the inability of the communication system to transmit and receive data effectively, thus failing to maintain reliable communication through redundant communication channels leads to disruption in data transmission	Mitigation in Progress
7	Mechanical	5	5	→	R	Given that the spaceship has to endure shock waves during landing, the spaceship might not be able to withstand the impact of the shock waves causing parts to become loose and break away from the rover, causing it to become permanently unstable	Mitigation in Progress
8	Thermal	5	5	→	R	Given that proper heat insulation spreads out heat so it is not concentrated in one area during the journey to the moon, improper usage of heat insulation on the rover might cause the spaceship to not conduct heat properly, causing the entire rover to burst into flames and lose all functionality as well as data collections	Mitigation in Progress
9	Power	3	3	→	R	Given that mechanical systems experience spikes in power while operating due to weak constant flowages of power, voltage spikes may affect the systems and cause temporary shortages causing a loss of data and functionality of the systems	Active monitoring
10	Mechanical	4	5	↑	W	Given that the mechanical system allows the rover to collect data and travel around while on the moon, the rough lunar terrain poses a risk to the break system, suspension, and experience chassis malfunctions, causing loss of parts and functionality	Mitigation in Progress

Table 42. Medium Criticality Risks

Medium Criticality Risks							
ID	System	L	C	Trend	Approach	Risk Statement	Status
11	Mechanical	3	3	→	M	Given that the rover's structural components must endure both thermal cycles and physical stress during operation, there is a medium risk that fatigue or stress fractures may develop, compromising the integrity of the structure over time.	Active Monitoring
12	Mechanical/ CDH (GNC)	3	4	→	W	Given that the Guidance, Navigation, and Control (GNC) system relies on sensors with temperature sensitivity, there is a medium risk that these sensors may fail to operate accurately in the extreme lunar environment, leading to navigation errors.	Mitigation in Progress
13	Thermal	3	3	→	W	Given that thermal control systems must maintain optimal temperatures for electronic components, there is a medium risk that inadequate thermal control could lead to component overheating or freezing, affecting system performance.	Active Monitoring
14	Power	3	4	→	M	Given that the power system needs to operate continuously during lunar night, there is a medium risk of battery depletion or failure in energy storage systems, potentially leading to power loss during critical mission phases.	Contingency Planning
15	Instrumentation	3	3	→	M	Given that instrumentation requires precise calibration, there is a medium risk that environmental factors, such as lunar dust or temperature fluctuations, could affect calibration accuracy, leading to incorrect data collection.	Active Monitoring
16	CDH	4	5	→	M	Given the the stochastic nature of lunar cycles on the terrain, there is a possibility of the rover entering dangerous regions with limited sunlight, resulting in significant battery loss, thus failing to provide sufficient power to the other subsystems	Mitigation in Progress

17	Planetary Protection	5	3	→	M	Given the stringent requirements for lunar biocontamination prevention, there is a possibility of contamination due to insufficient sterilization, resulting in mission non-compliance with planetary protection protocols, potentially causing mission delays or termination.	Mitigation in Progress
----	----------------------	---	---	---	---	--	------------------------

Table 43. Low Criticality Risks

Low Criticality Risks							
ID	System	L	C	Trend	Approach	Risk Statement	Status
17	Instrumentation	2	3	↑	A	Given that calibration is important for the system to properly work while collecting data, the instrumentation might not be calibrated correctly, causing it to be unable to transfer data/ provide inaccurate data to other systems	Active
18	Power	2	4	↓	R	Given that there may be unpredicted issues, the power might fail due to landing, environmental, and metrologicals, loose parts as well as choosing the wrong materials causing the system to be heavily impacted and cause the exterior to cave in, causing the rover to shut down and lose all functionality	Active
19	Power	2	2	→	A	Given that the power management system fuels the movement of the rover the power system might fail due to miscalculation, causing the system to provide less/more power than needed	Active

Payload Subsystem

The risk of dust infiltration into the payload instruments is identified through environmental analysis of the lunar surface conditions and lunar regolith. The primary mitigation strategy involves completing advanced sealing techniques and real-time dust monitoring systems, supported by the addition of duster filters at critical entry points. This is aligned with NASA's planetary protection standards, ensuring the integrity of scientific data, which has proven effective in similar lunar environments.

Power Subsystem

The risk of power generation reduction due to temperature extremes was identified through thermal analysis of the lunar environment. The primary mitigation strategy involves integrating solid-state batteries with enhanced thermal insulation and redundant power systems to maintain a stable power supply. This strategy is justified by the proven resilience of solid-state batteries under extreme conditions, as supported by research in advanced energy storage technologies for space applications from the NASA Thermal Control Systems Guide.

CDH Subsystem

The risk of radiation damage to the Command and Data Handling (CDH) components was identified through radiation environment analysis of analogous lunar missions. The primary mitigation strategy includes the use of radiation-hardened components, error-correcting codes, and additional shielding for critical areas. This approach is justified as it aligns with best practices in mitigating radiation in space systems, recommended in the NASA Systems Engineering Handbook.

Mechanical Subsystem

The risk of mechanical failure due to shocks and uneven lunar terrain was identified through mechanical stress testing and simulation of the lunar environment. The primary mitigation strategy includes the use of shock-absorbing materials like carbon fiber-reinforced polymers and extensive terrain adaptability testing. This approach is justified by the durability and resilience of advanced composite materials, which have been extensively tested and proven effective in environments with similar mechanical challenges, in alignment with the NASA Materials Testing Protocols.

Thermal Subsystem

The risk of thermal imbalance leading to component overheating or freezing was identified through thermal modeling of lunar surface conditions. The primary mitigation strategy involves implementing phase change materials (PCMs) and advanced insulation to manage heat distribution effectively, coupled with continuous temperature monitoring. This approach is justified as it employs state-of-the-art thermal management techniques that are critical for maintaining operational temperatures within NASA's defined limits for lunar missions as outlined in the NASA Thermal Control Guide.

Schedule and Budget

The risk of budget overruns and schedule delays was identified through financial risk analysis and historical data comparison from similar missions. The primary mitigation strategy includes the use of Earned Value Management (EVM) for continuous cost and schedule tracking, along with the establishment of contingency funds. This approach is justified by the effectiveness of EVM in providing early warnings of budget and schedule deviations, allowing for timely corrective actions.

Planetary Protection

The risk of biocontamination during lunar operations was identified through compliance review with planetary protection protocols. The primary mitigation strategy involves strict adherence to sterilization procedures and contamination control throughout the mission lifecycle. This approach is justified by the necessity to prevent biological contamination as per NASA's Planetary Protection Policy, ensuring the scientific validity of the mission and compliance with international agreement

4.1.2. Failure Mode And Effect Analysis

Failure Mode and Effect Analysis (FMEA) is conducted in alignment with NASA's Failure Analysis Standards under the Flight Assurance Procedure (FAP). The Functional Block Diagram is analyzed for anomalies and potential failures (Refer to the Interface Control Section), the FMEA team composing of the DPMR and the Risk Assurance Analyst are convened for discussion, and the functional FMEA is developed with a mandatory list of prioritized corrective actions (reference the Change Control section). Major risks are collected continuously throughout the mission from the engineering, science, and programmatic teams. Decision matrices are used to determine a recommended corrective action. The Root-Cause Analysis (RCA) Model by identifying major problems, defining a causal understanding, identifying solutions, and designing metrics to track effectiveness.

The most critical components are the Mechanical subsystem with a RPN of 504 and Cost/Budget with an RPN of 540. The mechanical subsystem, particularly involving mobility and structural integrity, may fail due to high loads and shocks encountered on uneven lunar terrain. This could lead to loss of mobility and inability to navigate the terrain. The primary cause is inadequate design considerations from material selection and faulty suspension and braking systems that cannot withstand high-impact shocks. The primary mitigation strategy is material optimization with carbon fiber-reinforced polymers which can withstand high strength-to-weight ratios, according to NASA's Materials and Structures Division. The behavior of mechanical components under various load conditions will be predicted under the Finite Element Analysis (FEA) Model. Inadequate funding and out-of-scope initiatives can cause mission cancellation. The primary cause is underestimation of cause and misjudgment from management, approving initiatives that are out of scope. The Cost Estimation Optimization technique such as parametric and analogous cost modeling will be used to predict costs accurately. In addition, management will work closely with Risk analysts to review all proposals, such as the Mission Control System, with available resources and cost to avoid overruns.

The following table represents the highest criticality risks and a trace down of the causes and effects of each risk in more detail.

Table 44. Failure Mode And Effects Analysis

Occurrence (Occ)	Severity (Sev)	Detection (Det)	Risk Priority Number (RPN)
1 - Remote <0.00001 probability of failure	1 - Minor No impact on Mission Capability	1 - Most detectable	Occ x Sev x Det
10 - Extremely High >0.2 probability of failure	10 - Catastrophic >75% loss of mission capability	10 - Least detectable	

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Instrument s	The instruments become brittle	Complete loss of functionality in the instruments due to instrument degradation under lunar conditions, causing data loss.	10	Exposure to sub-freezing lunar temperatures causing material degradation and embrittlement	5	Conduct thorough testing under NASA's Material Testing Protocols. If existing materials fail, explore alternatives. Only use materials rated for cryogenic temperatures such as Inconel or titanium alloys	9	450	Integrate additional insulation and protective coatings. Consider Multi-layer Insulation to prevent exposure to extreme cold. Continuous Monitoring and preemptive maintenance should be implemented
	Instruments are not calibrated accurately	Inability to collect accurate scientific data, resulting in mission objectives not being met.	8	Calibration errors due to environmental factors, such as temperature fluctuations and radiation.	4	Implement rigorous calibration checks and incorporate redundancy in calibration procedures. Use automated calibration systems with environmental compensation features	8	256	Conduct calibration in situ and post-deployment in a controlled environment to ensure accuracy. Utilize advanced calibration techniques like auto-tuning in response to environmental changes
Power	The system fails to generate 300-400W of power	Total system failure, leading to the mission's termination. Essential systems would be unable to operate.	10	Poor wire connections or power generation inefficiencies due to suboptimal design or environmental impacts like	7	Use redundant power generation systems and regularly inspect wiring and connections, particularly in high-risk areas. Test power systems under simulated lunar conditions	7	490	Design and implement a backup power system using advanced energy storage solutions like solid-state batteries or supercapacitors. Implement periodic power system diagnostics

				lunar dust.					
	Temporary power shortages	Critical systems may experience interruptions, potentially causing irreversible data loss or hardware damage.	9	Unexpected environmental stressors such as micrometeoroid impacts or thermal cycles.	6	Regular stress testing of power systems in simulated space environments. Incorporate shock and vibration damping materials to reduce impact stress	8	432	Include a redundant power bus and an automatic failover to battery reserves. Use robust power conditioning equipment to stabilize power output under varying loads
CDH	The system loses mission-critical data and commands	Mission failure due to the need for data recollection, wasting power/resources. Potential inability to control the rover.	10	Radiation-induced errors or SEUs (Single Event Upsets) in electronic components.	5	Use radiation-hardened components and incorporate EDAC (Error Detection and Correction) techniques to prevent data corruption	9	450	Shield critical components with radiation-resistant materials and place them deep within the spacecraft. Implement triple redundancy in memory storage and data transmission pathways
	The system navigates the terrain incorrectly	Obstacle detection failures leading to delayed pathfinding and potential physical damage	7	Inefficient pathfinding and detection algorithms that are slow to detect and react to changes in the terrain increases computational load and power consumption	5	Conduct simulation testing with computer software to identify the most efficient algorithm for pathfinding and the most accurate object detection and mitigation approach	4	140	Implement the RAPF Path Finding Algorithm to reduce computational load and create a risk-aware pathfinding algorithm to balance efficiency with hazard avoidance
	The system loses reliable connection with its channels	Intermittent data transmission leading to incomplete datasets and compromised	8	Signal interference or data corruption due to electromagnetic interference or	6	Use materials with high resistance to electromagnetic interference. Conduct regular signal integrity tests in a controlled environment simulating lunar conditions	7	336	Deploy redundant communication channels and incorporate dynamic frequency hopping to avoid interference. Use signal boosters and error-correction algorithms to maintain data integrity

