Team #28
Lunar Vanguard
Preliminary Design Review (PDR)

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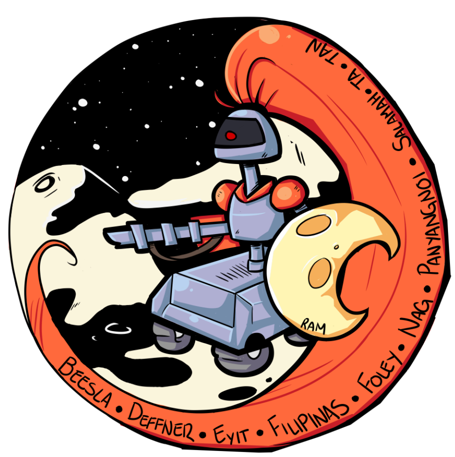

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Acronym

ADV	Advisory
CCB	Change Control Board
CDH	Command & Data Handling
CDR	Critical Design Review
CERR	Critical Events Readiness Review
ConOps	Concepts of Operations
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
CRF	Change Request Form
DR	Decommissioning Review
DRAM	Dynamic Random Access Memory
DSN	Deep Space Network
EEPROM	Electrically Erasable Programmable Read-Only Memory
EPROM	Erasable Programmable Read-Only Memory
ERE	Employee-Related Expenses
ESA	European Space Agency
ESD	Electro Static Discharge
F&A	Facilities and Administration
FY	Fiscal Year
GSFC	Goddard Space Flight Center

ISS	International Space Station
KDP	Key Decision Point
LAMP	Lyman Alpha Mapping Project (LRO instrument)
LEND	Lunar Exploration Neutron Detector (LRO instrument)
LHP	Looped Heat Pipe
LRO	Lunar Reconnaissance Orbiter (NASA Moon Orbiting Mission)
LVR	Lunar Vanguard Rover
MCR	Mission Concept Review
MLI	Multi Layered Insulation
MRR	Mission Readiness Review
ORR	Operational Readiness Review
PDR	Preliminary Design Review
PLAR	Post-Launch Assessment Review
PSR	Permanently Shadowed Region
RAM	Random Access Memory
RFA	Request for Action
ROM	Read Only Memory
RPN	Risk Priority Number
SIR	System Integration Review
STM	Science Traceability Matrix
TCS	Thermal Control System
TRL	Technology Readiness Level
TRR	Test Readiness Reviews

UHF	Ultra High Frequency
VCHP	Variable Conductance Heat Pipe
VIPER	Volatiles Investigating Polar Exploration Rover

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1. Mission Overview

1.1. Mission Statement

Lunar Vanguard is a discovery-class rover mission that aims to investigate the origin and composition of volatile substances located in a permanently shadowed region (PSR) at the lunar south pole in the area known as the Amundsen Rim. After landing on the Amundsen Rim, the Lunar Vanguard rover will travel into the Amundsen crater and make its way over to the Amundsen A's PSR, where it will systematically drill, extract, and analyze regolith samples for the abundance of water ice and stable isotopes (D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$) *in situ*. The goal of this mission is to better understand the composition and origin of lunar volatiles.

Lunar volatiles are substances–like water–that vaporize at relatively low temperatures. As the moon has no atmosphere, volatiles often evaporate off its surface and are lost to space (Gasparini 2024). However, temperatures in the lunar south pole's PSRs are cold enough to retain volatiles in solid form (Gasparini 2024). Furthermore, remote sensing devices monitoring the moon like LEND (an instrument on NASA's Lunar Reconnaissance Orbiter that uses neutrons to detect the presence of hydrogen) and LAMP (another instrument on NASA's Lunar Reconnaissance Orbiter that uses ultraviolet imaging spectrometry to assess the lunar surface) have identified possible reservoirs of water ice among these volatiles (Honniball et al. 2020). Since these devices are limited in what information they can provide (for example, LEND can measure hydrogen concentration, but cannot measure the bonds or depth of these concentrations), there remains much uncertainty about the nature, characteristics, and origin of lunar volatiles. Were they formed from a comet smashing into the moon, or are they solar in origin? Is there just a dusting of water ice slathered atop the surface levels or the regolith, or do the reservoirs run deeper into the regolith? The Lunar Vanguard aims to answer these questions by using a rover to perform *in situ* analysis of PSR volatiles.