		mission objectives.		lunar environment conditions.					
Mechanical	The system loses parts of the brake system, suspension, etc.	Potential mission failure due to the inability to navigate the lunar terrain. Critical mobility components could fail.	9	Harsh lunar terrain conditions not accounted for in the design.	7	Conduct extensive terrain simulation testing and use flexible materials that can adapt to lunar terrain. Employ redundancy in critical components(Team 26 - Systems Requi...).	8	504	Upgrade suspension components with advanced, flexible materials like carbon fiber-reinforced polymers. Conduct preemptive maintenance checks and use real-time monitoring of component health
	The system burns up, destroying it completely	Total mission failure due to the loss of all onboard systems.	10	Insufficient heat insulation or distribution, causing overheating during lunar day cycles.	6	Incorporate advanced thermal management systems, including heat pipes and phase change materials. Conduct thermal vacuum testing under extreme conditions(Team 26 - Systems Requi...).	8	480	Redesign the thermal system to include active cooling and enhanced insulation. Regularly monitor system temperatures with multiple sensors and adjust dynamically
	Mechanical maneuverability, and structure failure due to high loads and shocks on uneven lunar terrain	Loss of mobility, inability to navigate terrain, potential mission failure due to inability to reach targets or return data.	9	High loads and shocks from uneven and rough lunar terrain are not adequately accounted for in design.	7	Conduct thorough terrain simulation testing; use materials designed for high impact and shock resistance.	8	504	Enhance structural components with shock-absorbing materials like carbon fiber-reinforced polymers. Implement advanced suspension systems designed for uneven terrain.
Thermal	The system burns up, destroying it completely	Total mission failure due to the loss of all onboard systems.	10	Insufficient heat insulation or distribution, causing overheating during lunar	6	Incorporate advanced thermal management systems, including heat pipes and phase change materials. Conduct thermal vacuum testing under	8	480	Redesign the thermal system to include active cooling and enhanced insulation. Regularly monitor system temperatures with multiple sensors and adjust dynamically

				day cycles.		extreme conditions			
Cost	Budget overrun due to unanticipated complexities	Project cancellation or significant delays due to budget exceedance, reducing the scope of future missions.	9	Underestimation of costs related to material procurement, testing, and unexpected technical challenges.	8	Implement comprehensive cost modeling and risk assessment early in the project. Regularly review and update cost estimates to reflect actual spending trends	7	504	Establish a contingency fund to cover unexpected costs. Use Earned Value Management (EVM) to monitor project cost performance against the baseline
	Inadequate funding allocation	The inability to complete the mission within the allocated budget, leading to scope reduction or mission failure.	10	Insufficient initial budget allocation or unexpected cost escalations.	6	Conduct thorough budget forecasting and incorporate risk-based contingencies. Regularly update the budget based on real-time project data	9	540	Secure additional funding sources or adjust the mission scope to align with available resources. Implement rigorous financial monitoring and control mechanisms throughout the project

4.1.3. Personnel Hazards and Mitigations

The Personnel Hazards severity score is evaluated based on the NASA FMEA Severity Categories as follows: 1 (Catastrophic), 1R (Catastrophic), 2 (Critical), 2R (Critical), 3 (Significant), and 4 (Minor) as outlined in the Flight Assurance Procedure ([NASA](#)). VALKYR adheres to the standard risk assessment procedure defined in the FMEA and Risk Analysis sections. The Occupational Safety and Health Administration (OSHA) sets strict standards on training and health management such as the Personal Protective Equipment (PPE) Standard which the team adheres to ([Tarlengco 2024](#)), ensuring compliance during Inspection. The Office of Safety and Mission Assurance (OSMA) will work closely with the team to enforce mission assurance plans for safety, reliability, and quality and report incidents.

One significant workplace risk is improper machine usage, which can result from inadequate training or failure to adhere to safety protocols. This can lead to injuries such as cuts, bruises, or more severe harm. Ensuring that all personnel are properly trained and consistently follow safety guidelines is essential. Additionally, machines must be well-maintained to prevent malfunctions that could lead to accidents. Regular inspections and maintenance are critical to ensuring operational safety. Proper ventilation is also crucial, as insufficient airflow can cause the accumulation of harmful gasses, fumes, or dust, leading to respiratory risks or dizziness. Maintaining adequate ventilation helps ensure a clean and safe work environment.

The use of personal protective equipment (PPE) is another critical aspect of workplace safety. Without appropriate gear such as gloves, goggles, helmets, or aprons, workers are more vulnerable to injuries from chemicals, flying debris, heat, or sharp objects. PPE serves as a barrier between hazards and the worker, reducing the likelihood of injury. Electrical safety is also paramount; loose or damaged wiring can result in electric shocks, burns, or fires. Regular inspection and maintenance of electrical systems are necessary to mitigate these risks. Handling chemicals safely is essential to prevent burns, poisoning, or respiratory issues, and proper storage, adherence to handling protocols, and the use of PPE are vital for worker protection.

Workplace incidents such as slips, trips, and falls are common but preventable. Clear walkways, appropriate footwear, and good housekeeping practices significantly reduce these risks. Proper lifting techniques and the use of lifting aids are necessary to prevent musculoskeletal injuries. Fire and explosion risks arise from improper handling or storage of hazardous materials; adhering to strict storage guidelines, fire safety rules, and having emergency response plans in place are crucial for prevention. Radiation exposure from x-rays or radioactive materials poses serious health risks, including

burns or cancer; implementing proper shielding, limiting exposure, and following safety procedures are necessary to minimize these risks.

Financial management also plays a critical role in maintaining safety standards. Budget overruns may lead to rushed work or compromises in safety measures, so effective planning and adherence to the budget are essential. Stress and fatigue can increase the likelihood of errors and accidents; promoting a healthy work-life balance, providing support, and managing workloads effectively help mitigate these risks. Environmental factors such as noise and air quality must be controlled to prevent hearing loss, stress, and respiratory problems. Lastly, improper storage or disposal of chemicals can lead to dangerous reactions or environmental pollution, and failure to use protective gear correctly increases the risk of infection, which can affect staffing levels and project timelines.

5. Activity Plan

5.1. Project Management Approach

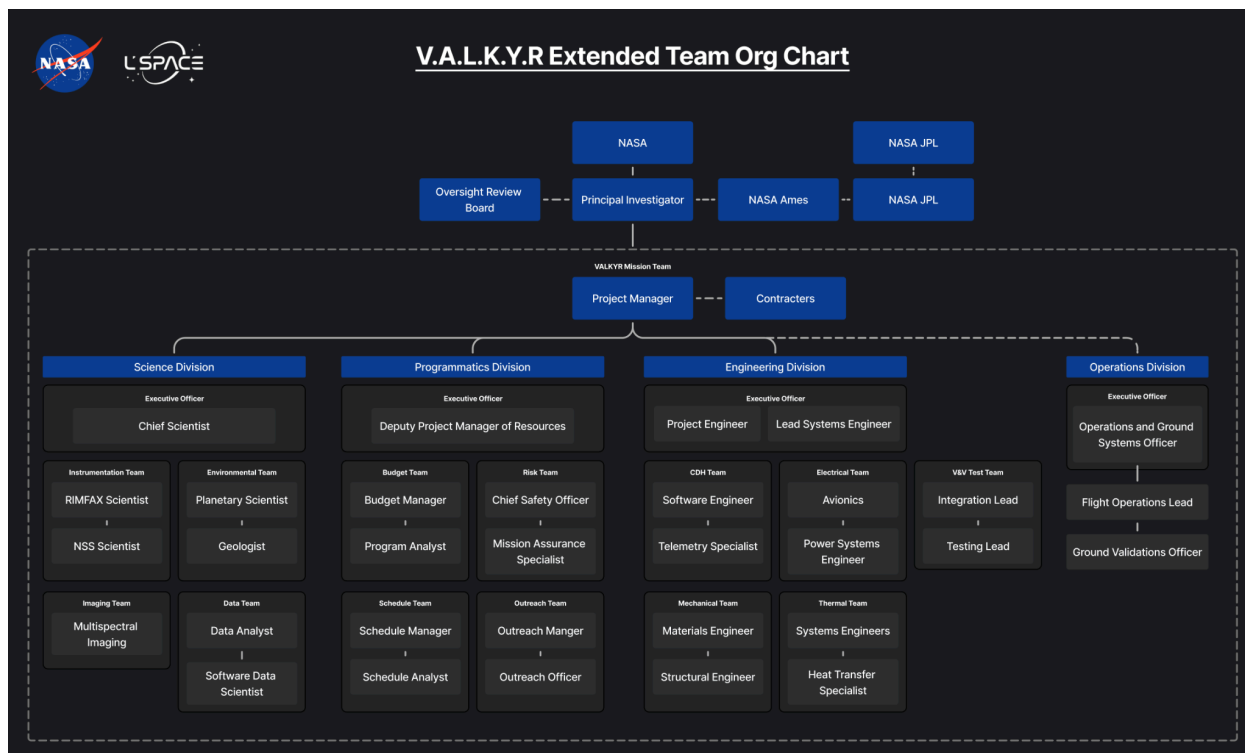


Figure 37. Team Organization Chart

The VALKYR Team is divided into several cross-functional departments including Science, Programmatics, Engineering, and Ground Operations. The Science team will consist of 9 members, growing to 11 members during the sample return stage when more data analysts and software engineers will be needed to process and analyze the data. Engineering Personnel will gradually grow from 10 to 14 between Phase C and Phase F, due to Verification and Validation Procedures, increased dependency on quality assurance professionals, and increased involvement of integration specialists to verify and plan testing procedures. Technicians will be sparse until Phase D when component assembly, integration, interfacing, and functional tests will be performed to ensure optimal performance and anticipate troubleshooting procedures six hours before launch (Knight, 2009). Administration Personnel will remain consistent at 2, with a fluctuation to 4 at Phase D due to increased operational demand during launch operations. Management and executive officers will remain consistent at 4 for the duration of the mission consisting of the Lead Systems Engineer, the Deputy Project Manager of Resources, Chief Scientist, and Project Manager. Refer to the Personnel Chart in Section 5.3.3.

Each division consists of specialized experts with domain expertise (refer to Figure A). The Science team personnel are chosen based on data analysis skills and previous R&D experience, making for a diverse team of experts to tackle complex sample return data and packing this for the general science community. The Programmatic team consists of safety specialists concentrating on analytical skills for calculated decision-making. This team is designed for greater project management expertise, enabling the team to communicate with other subteams to extract important information to make risk-informed decisions. The engineering team is equipped with additional members for launch and integration testing. The Operations team is composed of highly trained professionals in flight and strategic management, making this team well-suited for complex semi-autonomous mission control.

Team leaders are granted a degree of autonomy in managing their internal team operations, including decision-making and day-to-day operations. This is a similar decision-making structure used by the NASA Science Mission Directorate (SMD), which has demonstrated long periods of success for complex missions. However, critical decisions that impact other divisions must be made through consultation with other subteam leaders. When proposing the reduction of solar panels from two to one, the engineering team hosted a meeting with the programmatic team to identify potential risks, including fluctuations in power supply, which better informed this decision. Change requests and decisions are managed through a “Decisions Log” (Reference Section 1.11 Scope Management). However, the budgeting autonomy must be limited. Significant restraints are set in place to ensure that budgets are well-documented and allocations are managed by specialized teams. Division members, and executives, shall not hold the power to make large financial decisions. Rather, specialized financial and programmatic chairs will work with senior management and the NASA board of directors to allocate budget reserves to each subteam and manage decisions made. Extra reserves will be uncommitted for unforeseen challenges that can be used by subteam divisions in emergencies. This limited budget autonomy ensures a strict check on budget overruns in light of the recent descoping VALKYR has experienced (refer to Section 1.11.2). This perspective is endorsed by the Independent Review Board (IRB) who recommend that NASA missions “constrain annual budgets” to limit potential failures from misaligned budget proposals (AIP, 2023).

The engineering team is the largest and most complex division, affording extra organizational attention. It will start with 10 different members and as the mission progresses move into having 4 more. 3 of the original 10 are already taken up by our three subsystem leads, but we will have to make that into 4 because CDH currently does not have a dedicated member and add 2 members onto each of those teams bringing us to 12. This is where we will also include 2 V&V engineers to round out our whole team at 14 members. The leaders of each team will need to be flexible and able

to work across subsystems and the members of each team will need to be experienced with their subsystem, specifically in a space context for added expertise. The team leads are the only ones who can approve usages of budget and reserves and report those all to the LSE. Subteam members will work collaboratively together under their respective subteam leaders.

5.2. Mission Schedule

5.2.1. Schedule Basis of Estimate

The Mission Schedule in Figure 38 is designed to facilitate continuous moderation and change resilience through a meticulous allocation of temporal reserves. A rigorous design procedure is conducted through the identification of and communication with various stakeholders such as the leads systems engineer and contractors to ascertain key engineering decisions impacting the schedule. Under the assumption that no critical delays would occur, the mission will endure for at most 9 years, accounting for periods of planning and congressional review.

The schedule aligns with the U.S. government's fiscal year, which begins on October 1 and ends on September 30 the following year to ensure that Manufacturing plans are synchronized with federal budget cycles. In addition, the VALKYR Program Analyst team will consistently monitor the NASA Acquisition Forecast for up-to-date requirements and anticipated procurements to plan the schedule around (NASA, 2024). To account for manufacturing and procurement times, VALKYR conducts a comprehensive analysis on primary and alternative contractors and their associated lead times, which can be referenced in Section 1.7.

Through the analysis of a forty-mission data set, it is concluded that internal and external growth factors significantly influence schedule delays by 67.5% and 30% respectively (NASA, 2006). To account for possible delays, a 19% schedule reserve margin is applied for internal growth factors and a 5% margin applied for external growth factors. Instrument problems and Launch postponing are primary factors considered when calculating the schedule phases. This estimate is based on historical data from Type B Class Missions such as Apollo 15, 16, and 17 (NASA, 2024). This is contrary to industry standards for more accurate estimations.

The Mission Schedule will endure from September 2024 to September 2028, with the launch date scheduled at September 1st, 2028 and the land date scheduled for September 5th, 2028. The mission lifetime is based on the baseline assumption as a Type B Class Robotics Mission being 2-5 years in length (NASA, 2019). The launch period is due to the estimated travel time from Earth to the Moon which is 3 days for a robotic spaceflight mission traveling approximately 240,000 miles (IPAC, 2024). A 66% margin (2 days) is applied to account for external and internal growth factors in the execution phases for a total of 5 days spaceflight. The return date is scheduled for February 21, 2029. This is due to the total operational period being estimated at 100 days with a 66% (66 day) margin for unexpected logistical demands such as hazard mitigation and communication blackouts during zero-visibility periods. Increased margin

is also applied in anticipation of technical errors, due to the 49% increase in failure rates within the last decade

Baseline assumptions are made to simplify the estimation procedure. One major assumption supposes that there is no critical risk that succinctly compromises the risk, including high priority operational risks and massive budget cuts. At the same time, a comprehensive contingency analysis procedure is conducted at each phase of the mission to ensure that no critical risks and uncertainties are unaccounted for. Schedule performance will be continuously monitored through the Schedule Performance Index, or SPI, to regularly assess points for altering the schedule (NASA, 2021).

5.2.2. Mission Schedule

Phase A

Phase A is sustained through a 13 month period, which includes pre-phase concept development. Due to possible alterations in mission architecture and budget from exchange across various government and contract stakeholders, a 3 month margin is applied. To lay the foundation for future development, Decision-Making Frameworks and Systems Design Procedures must be established. Baseline assumptions and stakeholder alignment is achieved at this period. The 13 month period was calculated according to the estimated time based on the analogous Lunokhod 1 mission ([NASA](#), 1970).

Phase B

Phase B is sustained through a 11 month period. This period requires that a comprehensive systems-level design is curated with feasible and acceptable requirements and risks. A 3-month margin is applied to ensure all risks and mitigation strategies are thoroughly addressed to ensure a robust design foundation is established before proceeding to fabrication planning. This phase is marked by a presentation to the Office of Management and Budget (OMB) for approval ([NASA](#), 2019).

Phase C

Phase C is sustained through a 12 month period. The date January 20th, 2027 was chosen due to the tradition of KDP D being placed at the end of the preliminary design review, ensuring that all designs meet specifications based on the NASA Procedural Requirements (NPR) 7120.5 ([NASA](#) 2024).

Fabrication and assembly plans are developed to ensure design maturity. Communications with government agencies and relevant contractors are sustained through this period to continuously update lead times. Ground Testing Procedures are

finalized for initial tests and evaluations. Trade studies and crosscutting analysis is performed to verify systems compatibility. Configuration management is defined to track communication interfaces within the rover and with ground stations. The Critical Design Review (CDR) is the critical step of this procedure that must be approved before facilities and manufacturing can begin. Due to a higher contingency profile and dependencies on testing facilities and procurement contractors, this time period is calculated with more margin for error.

Phase D

Phase D is sustained through a 13 month period. All facilities and contractors must be consulted, and materials inventory obtained to execute the fabrication plans. The date January 10, 2028 was selected as the milestone for KDP E due to manufacturing and procurement decisions to source contractors near the KSC, travel and integration times have been reduced to a year-long period as opposed to the traditional 1 to 2 year timeframe ([Martin](#) 2011).

During this period, a multi-disciplinary review panel will be held to finalize contractors in preparation for the Critical Design Review (CDR). The VALKYR team will prepare testing at various stages, such as component testing, integration, and systems validation which can delay the timeline to troubleshoot unaccounted errors uncovered in this process. Upon approval of the CDR, VALKYR will maintain consistent contact with manufacturers to monitor fluctuations in cost and potential supply chain issues that could impact procurement times. These potential delays are accounted for in the schedule period. A 3-month margin accounts for integration errors and human error, which accounts for 80-95% of failures and delays ([Johnson](#), 2008). Official launch will occur from Cape Canaveral adjacent to the Kennedy Space Center in Florida.

Phase E

Phase E is sustained through a 60 month period which is the typical operational lifespan of lunar rover missions ([NASA](#) 2019). KDP F is set for October 1, 2028 due to the transition period between systems integration and launch. The typical testing period is 1-2 years before launch, as evidenced by the Mars Exploration Rover (MER) Project that lasted between early 2001 and spring 2003 ([NASA](#) 2024).

This period includes periods for Science Analysis after the Operational period ends. The operational period will expand 6.5 lunar days, or 177 earth days for an 18 km distance before returning imagery to the ground-stations. On-ground software must be properly configured to handle data transfer with the LRO and spacecraft. The concept of operations must be flexible and resilient enough to adapt to unexpected circumstances, due to autonomous, self-correcting systems already in place to mitigate delays on-the-surface. A 5 month period accounts for this uncertainty to ensure that high

quality data is transferred, and that hazards are properly moderated throughout the mission lifecycle. The end of the 177 day period of operations is marked by closeout (EOM).

Phase F

Phase F is sustained through a 3 month period. The Final Data Review is completed September 25, 2033 which is consistent with the standard review period under the NASA Data Management Plan to ensure that all collected data is of utmost quality ([NASA](#) 2018).

This is where data is documented and packaged to ship to relevant stakeholders including government bodies, contractors, and the public sector. VALKYR Scientists collaborate with engineers, data analysts, and communication specialists to translate science data into comprehensible units for the general public. The team will employ a rigorous Data Standardization procedure, where data is translated to specific formats according to protocols. The VALKYR team accounts for the potential delays due to the technical and complex nature of data analysis and potential travel delays.

Outreach initiatives are carried out to full capacity, including sending off key scientists and engineers to share mission updates at scientific conferences such as the AIAA SciTech Forum Presentation (refer to Section 1.5 for more details).

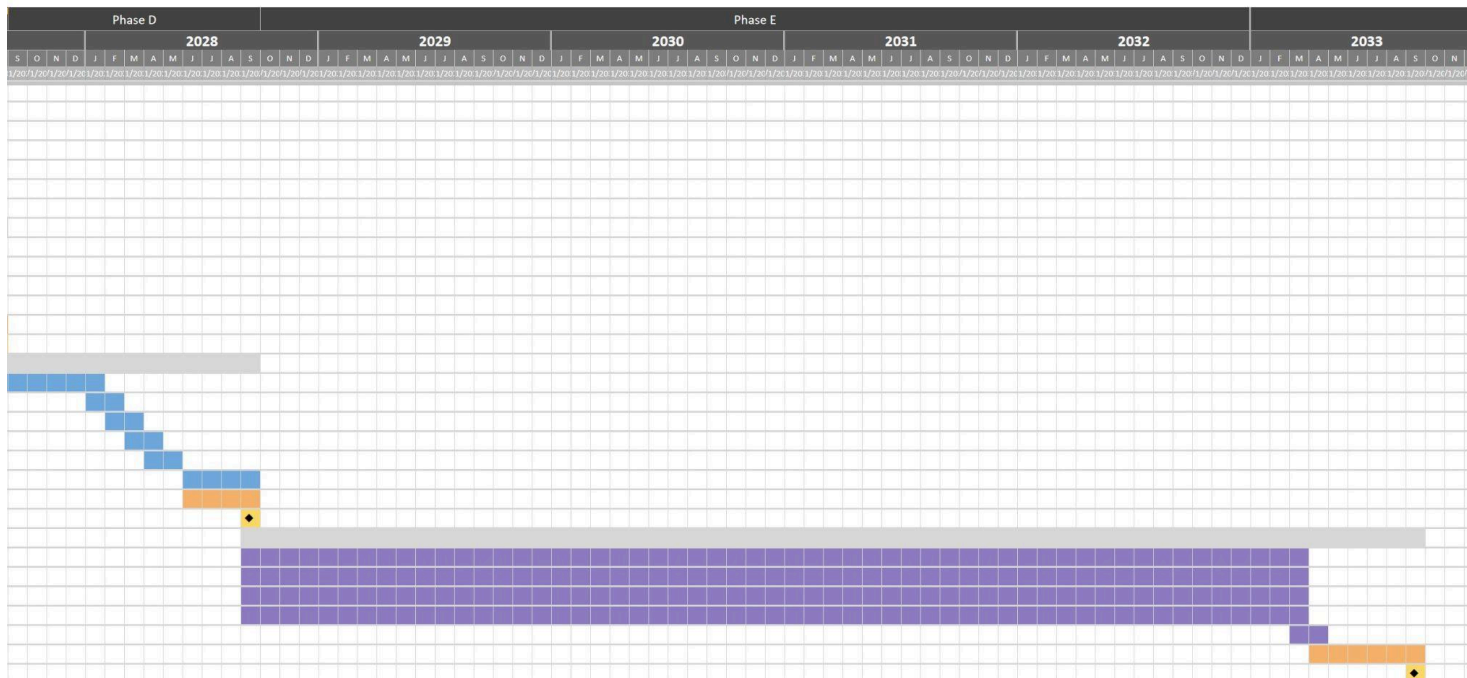
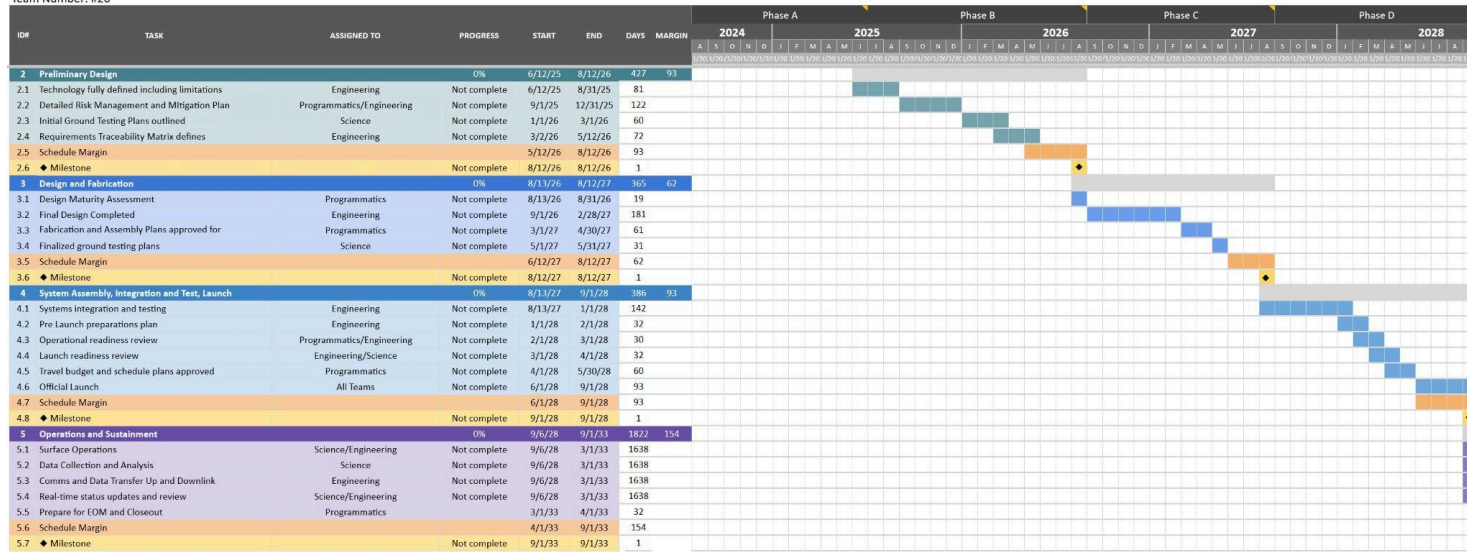
A Gantt chart can be found on the following page which outlines each phase in detail. This serves as the management structure for Mission VALKYR to break down each operational milestone into actionable chunks.