Discerning the origin of these volatiles will be done using stable isotopes D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$ since these are considered standard for assessing geochemical origin, evolution, and similarity of planetary bodies (Webster et al. 2023). Scientists often use a combination of these ratios to determine whether something has a solar or cometary origin. These ratios can also be used to compare similarities among planetary bodies themselves, something which is of particular interest when it comes to the moon as there are a multitude of theories which purport that the moon was formed from the Earth. If the volatiles on the moon herald back to that time, a comparison between spectral analysis of stable isotopes on both bodies should be similar.

Understanding the answers to these questions doesn’t just hold historical importance; it also could have a huge impact on future lunar habitation and the Moon-to-Mars pipeline. If there is an abundant, potable reserve of water ice on the moon, lunar habitats can tap into the supply and less water would have to be shipped from Earth to the Moon. Alternatively, water could be used on the moon for manufacturing, cooling, or fuel purposes, making travel from the moon to distant planets a little easier (extra fuel could be generated on the moon instead of being shipped all the way from Earth).

As an uncrewed mission, Lunar Vanguard will retrieve this vital information without expending manpower or putting human lives at risk. Crucial scientific data regarding the past and knowledge about future habitation resources will also be obtained, which sets the stage for another one of Artemis's main objectives: Developing safer and more environmentally-friendly (and science-backed) crewed journeys to the moon and beyond in the future.

1.2. Science Traceability Matrix

In order to assist with Artemis Science Objective 2 (understanding the character and origin of lunar polar volatiles), the Lunar Vanguard mission will be conducting an uncrewed discovery mission to extract and analyze samples of lunar regolith in the Amundsen A PSR *in situ*.

The mission's primary science objectives are:

> Artemis Science Objective 2a: Determine the compositional state (elemental, isotopic, mineralogic, and compositional distribution (lateral and with depth) of the volatile component in the lunar polar region.
>
> Artemis Science Objective 2b: Determine the source(s) for lunar polar volatile deposits (NASA 2020).

These objectives were selected for two reasons. First, understanding the state and source of lunar volatiles is key to understanding how much water is available on the moon for future human use. As discussed later in this document, Neutron spectral analysis has already been conducted on the moon by missions like the Lunar Reconnaissance Orbiter (LRO), which reveals the south pole of the moon to be hydrogen-rich (Colaprete et al. 2016). However, without an *in situ* analysis of lunar regolith or a lab analysis of samples collected *in situ*, it is difficult to tell how much of the hydrogen is actually water. By focusing on data collection for Artemis Science Objectives 2a and 2b, the Lunar Vanguard mission will help pave the way for a better understanding of lunar volatiles. This is vital since water, in particular, has many uses for future space exploration such as fuel generation, human nourishment, manufacturing, lunar agriculture, and even waste management.

Second, there is a strong overlap between the physical properties that are being observed within goals 2a and 2b. This allows the Lunar Vanguard mission to fulfill several of the constraints expressed within the Mission Task document. In order to fulfill both objectives, the team will use TRIDENT, a temperature-sensing drill (discussed in SRR section 1.5.6) and Tunable Laser Spectrometer (also discussed in SRR 1.5.6), which fits within the two-instrument limit. The processes set up to fulfill both objectives are similar: drill into regolith and extract samples, prepare the sample for mass spectrometry, conduct mass spectrometry, and analyze then record the results of the experiment. Therefore, the Lunar Vanguard rover design can be streamlined around this shared operation, reducing the amount of money, mass, and volume required.

As a third instrument to sense the presence of hydrogen is unable to be added (due to top-level instrument quantity constraints), the rover will split its overall sampling region of Amundsen A into a grid of 80 cells and sample from the center of each cell. The size and distribution of cells within this grid will be refined in further design reviews according to the hydrogen distribution of Amundsen A according to past data from LEND and LAMP.

To delve further into the specifics, the overarching science goal 2a (determine the compositional state of lunar volatiles) has been broken down into the following science objective:

> Mission Objective 1: Determine the water ice abundance of Amundsen A PSR within the top 1 meter of regolith to at least +/- 5% accuracy.

This will be accomplished by taking the regolith samples extracted by the drill unit. This is done in 10 cm segments to ensure the drill does not overheat and samples have a more granular level of precision. Also, measurements are taken of temperature, mass, and water abundance using the Tunable Laser Spectrometer. These results will be recorded *in situ*, then sent back to the orbiter, where they will be compared to past LEND and LAMP maps of Amundsen A collected over the years to get a better idea of what level of hydrogen was expected to be present and what amount of water ice was actually found *in situ*. Since *in situ* spectral analysis of stable isotopes can be notoriously difficult on planetary bodies, the Lunar Vanguard rover will be equipped with three Tunable Laser Spectrometers whose design has proven functionality on past NASA missions (more about this can be read in SRR section 1.5.6).