Note: The launch date detailed on the Gantt chart represents the window of time the launch can happen to account for early development.

Figure 38. Mission Schedule

MISSION VALKYR Mission Schedule

Team Number: #26



5.3. Budget

5.3.1. Budget Basis of Estimate

The basis for the budget estimate is largely contingent upon the direct cost subsystems, as most of the funding will pertain to them. The rate of inflation starting at Phase C is consistent with the 2023 inflation rate, 154% from 2004, and rises at a consistent rate of 2.6% throughout each subsequent fiscal year. These inflation rates are taken into account for all cost estimation-related figures. The budgeting allocation and cost estimation should be interpreted in 2023 dollars.

Personnel

All personnel costs are based on a set salary for each role in the mission. These costs are detailed in the table below.

Personnel Salary Estimates	
Science Personnel Salary	\$80,000
Engineering Personnel Salary	\$80,000
Technicians Salary	\$60,000
Administration Personnel Salary	\$60,000
Project Management Salary	\$120,000

Table 45. Salary Of Mission VALKYR

These costs are consistent and realistic in relation to project scope and follow the General Schedule (GS) pay scale ([United States of America](#), 2024).

Travel

All travel costs were calculated with the following criteria: Average economy price of an airline ticket to Orlando, FL from an arbitrary location in the United States, price of a room at the Holiday Inn Express at Cape Canaveral, Price of an Uber from the airport and to Cape Canaveral from the airport, and based off of the Per Diem rate estimation on the GSA.gov website. Each of these subcategories takes phase and personnel count into consideration ([United States of America](#), 2024).

Outreach

All outreach costs are calculated according to ongoing costs of education initiatives and the travel, personnel, and sales collateral costs for exhibitions at Science Conferences. The costs are determined based on historical costs of exhibition engagements landing around \$20,000, grant money donated to K-12 Robotics Competitions, and the cost of art exhibitions. Outreach materials are determined based on historic exhibitions hosted by NASA. Personnel are directly based on the average salary of outreach officers at NASA. Particular phases have significant increases in costs accounting for conference engagements.

Direct Costs

All direct costs are a conglomerate of Mechanical, Power, Thermal, Comms & Data Handling, Payload, and Facilities. Each of these categories takes phase and personnel count into consideration. Each subsystem has an equation that converts the specifications of that subsystem into a cost, shown in thousands of 2004 dollars, and is then converted into 2023 dollars. These equations for each subsystem are detailed in the direct costs section.

5.3.2. Total Mission Cost

The final cost estimate for Mission VALKYR is detailed in the table below.

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
FINAL COST CALCULATIONS							
Total F&A	\$1,228,318	\$1,260,254	\$1,292,190	\$1,324,127	\$0	\$0	\$5,104,889
Total Projected Cost	\$33,122,208	\$34,087,786	\$52,844,225	\$37,813,541	\$4,724,907	\$4,662,189	\$167,254,856
Total Cost Margin	\$1,320,000	\$1,354,320	\$1,578,000	\$2,781,240	\$367,235	\$341,712	\$7,742,507
	4.0%	4.0%	3.0%	7.4%	7.8%	7.3%	
Total Project Cost (Including Margin)	\$34,442,208	\$35,442,106	\$54,422,225	\$40,594,781	\$5,092,141	\$5,003,901	\$174,997,362

Table 46. Final Cost Calculations for Mission VALKYR.

These costs represent the sum of each fiscal year for each category of cost (personnel, travel, direct costs, outreach). The emergency margin is then added to the end total to get the final number highlighted in green.

5.3.3. Personnel Budget

The following table describes the personnel allocation for this mission.

Personnel Allocation Table

	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6
Science Personnel:	9	9	9	9	11	11
Engineering Personnel:	10	10	11	13	14	14
Technicians:	1	1	3	13	5	2
Administration Personnel:	2	2	2	4	3	3
Management Personnel:	4	4	4	4	4	4

Table 47. Allocation of personnel throughout each phase of the mission

This personnel allocation results in the following personnel costs, which include salary and ERE (Employee Related Expenses). The personnel costs are described in the table below.

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
PERSONNEL							
Science Personnel	\$720,000	\$720,000	\$720,000	\$720,000	\$880,000	\$880,000	\$4,640,000
Engineering Personnel	\$800,000	\$800,000	\$880,000	\$1,040,000	\$1,120,000	\$1,120,000	\$5,760,000
Technicians	\$60,000	\$60,000	\$180,000	\$780,000	\$300,000	\$120,000	\$1,500,000
Administration Personnel	\$120,000	\$120,000	\$120,000	\$240,000	\$180,000	\$180,000	\$960,000
Project Management	\$480,000	\$480,000	\$480,000	\$480,000	\$480,000	\$480,000	\$2,880,000
Total Salaries	\$2,180,000	\$2,180,000	\$2,380,000	\$3,260,000	\$2,960,000	\$2,780,000	\$15,740,000
Total ERE	\$608,438	\$608,438	\$664,258	\$909,866	\$826,136	\$775,898	\$4,393,034
Personnel Margin	\$191,400	\$196,376	\$228,810	\$403,280	\$316,958	\$294,930	\$1,631,755

TOTAL PERSONNEL (Excluding Margin)	\$2,788,438	\$2,860,937	\$3,202,559	\$4,495,116	\$4,179,894	\$4,018,165	\$21,545,109
---	-------------	-------------	-------------	-------------	-------------	-------------	---------------------

Table 48. Personnel allocations for Mission VALKYR

Personnel costs consider the following factors: Inflation, number of personnel, and estimated salary for each type of personnel ([NASA](#) 2024). These values are multiplied together to obtain the final values present in the chart above.

Personnel Allocation by Phase

Phase C (Years 1-3):

- **Science Personnel:** Nine members remain consistent to establish a solid research foundation.
- **Engineering Personnel:** Starts with ten, increasing to eleven by Year 3 to support development activities.
- **Technicians:** Increases from one to three by Year 3, aligning with growing technical demands.
- **Administration Personnel:** Two staff members support operational needs.
- **Management Personnel:** Four members provide consistent leadership and oversight.

Phase D (Year 4):

- Personnel needs a peak with thirteen engineers and technicians to handle intensive development and assembly tasks.

Phase E (Year 5):

- **Science Personnel:** Increases to eleven for heightened research activities.
- **Engineering Personnel:** Rises to fourteen for final design and troubleshooting.
- **Technicians:** Reduces to five as focus shifts to operational readiness.
- **Administration Personnel:** Adjusts to three to manage increased documentation.
- **Management Personnel:** Remains at four to oversee activities.

Phase F (Year 6):

- Personnel requirements taper off as tasks move to operations and monitoring, reflecting a stabilization of resources.

The total personnel cost over six years is \$15,740,000, covering salaries essential for hiring skilled professionals. Employee Related Expenses (ERE) total \$4,393,034, accounting for benefits and other employee-related costs. A Personnel Margin of \$1,903,714 provides a financial buffer for unforeseen adjustments. The cumulative total personnel cost is \$21,545,109.

5.3.4. Travel Budget

Each factor of travel costs, which includes flight costs, hotel cost, transportation cost, and per diem cost, had their own unique considerations. These considerations for each factor are detailed below.

- **Flight Cost:** Flight costs were determined by selecting the average economy flight cost from any arbitrary location in the U.S. ([Skyscanner](#) 2024) and multiplying that cost by the number of people and the number of days each person needs to be on-site
- **Hotel Cost:** Hotel costs were determined by selecting an individual hotel ([Holiday Inn Express](#), 2024), and multiplying the number of people by the number of nights staying and the price of the hotel
- **Transportation Cost:** Transportation costs were calculated by averaging the cost of an Uber ([Uber](#), 2024) from the hotel to the site and multiplying by the number of people and the minimum amount of trips needed from the hotel to the site.
- **Per Diem Cost:** Per diem costs were calculated using the official GSA per diem costs at Cape Canaveral for fiscal year 2024 ([United States of America](#), 2024). Each person is given \$8,500 per fiscal year.

Each cost is adjusted for inflation accordingly and shown in the table below.

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
TRAVEL							
Total Flights Cost	\$66,000	\$66,000	\$75,000	\$129,000	\$99,000	\$90,000	\$525,000
Total Hotel Cost	\$76,120	\$76,120	\$86,500	\$148,780	\$114,180	\$103,800	\$605,500
Total Transportation Cost	\$33,000	\$33,000	\$37,500	\$64,500	\$49,500	\$45,000	\$262,500
Total Per Diem Cost	\$26,400	\$26,400	\$30,000	\$51,600	\$39,600	\$36,000	\$210,000
Travel Margin	\$17,160	\$17,606	\$20,514	\$36,156	\$28,417	\$26,442	\$146,295
Total Travel Costs (Excluding Margin)	\$201,520	\$206,760	\$240,908	\$424,603	\$333,717	\$310,524	\$1,718,031

Table 49. Travel Allocations for Mission VALKYR

5.3.5. Outreach Budget

The outreach budget was calculated based on historical budgets spent on Science Conferences featuring frequented NASA presence. The AIAA SciTech Forum Presentation has a membership fee of \$1,000 to \$1,200 for registration, which averages to \$37,000 for a team of 37 personnel during Phase F, when the VALKYR team will travel on-site to deliver the post-mission presentations ([AIAA](#), 2024). In addition, Mission VALKYR invests around \$20,000 in grants delivered to K-12 and upper education communities to host lunar robotics competitions and facilitate educational opportunities for underrepresented communities ([FIRST](#), 2024). Budgets shift over each phase due to periods of conference attendance and exhibition events, which significantly inflate costs. Please refer to Section 1.12 for a detailed breakdown of the budget, including comprehensive explanations of the necessity for each outreach initiative.

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
OUTREACH							
Total Outreach Materials	\$52,192	\$68,015	\$57,323	\$51,818	\$40,289	\$61,425	\$331,062
Total Outreach Venue Costs	\$41,614	\$84,808	\$91,645	\$36,465	\$75,293	\$50,298	\$380,123
Total Outreach Travel Costs	\$54,021	\$88,024	\$6,755	\$8,286	\$1,922	\$79,182	\$238,190
Total Outreach Services Costs	\$74,003	\$82,738	\$93,067	\$76,000	\$43,887	\$74,228	\$443,923
Total Outreach Personnel Costs	\$30,000	\$30,000	\$30,000	\$30,000	\$30,000	\$30,000	\$180,000
Outreach Margin	\$13,200	\$13,543	\$15,780	\$27,812	\$21,859	\$20,340	\$112,535
Total Outreach Costs (Excluding Margin)	\$251,830	\$362,778	\$293,287	\$218,369	\$211,296	\$333,500	\$1,671,061

Table 50. Outreach Allocations for Mission VALKYR

5.3.6. Direct Costs

The direct costs for Mission VALKYR can be broken down into Mechanical, Power, Thermal, Command & Data Handling, Science Instrumentation, Manufacturing, and Testing. Each category below describes how each cost associated with each subsystem was arrived at. All subsystems used NICM CER/SER equations to determine cost. These formulas produce a dollar amount in the thousands consistent with the value of a dollar in 2004. This number is then multiplied by 1000 and multiplied by the rate of inflation in 2023 (154%). These costs are then divided by amount of fiscal years phases C-D take, and evenly distributed throughout each year. Each cost is also multiplied by the estimated rate of inflation that compounds each year. This rate is 2.6%.

Mechanical

Mechanical costs were calculated by the following formula.

$$219 \cdot MechMass^{0.41} \cdot TotalMaxPwr^{0.52}$$

MechMass is the total mass of the mechanical system in kilograms and
TotalMaxPwr is the total maximum power of the mechanical system in watts.

Power

Power costs were calculated by the following formula.

$$1516 \cdot ElecMass^{0.74}$$

ElecMass is the total mass of the power system in kilograms.

Thermal

Thermal costs were calculated by the following formula.

$$642 \cdot ThermMass^{0.62}$$

ThermMass is the total mass of the thermal system in kilograms.

Command & Data Handling

Command & Data handling costs were calculated by the following two formulas.

$$1516 \cdot ElecMass^{0.74}$$

$$236 \cdot ElecMass^{0.69}$$

ElecMass is the total mass of the Command & Data handling system. These two formulas are computed and then added together to get the final dollar amount. The first equation is the same as the power equation, and the second equation is unique to Comms & Data Handling.

Science Instrumentation

Science Instrumentation costs were calculated using the “Active Microwave Instruments” and “Body Mounted In-Situ Instruments” formulas. These formulas are described below.

Active Microwave Instruments

$$1,244 \cdot TotalMass^{0.36} \cdot TotalMaxPwr^{0.50}$$

Body Mounted In-Situ Instruments

$$652 \cdot TotalMass^{0.62} \cdot TotalMaxPwr^{0.44}$$

TotalMass represents the mass of the individual instrument and *TotalMaxPwr* represents the total max power of the individual instrument.

Manufacturing

Manufacturing costs are determined by the following formula.

$$DirectCost + MgmtCost + SysCost + ProdCost + IntCost$$

DirectCost represents the total cost of all subsystems *MgmtCost*, *SysCost*, *ProdCost*, and *IntCost* are all determined with their separate formulas which are dependent on *DirectCost*. These formulas are detailed below.

MgmtCost

$$0.11 \cdot DirectCost^{0.95}$$

SysCost

$$0.24 \cdot DirectCost^{0.89}$$

ProdCost

$$0.01 \cdot DirectCost^{1.1}$$

IntCost

$$0.03 \cdot DirectCost^{1.11}$$

Testing

Testing costs are determined by the following formula.

$$TVAC + EMI + VIBE + Ambient$$

Each variable in this formula has its own formula that is dependent on the final manufacturing cost. This variable is represented by *ManuCost*.

$$TVAC \\ ManuCost \cdot (0.3 \cdot 0.5)$$

$$EMI \\ ManuCost \cdot (0.3 \cdot 0.25)$$

$$VIBE \\ ManuCost \cdot (0.3 \cdot 0.125)$$

$$Ambient \\ ManuCost \cdot (0.3 \cdot 0.125)$$

All individual costs are detailed in the chart below.

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
DIRECT COSTS							
Mechanical Subsystem	\$3,576,775	\$3,576,775	\$3,576,775	\$3,576,775	\$0	\$0	\$14,307,102
Power Subsystem	\$4,335,739	\$4,335,739	\$4,335,739	\$4,335,739	\$0	\$0	\$17,342,956
Thermal Control Subsystem	\$953,265	\$953,265	\$953,265	\$953,265	\$0	\$0	\$3,813,060
Comms & Data Handling Subsystem	\$758,986	\$758,986	\$758,986	\$758,986	\$0	\$0	\$3,035,944
Guidance, Nav, & Control Subsystem (TBD)	-	-	-	-	-	-	\$0
Science Instrumentation	\$2,658,413	\$2,658,413	\$2,658,413	\$2,658,413	\$0	\$0	\$10,633,653
Spacecraft Cost Margin	\$438,240	\$449,634	\$523,896	\$923,372	\$0	\$0	\$2,335,142
Total Spacecraft Direct Costs	\$12,283,179	\$12,602,541	\$12,921,904	\$13,241,267	\$0	\$0	\$51,048,891

(Excluding Margin)							
Manufacturing Facility Cost	\$12,591,480	\$12,591,480	\$25,514,314	\$12,922,834	\$0	\$0	\$63,620,107
Test Facility Cost	\$3,777,444	\$3,777,444	\$7,654,294	\$3,876,850	\$0	\$0	\$19,086,032
Facility Cost Margin	\$660,000	\$677,160	\$789,000	\$1,390,620	\$0	\$0	\$3,516,780
Total Facilities Costs (Excluding Margin)	\$16,368,923	\$16,794,515	\$34,893,376	\$18,110,060	\$0	\$0	\$86,166,875

Table 51. Direct Cost Allocations for Mission VALKYR

5.4. Scope Management

5.4.1. Change Control Management

Mission VALKYR adheres to a strict procedure for managing change to ensure that clear procedures are adhered to when processing and mitigating risks associated with changes. The mission aligns with the NASA Configuration Control Management System (CCM) following a systematic procedure of root cause analysis, change identification, effect traceability, change proposal, and documentation ([NASA](#) 2021) . This procedure is executed through cross-involvement of external stakeholders, the management team, relevant personnel, and contractors who collectively identify baseline requirements for the change. A rigorous internal procedure is similarly carried out by recording all change requests in a formal audit document (Figure A) and their associated status throughout the lifecycle of the mission's development. A comprehensive report of reasoning must be delivered alongside each change request, establishing its necessity relative to the science objectives or maintenance of acceptable risks.

The procedure begins with a crowdsourcing methodology that allows all team members, regardless of position, to contribute changes by documenting these in the change audit document. The Risk Analyst, Project Manager, and Subteam Lead will then host a boardroom meeting to review the change, assign risk, and priority level in alignment with the Risk-Informed Decision Making (RIDM) Method. Deliberations and open discussion take place through a democratic process, where a final vote will be taken to decide on the change proposal's criticality and relevance to the mission goals. Given change requests with multiple dependencies, a comprehensive impact analysis is performed through the Programmatic Team to assess impacts on risk profiles and cost. For instance, when evaluating the requested reduction of solar panels from two to one, a comprehensive trade study was conducted in collaboration between the Electrical Engineers and Risk Analyst to identify possible alternatives and validate the decision.

Following the identification of necessary changes, the VALKYR management team will issue a formal change request report submitted to the MSFC Form 4657, the official NASA Change Request Standard ([NASA](#) 2021). The submission must identify the issue at hand, relevant contingencies and dependencies on the issue, and how the requested change addresses this. The status upon submission will be carefully monitored and communicated with the team while other alternative plans put in place in the event of a rejected proposal ensures that the mission continues to move forward.

Following approval from the Review Managers and Standard Review Board (SRB), Mission VALKYR will institute a comprehensive procedure to ensure closure of the proposed change. The leadership team will reconvene to review stakeholder feedback

and select changes to implement in alignment with the mission's scope. Feedback will be sorted and prioritized in categories based on impact, urgency, and alignment with project goals through the Team's Task Management System. Requests for Action (RFA) will be judged on a stricter criteria than Advisory Comments (ADV) due to requirements for formal tracking and submission closure reports that require extra attention. Each relevant team lead is responsible for curating a detailed response plan in joint evaluation with the team's available resources and timeline margins.

Throughout the implementation period for approved changes, the Continuous Risk Management System (CRM) will be set in place to ensure that contingencies are consistently managed as a result of the change. Implementation is tracked in modules through an Actions Log with associated dates, status, and responsible parties moderated by the management team. The Change Process is finalized once final closure is achieved. These records are maintained internally by the team to ensure traceability and future reference.

Table 52. Change Control

ID	Category	Decision	Responsible Party	Risks involved	Date	Rationale	Approved?
D002	Subsystem	Change of rover's power system storage	Power Subsystem Lead	The system used the batteries as the main power storage system and used the supercapacitor as a backup for failure. The risk that arises is that the power reservoir (backup) is now being used for two purposes instead of one.	2024-06-17	To reduce costs and mass, the rover now depends on a hybrid system that uses both batteries and a supercapacitor.	Approved
D003	Subsystem	Addition of new component (SMS)	Power Subsystem Lead	Integrating the hybrid model makes the vehicle more reliable; however, it adds some extra weight.	2024-06-17	Due to the change in the power system's storage a supercapacitor management system (SMS) is needed.	Approved
D004	Subsystem	Change of rover's solar panels quantity	Power Subsystem Lead	No risk is involved in this change since the solar panel is custom made to fit our requirements.	2024-06-17	In order to reduce cost and mass the solar panels have been reduced to just one instead of two.	Approved
D005	Subsystem	Change in sun sensor quantity.	Mechanical Subsystem Lead	No risk is involved in this change since one sun sensor will be able to track the sun's direction effectively.	2024-06-18	To reduce cost and mass. One sun sensor will be enough to effectively track the sun's position to ensure the solar panels are aligned properly.	Approved
D006	Subsystem	Change in electric actuator quantity.	Mechanical Subsystem Lead	No risk is involved in this change since the power system has been reduced to one solar panel.	2024-06-18	To reduce cost and mass. Only one electric actuator is needed since there will only be one solar panel.	Approved

5.4.2. Scope Control Management

Overall Scope Management Strategy

The primary mitigation strategy centers on stringent prioritization of high-value science data. This approach leverages existing infrastructure and open-sourced scientific methods, ensuring that the mission objectives are met despite budget constraints. The Work Breakdown Structure (WBS) will subdivide the project scope into modulated components, facilitating better management of cost, schedule, and performance data to understand interdependencies between elements. This approach enables prioritization of factors that hold the greatest risk of mission cancellation. Continuous monitoring of the project health will align performance to established objectives throughout the scope management lifecycle. The Earned Value Management (EVM) technique is an effective monitoring technique for project performance that integrates scope, schedule, and cost parameters. This allows for early detection of scope creep, based on the Journal of Modern Project Management. A phased approach is employed to identify and prioritize the most critical science objectives, with emphasis on resources and design choices that directly impact data return. This structured prioritization ensures that key scientific goals remain achievable even under reduced budgets.

Addressing the Mission Descope

The recent budget cut necessitated a strategic reevaluation of the mission's scope, focusing on maintaining the integrity of critical science objectives while re-evaluating unnecessary components. The WBS was leveraged to systematically identify and prioritize essential tasks that contribute to quality science data. This method ensures that, despite reduced resources, the mission's core objectives remain achievable. According to the research in the *International Journal of Project Management*, WBS is effective in maintaining project docs by breaking down complex tasks into manageable components, allowing for targeted descoping that minimize disruption to mission-critical goals. Decomposing each task level based on the concept of operations timeline (refer to the Concept of Operations section) enabled targeted descoping of areas that contributed less to mission success. Specifically, a lowered Technology Readiness Level (TRL) for the instruments, such as the Neutron Spectrometer System (NSS) was deemed an acceptable tradeoff to maintain the data processing reliability of the CDH subsystem (a higher priority task). Data processing demands significantly more time, where subsystem failures can jeopardize all data stored, while lowering instrumentation TRL maintains core operational integrity with only minor performance issues that can be mitigated through increased testing (Review FMEA Analysis). A study from MIT

highlighted the CDH system can critically impact schedule delays due to multiple potential points of failure during the data processing procedure ([Kenley et al. 2012](#)).

Additional engineering components were systematically evaluated under the WBS Structure. Specifically, the mission has implemented the following changes:

1. A reduction from two to one Solar Panel was identified as a strategic move to reduce mass and cost without jeopardizing the necessary power supply. The efficiency of the supercapacitor will be enhanced to increase storage efficiency instead of increasing collection, a proven effective way to manage power under a constrained operational environment ([G.F. Dubos et al. 2007](#)).
2. A reduction of Electric Actuators to one accompanies the reduction in solar panels which optimizes mass and cost while maintaining sufficiency mechanical support.
3. A reduction of sun sensors to one accompanies the reduction in solar panels to reduce component redundancy while maintaining operational capabilities.
4. A change in the Structural-Thermal Model (STM) is driven by the reduction of systems complexity while maintaining necessary data protection.

Overall, these changes collectively maintained the core science objectives while optimizing resource allocation toward essential systems such as CDH and incorporating a larger supercapacitor. The WBS process facilitated a detailed evaluation of areas with least impact on the mission's core objectives. The EVM technique will be applied to monitor project performance continuously throughout the budget cut to enable teams to make iterative, informed decisions on resource allocation. In the event of additional funding, the mission will work to enhance scientific returns. This could include reintegrating descope components and improving the data collection reliability through improved TRLs. A phased approach to scope expansion would allow the team to prioritize integration based on mission-critical needs and resource availability.

Addressing Mission Scope Increase

If additional funding is received, the team would prioritize the integration of advanced components and increased reliability of components that directly impact science collection. The WBS would guide this process to address the most critical elements first to maximize the mission's scientific return. The additional time gained from a delayed launch would be used to further refine and test the components through additional V&V testing before deployment.

Additional funding would be allocated to increasing the TRL of critical instruments and subsystems. In addition, additional testing and simulations would be pursued to mitigate failure. A Ground And Flight Data (GFDS) System will be developed to facilitate smoother interactions between the mission operators and spacecraft. This system would also enhance data evaluations post-mission. A delayed launch date will be used for additional systems integration testing to optimize rover performance.

Forecasting Future Scope Management

The scope management plan for future planning incorporates advanced forecasting and simulation techniques widely used in the aerospace industry, such as Monte Carlo simulations, decision trees and scenario planning. These methods allow the team to anticipate potential challenges and proactively adjust scope to mitigate risks that can lead to mission cancellation. Monte Carlo Simulations will be used to model the probability distribution of outcomes based on cost, schedule, and technical performance parameters. This is helpful for assessing the risk of possible scenarios that evolve from different decision points. For example, it can predict the likelihood of a project delay from a reduction in instrumentation TRL, helping the team prepare contingency plans or select a less risky area to descope ([K.C. Robert et al. 2012](#)). Decision trees help map decisions and their associated risks and rewards. This can determine whether descope of non-critical components would yield high return on mission success or whether reinvestment in other areas would be more beneficial. Scenario Planning will be used to identify potential risk scenarios caused by a descope measure and whether mitigation actions effectively balance risk, cost, and schedule when addressing them. For example, calibration failure of an instrument due to lower TRL can be pre-planned to ensure mission continuity (G.F. Dubos et al. 2007). These methodologies are versatile and can be adapted across different levels of the mission lifecycle depending on mission needs.

5.5. Outreach Summary

The VALKYR Outreach Strategy recognizes the importance of delivering trustworthy and publicly accessible science. The mission's outreach initiatives are designed to facilitate community discussion on the most critical questions regarding the presence of life-sustaining volatiles on the lunar surface. Our strategy includes strategic engagement at aerospace conferences and research partnerships to increase public discussion over our mission objectives within the general science community.

Due to the required descoping of the mission, outreach efforts have shifted toward crowdsourced science through citizen-led research and public science forums to disseminate complex data. The mission dedicates \$1,835,811 to continuous youth engagement and workforce development programs in addition to STEM conferences to promote citizen-led research initiatives. A dedicated office for outreach initiatives ensures special attention is given to translating complex scientific concepts gathered throughout the mission into educational engagement opportunities for the general public.

Table 53. Breakdown of Activities

ID	Activity	Location	Goal of Activity	Details of Activity	Success Metric
1	AIAA SciTech Forum Presentation	Reston, VA	Dissemination of Science data to the Science community to promote research.	VALKYR representatives will present at the annual aerospace conference with 6,000 attendees and 1,100 government groups, showcasing scientific discoveries from the mission in an easy-to-understand way.	Number of research collaborations formed, measured by signed MoUs
2	K-12 Simulated Lunar Mission Challenge	National	Hands-on engagement with the youth community.	In partnership with the FIRST Robotics Competition Nonprofit, VALKUR will sponsor a robotics challenge to design and develop a Lunar Rover Mission Concept.	Percentage of participants pursuing further STEM education, tracked through a follow-up survey
3	Partnership with MUREP to host continuous workshops	National	Engage underrepresented research communities.	In partnership with the Minority University Research & Education project funded by NASA, VALKYR will sponsor fellowship opportunities to learn and engage in hands-on projects relevant to the mission.	Number of mission-relevant research papers published by participants, tracked by citations

4	Digital VALKYR Gallery, ARTECHHOUSE partnership	Washington, DC	Effectively communicate the exciting nature of the mission to the general public.	ARTECHHOUSE is an established NASA partner. VALKYR will host an immersive, digital art experience demonstrating the exciting nature of the mission to the general populace.	Number of visitors over time, measured in weeks and months
5	USA Science & Engineering Festival	San Diego, CA	Engage Higher Education Communities.	VALKYR will establish an interactive exhibition showcasing the latest mission discoveries with live demonstrations and meet-and-greets with NASA experts.	Number of visitors over time, measured in weeks and months
6	Digital Exhibition on the NASA website	Digital	Engage the digital community through social media.	VALKYR will adopt a dedicated page on the nasa.gov website to display recent scientific discoveries and to create an interactive platform for digital nomads to explore detailed profiles of the mission subcomponents.	Number of viable crowdsourced ideas submitted, measured by contribution to mission

Science Community

In light of budget cuts during the Systems Design Processes in Phase A, the involvement of the science community has become of utmost importance to the VALKYR mission. Crowdsourcing science and funding research initiatives will become critical sources of ideas and data analysis that reduce the personnel costs for the mission. Active participation in research conferences such as the AIAA SciTech Forum supports the dissemination of mission operations to the brightest minds in the science community. This not only secures immediate feedback on the mission goals from the science community, but aids in forming strategic research partnerships. In addition, VALKYR will host public exhibitions sharing in-house research and science data with participants, increasing appreciation for the VALKYR mission as a whole. To measure the effectiveness of this approach, the primary metrics will be the number of signed Memorandums of Understanding (MoUs) which serve as documents of intent for future research collaborations. The goal is to secure at least 5 high-impact partnerships that result in actionable research supporting Artemis' science objectives.

K-12 Schools

VALKYR strives to develop the next generation of scientists and engineers through hands-on, mission-congruent experience that exposes youth to experiences relevant to the mission concept. The primary initiative involves a partnership with the FIRST Robotics Competition, an international Nonprofit Organization dedicated to hands-on

robotics manufacturing with a series of gamified competitions. VALKYR will sponsor the 2026 Season Robotics Challenge with a rover design concept congruent to the VALKYR lunar rover. This initiative will create an exciting platform for knowledge development and hands-on industry experience for youth. In addition to sponsoring this challenge, the VALKYR Team will be equally engaged in digital webinars and visits to local K-12 schools to share the mission's purpose and engineering process in an accessible way. A tailored design engineering curriculum and handbook will be developed in partnership with FIRST to inspire the next generation of innovators with the tools and resources they need to excel. Follow-up surveys and enrollment data will be used to assess participation in further STEM education, with a target of 30% of participants enrolling in STEM programs post-competition.

Universities and Higher Education

VALKYR will partner with several high-education institutions, including the NASA Community College Aerospace Scholars Program (NCAS), to increase accessibility to complex engineering design topics relevant to the design process of the VALKYR Lunar Rover. The initiative includes a significant partnership with the USA Science and Engineering Festival which includes a public exhibition of the VALKYR Mission and Research findings. The goal is to inspire the next generation of collegiate researchers to sponsor and propose programs at their universities relevant to volatile chemical composition or relevant scientific analysis to the mission. Representatives of the VALKYR Team will host guest lectures and speaker engagement events at universities to encourage active university engagement with aerospace initiatives. The goal is to receive at least 10 high-quality research proposals that can be integrated into the mission's strategy. The relevance and alignment of these proposals will be rigorously assessed to ensure they contribute directly to the mission's success.

Community Engagement

VALKYR's primary objective prioritizes the wide dissemination of information to the general public. The mission's strategic initiative prioritizes community exhibitions that present complex scientific data in artistically engaging ways. The partnership with the ARTECHOUSE is in the most favorable position for growth, due to existing demonstrations of the James Webb Space Telescope and "Beyond the Light" hosted in partnership with NASA (NASA, 2023). The VALKYR Team will be an active participant during the design procedure and collaborate in ensuring a balance between scientific accuracy and artistic integrity. Recognizing the importance of democratizing scientific knowledge for the general public, this partnership is an effective way to create engaging

experiences to bring space science to life. The success of this event will be measured by the number of visitors over time and qualitative surveys with feedback. A sample of a poster and merchandise for these events is shown below. An example of the gift shop to support public appreciation and to increase funding for the mission is also represented below.

Figure 39. Community Engagement



Underrepresented Communities

VALKYR is committed to involving representatives from all backgrounds, genders, ethnicities, and socioeconomic backgrounds in the mission design. In partnership with the Minority University Research and Education Project (MUREP) under NASA (NASA, 2024), VALKYR will establish research and fellowship opportunities to accelerate the progress of the mission and to ensure accessibility of Earth science data to underserved communities. VALKYR will make efforts to instate Language Access Plans to translate mission details across multilingual communities, making communication of the mission objectives more accessible. Given the systematic barriers present in a meritocratic and science-driven group, the mission team has determined it necessary to conduct targeted outreach and grant programs to historically underrepresented groups to increase access to workforce development opportunities. The success of these initiatives will be measured by the number of mission-relevant research papers published by participants, with a specific focus on papers that are cited and integrated into the mission's strategy. The goal is to produce at least five peer-reviewed papers that contribute directly to mission outcomes.

Digital Presence

VALKYR will maintain a consistent and wide-reaching online presence through immersive digital experiences and a comprehensive mission introduction on the official NASA webpage. The design must include a concise summary of the mission's objectives and alignment with the strategic goal of lunar sample collection, as stated in the most recent decadal survey. Key mission details including the planned launch date, mission duration, and the spacecraft technology will be detailed for public transparency. Continual updates and extraneous resources and media will be publicly available for educational purposes. The website's objectives are to define the science objectives, instrumentation, and mission operations colloquially, to encourage public discussion over the mission. The primary metric for this initiative will be the number of feasible crowdsourced ideas submitted, with success measured by the implementation rate of these ideas and their contribution to the mission strategy. The target is to receive at least 20 high-quality submissions, with a minimum implementation rate of 25%.

A Robust social media campaign will also be launched to extend the reach of a national audience. A sample of the social media posting schedule is below.

Table 54. Sample Social Media Posting Schedule

Day	Platform	Content	Visuals
Monday	Instagram	Behind-the-scenes look at VALKYR's mission control team, focusing on the tech and teamwork. Incorporating a human element further engages layman audiences.	Photo of the Mission Control Station and Operators managing the console.
Wednesday	Twitter	Fun fact about lunar exploration and exploration of the lunar poles (ex: studying ice deposits which have been untouched for billions of years) with a link to VALKYR's latest blog post on the NASA website.	Gif of the Lunar PSRs
Friday	Instagram	Short video clip from the ARTECHOUSE partnership exhibit showcasing the mission's art-science collaboration.	Video Reel Preview
Sunday	LinkedIn	Professional update on VALKYR's latest research findings, targeting the academic and professional community.	Research data visualization

6. Conclusion

The next milestone for the team would be to collaborate on all of their data more succinctly. Each subsection has been working diligently to integrate information and with further reiterative collaboration the team can continue to resolve areas of concern. The science team can help support any additional research required to help provide plausible solutions or potential parameters based on the research. The mechanical team is working towards defining and finalizing manufacturing procurement along with CAD models and 2-D drawings for the rover. The CDH team is working on ensuring the accuracy of all of their information. Programmatic is working to ensure the mission success criteria, budget, and schedule are updated to achievable and acceptable risks for each subsystem.

Should the team be given additional time the science team would have been able to work directly with the engineering team on further analysis of their created system and how closely related it is to current systems researched. The mechanical team would also look to define more risks to mitigate as well as the mass and dimensions of the rover. The CDH Team would contact potential suppliers to get updated lead times and begin ordering the components of the CDH system to be put together. Programmatic would have engaged in more collaborative sessions with engineers and the science team for further risk analysis and mitigation.

For the MDR, a comprehensive timeline was developed to outline the lifecycle of the Mission Definition Review. The timeline was separated into two separate “Sprints” in alignment with an Agile Management Architecture. This ensured that Programmatic could progress on stand-alone tasks that were not dependent on the engineering and science teams. This gave more time for Systems Requirements to get finalized and approved with confidence so that the handoff between engineering and programmatic the second Sprint would be clear without anomalies. In addition, a breakdown of deliverables by department and “primary” owner gave ownership to team members over their tasks. Clear expectations were established and extraneous activities such as weekly assignment forms were removed to ensure that efforts were focused on the final deliverable. Each team collaborated to help drill down into their respective efforts to see the end product through to completion.

Moving forward further collaborations between subteams will help refine the mission to the final sprint. The mechanical team in defining, formalizing, and creating alternatives to the manufacturing and procurement of mechanical components and updating the CAD. The CDH plans to acquire an accurate lead time estimate for each manufacturer. The science team plans to fill in any discrepancies in information. The programmatic team will hold the team accountable for financial and scheduling constraints.

References

- AAC Clyde Space. "Sweden's AAC Clyde Space Solutions Rocket to the Moon." AAC Clyde Space. Accessed July 20, 2024.
<https://www.aac-clyde.space/case-studies/swedens-aac-clyde-space-solutions-rocket-to-the-moon/>.
- A123 Systems. "26650 Battery Datasheet." Accessed July 21, 2024.
https://a123batteries.com/product_images/uploaded_images/26650.pdf.
- Ansari, M. S. I., & Haq, M. A. (2018). Radar Imager for Mars' subsurFAce eXperiment: A HIGH RESOLUTION GROUND PENETRATING RADAR FOR MARS. In 39th Asian Conference on Remote Sensing: Remote Sensing Enabling Prosperity, ACRS 2018.
- Avnet. "Inertial Measurement Units (IMU)." Accessed July 21, 2024.
<https://www.avnet.com/shop/us/c/sensors-transducers/motion-position-sensors/inertial-measurement-units-%28imu%29/>.
- Barry, Caela. n.d. "Weather on the Moon." science.nasa.gov. Accessed June 3, 2024.
<https://science.nasa.gov/moon/weather-on-the-moon/>.
- Campola, Michael, and Ken LaBel. 2021. "Single Event Effects." RadHome.
<https://radhome.gsfc.nasa.gov/radhome/see.htm>.
- Cheng, Li, and Robert Williams. 2021. "Thermal Management of Electronics in Space: Challenges and Solutions." *IEEE Transactions on Aerospace and Electronic Systems* 57 (3): 1125-1134. <https://doi.org/10.1109/TAES.2021.3058267>.
- Cool Cosmos. "How Long Does It Take to Travel to the Moon?" Accessed July 20, 2024.
<https://coolcosmos.ipac.caltech.edu/ask/174-How-long-does-it-take-to-travel-to-the-Moon->.
- Dixit, Mrigakshi. (2023). "How Space Radiation Threatens Lunar Exploration." Smithsonian Magazine.
<https://www.smithsonianmag.com/science-nature/how-space-radiation-threatens-lunar-exploration-180981415/>.
- Doe, John, Sarah Thompson, and Emily Walker. 2020. "Active Thermal Control in Spacecraft: Techniques and Applications." *Progress in Aerospace Sciences* 123: 1-17. <https://doi.org/10.1016/j.paerosci.2020.100630>.

- Duke, Michael B. 2006. "Development of the Moon." *Reviews in Mineralogy and Geochemistry* 60, no. 1 (January): 597–655.
<https://doi.org/10.2138/rmg.2006.60.6>.
- EaglePicher. "Lithium-Ion Battery Chemistries." Accessed July 21, 2024.
<https://www.eaglepicher.com/technology/battery-chemistries/lithium-ion/>.
- Foust, Jeff. "Supply Chain Challenges Also Present Opportunities for the Space Industry." *SpaceNews*, July 17, 2023. Accessed July 20, 2024.
<https://spacenews.com/supply-chain-challenges-also-present-opportunities-for-the-space-industry/>.
- Glenair. "PowerTrip Connectors." Accessed July 21, 2024.
<https://www.glenair.com/powertrip/index.htm/>.
- IMPERX. "CMOS Cameras: SFP-C1640." Accessed July 21, 2024.
<https://www.imperx.com/cmos-cameras/SFP-C1640/>.
- Johnson, Philip, and John Burgee. 2023. "HORUS — Identification and Characterization of Science Targets and Hazards in Shadowed Regions Across the Artemis Exploration Zone." *Artemis III Landing Regions*.
<https://ui.adsabs.harvard.edu/abs/2023LPICo2989.2021B/abstract/>.
- Jost, Kevin. "NASA Awards Lunar Terrain Vehicle Contracts for Artemis Missions." *Futurride*, April 4, 2024.
<https://futurride.com/2024/04/04/nasa-awards-lunar-terrain-vehicle-contracts-for-artemis-missions/>.
- Kenley, C. Robert, and Bernard El-Khoury. "An Analysis of TRL-Based Cost and Schedule Models." April 30, 2012. Accessed August 11, 2024.
<https://dspace.mit.edu/handle/1721.1/84014>.
- Kring, David. 2023. "Elevation Changes and Slope that May Affect EVA Workload Near Potential Artemis Landing Sites." *IEEE* 1, no. 1 (June): 1-17.
- Lin Engineering. "BL17E19-01." Accessed July 21, 2024.
<https://www.linengineering.com/products/brushless-motors/standard-bldc-motors/bl17-series/bl17e19-01/BL17E19-01/>.

- Maxon Group. "GPX22 3-Stage Planetary Gearhead." Accessed July 21, 2024.
<https://www.maxongroup.com/maxon/view/product/gear/planetary/GPX/GPX22/GPX22-3-Stufig-A/GPX22AAKLSL0111CPLW/>.
- Microchip Technology Inc. "SA50-120-12S." Accessed July 21, 2024.
<https://www.microchip.com/en-us/product/SA50-120-12S/>.
- Midwest Aero. "Linear Actuator Exchange." Accessed July 21, 2024.
<https://www.midwestaeroltd.com/product-page/linear-actuator-exchange/>.
- Moriarity, Daniel. 2024. "Mineralogical Characterization of the Lunar South Polar Region: 1. The Artemis Exploration Zone." *JGR Planets* 129, no. 4 (April): 2043-2-65.
- Mouser Electronics. "Product Matrix." Accessed July 21, 2024.
https://www.mouser.com/datasheet/2/257/ProductMatrix_3000489_3-1863549.pdf/.
- NASA. "Commercial Lunar Payload Services." NASA. Last modified October 24, 2023.
<https://www.nasa.gov/reference/commercial-lunar-payload-services/>.
- NASA. 2023. "Exploration Systems Development Mission Directorate." NTRS.
https://ntrs.nasa.gov/api/citations/20230002706/downloads/M2MADD_ESDMD-01%28TP-20230002706%29.pdf/.
- NASA. "Success, Failure, and NASA Culture." NASA APPEL Knowledge Services, September 1, 2008. Accessed July 20, 2024.
<https://appel.nasa.gov/2008/09/01/success-failure-and-nasa-culture/>.
- National Aeronautics and Space Administration. "Commercial Lunar Payload Services." NASA. Last modified October 24, 2023.
<https://www.nasa.gov/reference/commercial-lunar-payload-services/>.
- Nguyen, Minh, and Andrew Roberts. 2018. "Risk Mitigation in Spacecraft Design: Thermal Subsystem Focus." *Acta Astronautica* 156: 48-56.
<https://doi.org/10.1016/j.actaastro.2018.01.003>.
- Podder, Prajoy, Tanvir Zaman Khan, Mamdudul Haque Khan, and M. Muktedir Rahman. "Comparative Performance Analysis of Hamming, Hanning and Blackman

- Window." *International Journal of Computer Applications* 96, no. 18 (June 2014). Khulna University of Engineering & Technology, Khulna-9203, Bangladesh.
- Poppe, AR, and S. Xu. 2021. "ARTEMIS Observations of Lunar Nightside Surface Potentials in the Magnetotail Lobes: Evidence for Micrometeoroid Impact Charging." *Geophysical Research Letters* 48, no. 15 (August): 3.
- Prem, Parvathy. n.d. "Lunar Volatiles and Solar System Science," A White Paper Submitted To The Decadal Survey in Planetary Science and Astrobiology 2023-2032. arxiv.org. <https://arxiv.org/pdf/2012.06317>.
- Pumpkin Space Systems. "Lunar Rover Solar Panel." Accessed July 21, 2024. https://www.pumpkinspace.com/store/p217/Lunar_Rover_Solar_Panel.html/.
- QCC. "Dyna-Plus Actuators (Formerly Barber Colman)." Accessed July 21, 2024. <https://www.qcc.parts/store/Dyna-Plus-Actuators-Formerly-Barber-Colman-c33898043/>.
- Repository, Georgia Tech. "AIAA 2007-6020-357." Accessed August 11, 2024. <https://repository.gatech.edu/bitstream/handle/1853/26285/AIAA-2007-6020-357.pdf>.
- Rocket Lab USA. "Solar Systems." Accessed July 21, 2024. <https://www.rocketlabusa.com/space-systems/solar/>.
- Russell, Patrick. 2021. "Mars 2020 Radar Imager for Mars' subsurFAce eXperiment (RIMFAX) PDS Archive Calibrated Data Record (CDR) Software Interface Sp." PDS Geosciences Node. https://pds-geosciences.wustl.edu/m2020/urn-nasa-pds-mars2020_rimfax/document/rimfax_cdr_sis.pdf.
- Sathyan, Sachana, Megha Bhatt, Monalisa Chowdhury, Philipp Glaser, Dibyendu Misra, Neeraj Srivastava, Shyama Narendranath, K.S. Sajinkumar, and Anil Bhardwaj. "Potential Landing Sites Characterization on Lunar South Pole: De-Gerlache to Shackleton Ridge Region," 2023.
- Schaefer, Bernd, and Srivatsan Seeni. "IAC-08-B4.4.6 - Wireless Communication for Mars Rovers and Sensor Networks." German Aerospace Center (DLR), 2008.

- Accessed July 20, 2024.
https://elib.dlr.de/55987/1/IAC_Final_Manuscript_Schaefer_Seeni.pdf/.
- Skeleton Technologies. "SkelCap Cells Datasheet." Accessed July 21, 2024.
<https://1188159.fs1.hubspotusercontent-na1.net/hubfs/1188159/02-DS-220909-SKELCAP-CELLS-1D.pdf/>.
- Smith, James, Rachel Johnson, and Michael Lee. 2019. "Simulation of Space Environments for Lunar Rover Thermal Testing." *Journal of Spacecraft and Rockets* 56 (2): 233-245. <https://doi.org/10.2514/1.A34327>.
- Stopar, Justin. 2023. "A Rationale for Faustini Rim A with Emphasis on Impact History and Volatiles." Artemis III Candidate Landing Regions Workshop (2023).
https://www.hou.usra.edu/meetings/Artemis_III_2023/pdf/2024.pdf/.
- Thomas, William. "NASA Scrambles to Find 'Viable' Path for Mars Sample Return." American Institute of Physics. Last modified October 27, 2023.
<https://ww2.aip.org/fyi/nasa-scrambles-to-find-viable-path-for-mars-sample-return>
- TE Connectivity. "Busbar Connectors." Accessed July 21, 2024.
<https://www.te.com/en/products/connectors/power-connectors/busbar-connectors.html?tab=pgp-story/>.
- U, Victor, Nwanko J, and Michael Kio. 2020. "The Impact of Space Radiation Environment on Satellites Operation in Near-Earth Space." *IntechOpen* 1, no. 5 (June): 52.
- U.S. General Services Administration. "Per Diem Rates Results: Cape Canaveral, FL - Fiscal Year 2024." GSA. Accessed July 20, 2024.
https://www.gsa.gov/travel/plan-book/per-diem-rates/per-diem-rates-results?action=perdiems_report&fiscal_year=2024&state=FL&city=Cape%20Canaveral&zip=.
- Vicor. "Isolated and Regulated DC-DC Converters." Accessed July 21, 2024.
<https://www.vicorpower.com/dc-dc/isolated-regulated/>.
- Wendel, JoAnna. 2022. "How many space rocks hit the moon every year?" *Live Science*. <https://www.livescience.com/how-many-moon-meteorites/>.
- Wilcox, Kevin. 2023. "NASA Prepares for First CLPS Missions | APPEL Knowledge Services." NASA APPEL Knowledge Services.
<https://appel.nasa.gov/2023/12/15/nasa-prepares-for-first-clps-missions/>.

Williams, JP. 2019. "Seasonal Polar Temperatures on the Moon." JGR Planets 123, no. 10 (August): 2521.

Williams, JP, and Ben Greenhagen. 2019. "Seasonal Polar Temperatures on the Moon." JGR Planets 124, no. 10 (August): 2505-2521.

Williamson, J., and P. Spelt. "Bird-inspired Velocity Optimization for Unmanned Aerial Vehicles in Urban Environments." International Journal of Aeronautical Engineering 12, no. 3 (2021): 241-250. Elsevier.

"DC-DC Isolated Converters | Vicor DC-DC Products and Solutions." n.d. Vicor Corporation. Accessed August 11, 2024.
<https://www.vicorpower.com/dc-dc/isolated-regulated>.

"Lithium Ion Cells | Lithium Battery Cells | EaglePicher." n.d. EaglePicher Technologies. Accessed August 11, 2024.
<https://www.eaglepicher.com/technology/battery-chemistries/lithium-ion/>.

"Lunar Rover Solar Panel." n.d. Pumpkin, Inc. Accessed August 11, 2024.
https://www.pumpkinspace.com/store/p217/Lunar_Rover_Solar_Panel.html.

"Protect Circuits with Series 970 PowerTrip® Connectors." n.d. Glenair. Accessed August 11, 2024. <https://www.glenair.com/powertrip/index.htm>.

"SA50-120-12S." n.d. Microchip Technology. Accessed August 11, 2024.
<https://www.microchip.com/en-us/product/SA50-120-12S>.

"Solar Solutions." n.d. Rocket Lab. Accessed August 11, 2024.
<https://www.rocketlabusa.com/space-systems/solar/>.

"Types of Power Bus Bar Connectors." n.d. TE Connectivity. Accessed August 11, 2024.
<https://www.te.com/en/products/connectors/power-connectors/busbar-connectors.html?tab=pgp-story>.

"Where's the Water? Two Resource-Hunting Tools for the Moon's Surface." 2019. NASA.
<https://www.nasa.gov/solar-system/moon/wheres-the-water-two-resource-hunting-tools-for-the-moons-surface/>.

“7.0 Thermal Control.” 2024. NASA.

<https://www.nasa.gov/smallsat-institute/sst-soa/thermal-control/#7.3.3>.

2015. RIMFAX - ground penetrating radar.

<https://www.ffi.no/en/news/rimfax-ground-penetrating-radar>.

“Commercial Lunar Payload Services.” n.d. NASA. Accessed August 12, 2024.

<https://www.nasa.gov/reference/commercial-lunar-payload-services/>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=PEREGRN-1-02>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=PEREGRN-1-02>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=PEREGRN-1-02>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=1998-001A-02>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=2004-030A-02>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=1998-001A-02>.

“NSSDCA - Experiment - Details.” n.d. NASA - NSSDCA - Experiment - Details.

Accessed August 12, 2024.

<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=PEREGRN-1-02>.

“Perseverance Science Instruments.” n.d. NASA Science. Accessed August 12, 2024.

<https://science.nasa.gov/mission/mars-2020-perseverance/science-instruments/#sensors>.

“Perseverance Science Instruments.” n.d. NASA Science. Accessed August 12, 2024.
<https://science.nasa.gov/mission/mars-2020-perseverance/science-instruments/#sensors>.

“RIMFAX Sample Radargram.” n.d. NASA Science. Accessed August 12, 2024.
<https://science.nasa.gov/resource/rimfax-sample-radargram>.

2010. 0751 - H122 - Basic Health Physics - 05 - Radiation Detectors - Overview.

<https://www.nrc.gov/docs/ML1122/ML11229A672.pdf>.

“Appendix E: Creating the Validation Plan with a Validation Requirements Matrix.” 2023.
NASA.

<https://www.nasa.gov/reference/appendix-e-creating-the-validation-plan-with-a-validation-requirements-matrix/>.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the team used ChatGPT, Claude, and other Artificial Intelligence Assistants to facilitate the writing process by enhancing clarity, researching credible sources in a more time-efficient manner, and refining content. Certain sections such as table information and narratives were evaluated with AI to align with technical writing standards. After using this tool, the team reviewed and edited the content as needed and took full responsibility for the content of the deliverable. Certain images in the outreach section were also generated by AI for operational efficiency, and are consistent with industry standards.

Appendix

Appendix A. Mission VALKYR Plans for Resolution

ID	Location (page)	Description	Plans and Timelines for Resolution
1	4	Mission name	Team 26 will be voting and discussing a potential mission name in a future team meeting.
2	4	Landing site location	Team 26 currently has a region of interest and will use JMARS to justify the selection by the SRR deliverable.
3	4	Lunar days	The Science Team will do further research on the duration of lunar days to examine volatile processes by the SRR deliverable.
4	4	Spectrometer	The Science Team will do further research to determine the specific type of spectrometer required to accomplish both science goals by the SRR deliverable.
5	5	Instrument for hydrogen detection	The Science team will do further research on selecting the optimal spectrometer for hydrogen by the SRR deliverable.
6	5	Instrument parameters	The Science Team will do further research to specify instrument parameters based on mission requirements.
7	6	Depth of subsurface reflections	The Science Team will decide on the depth for detecting subsurface reflections.
8	6	Measurement range for hydrogen detection	The Science team will do further research to calibrate and test the measurement range for hydrogen detection.
9	6	Area for subsurface exploration	The Science Team will do further research to define the area for subsurface exploration based on initial data analysis.
10	7	Lunar temperature range	The Science Team will do further research on the specific operational temperature range for the lunar environment.
11	7	Dielectric properties	The Science Team will do further research to measure and specify the dielectric properties of subsurface layers.

Appendix A. Mission VALKYR Plans for Resolution (Continued)

ID	Location (page)	Description	Plans and Timelines for Resolution
12	7	Subsurface signal changes	Further research to characterize changes in subsurface signals by the Science Team.
13	8	Child requirement	The Engineering Team will discuss if Mission Requirement MR-1 has a child requirement by the SRR deliverable.
14	9	Internal temperature limits	Further research to define internal temperature limits based on thermal analysis by the Engineering Team for the SRR deliverable.
15	10	Operating temperature range	Further research to specify the operating temperature range during thermal testing by the Engineering Team for the SRR deliverable.
16	10	Time to collect data	The Science Team and Engineering Team will do further research on the length of the mission by the SRR deliverable.
17	11	Wattage	The Engineering Team will design power system during the design process by the SRR deliverable.
18	12	Child requirement	The Engineering Team will determine the child requirement for the CDH system for the SRR deliverable.
19	12	Child requirement	The Engineering Team will determine the child requirement for the payload system for the SRR deliverable.

Appendix C: Team 26 Overview

Team Members	Role	Major	Relevant Skills	Time Commitment Per Week
Joel Bhattarai	Lead Systems Engineer	Mechanical Engineering	Trade studies, experience writing a Preliminary Design Review (PDR)	10 Hours
Andrea Zabala	Electrical Engineer	Physics, Mechanical Engineering	Knowledge in materials and power supplies, CAD modeling	8-10 hours
Giovanna Camacho	Chief Scientist	Systems Engineering	B.S. and M.S. in Engineering	14 hours
Jasmine Wu	Project Manager & Computer Hardware Engineer	Cognitive and Computer Science	Multiple management roles, product development, ui/ux design, full stack development	10-20 Hours
Harvey Yang	Mission Assurance Specialist	Civil Engineer/Urban Planning	MATLAB, club treasurer	4 Hours
Luis Rodriguez	Thermal Engineer	Mechanical Engineering	Mechanical design	As Needed
Torin Nelson	Deputy Project Manager of Resources & Computer Hardware Engineer	Computer Science	Knowledge of computers, effective research	As Needed
Vincent Dang	Project Engineer & Mechanical Engineer	Mechanical Engineering	Solidworks, MATLAB, knowledge of engineering topics	10-15 hours