Similarly, science goal 2b (determine the source(s) for lunar volatiles) was parsed down to the following science objectives:

> Mission Objective 2.1: Determine the temperature of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.2: Determine D/H stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.3: Determine $^{18}O/^{16}O$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.4: Determine $^{13}C/^{12}C$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.5: Determine $^{15}N/^{14}N$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.

These objectives’ observables follow a similar process to the former: Samples will be extracted in 10 cm chunks, prepared for mass spectrometry (using a robotic arm, pyrolytic oven, and gas chromatography device), analyzed, ratios calculated, and results recorded.

Deuterium to protium (D/H) is a ratio comparing stable hydrogen isotopes which is often used to assess hydrological cycles and better understand planetary processes. For example, scientists use the D/H ratio to conclude that Jupiter and Saturn have solar origins, whereas Earth, Mars, Enceladus, and Titan are closer to having their origins in comets (Webster et al. 2023). It may provide unique insights as to where the moon's volatiles originated (Saal 2011).

$^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$ are important for a similar reason: Since different volatile-bearing planetary bodies have differing $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$ ratios, the moon's $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$ ratios can be compared to other known sources of water to see if the lunar volatiles originated there (Young 2016). This is because the C, H, N, and O stable isotopes, when viewed together, tell a rough story about the geochemical origin and evolution of the planetary substance being examined (Webster et al. 2023). Since the Moon has no atmosphere of its own and acts as a historical record of planetary processes, learning this story and its similarity to (and origin in) other planetary bodies could contribute significantly to current scientific understanding (Sutter 2020).

Table 1. Science Traceability Matrix

<table>
<tr><th rowspan="2">Science Goals</th><th rowspan="2">Science Objectives</th><th colspan="2">Science Measurement Requirements</th><th colspan="2" rowspan="2">Instrument Performance Requirements</th><th rowspan="2">Predicted Instrument Performance</th><th rowspan="2">Instrument</th><th rowspan="2">Mission Requirements</th></tr>
<tr><th>Physical Parameters</th><th>Observables</th></tr>
<tr><td rowspan="6">Artemis Science Objective 2a: Determine the Compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.</td><td rowspan="6">Determine the water ice abundance of at least one of Amundsen A PSR, within the top 1 meter of regolith to at least +/- 5% accuracy.</td><td rowspan="3">Measure the relative abundance of water (H_2O) in a mass spectrum of each 10 cm sample of regolith up to the 1m depth.</td><td rowspan="3">Collect a regolith sample in 10cm bits until the full 1m depth is extracted. Use heat to sublimate water within the sample. Use mass spectrometry to observe and quantify the presence of water molecules.</td><td>Wavelength Range</td><td>1.4 - 1.9 μm</td><td>1 - 12 μm</td><td rowspan="3">Tunable Laser Spectrometer</td><td rowspan="3">Instrument shall take and heat augured 1 meter regolith sample to sublimate volatile samples, then utilize a wavelength between 1.4-1.9μm to identify the abundance (amount) of water volatiles in the sample.</td></tr>
<tr><td>Integration Range</td><td>Needs to assess each sample individually; sample collection time and relocation estimated to be 10 minutes</td><td>Capable of processing, assessing, and recording the results of H_2O abundance within 10 minutes (measurement takes less than a minute)</td></tr>
<tr><td>Sensitivity</td><td>~1 parts per billion</td><td>1 parts per billion - 1 parts per trillion</td></tr>
<tr><td rowspan="3">Measure the mass and regolith strength of each 10cm regolith sample.</td><td rowspan="3">Collect a regolith sample in 10cm bits until the full 1m depth is extracted. For each sample, measure the mass in grams.</td><td>Sturdiness</td><td>Capable of cutting through solid volatile and lunar regolith and collecting a sample</td><td>Capable of cutting through solid volatile and lunar regolith and collecting a sample</td><td rowspan="3">TRIDENT Drill</td><td rowspan="3">Instrument shall collect an augured 1meter's worth of samples in 10cm bit increments. The instrument shall then record the mass and strength of each sample.</td></tr>
<tr><td>Functional Temperature Range</td><td>~20-100K</td><td>~20-100K</td></tr>
<tr><td>Soil strength</td><td>Assesses the strength of lunar regolith</td><td>Capable of analyzing the strength of a 10cm lunar regolith sample in chunks.</td></tr>
</table>

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
				Collects in 10cm bit piecewise fashion	Collects samples in chunks of 10cm and records information about mass	Collects samples in chunks of 10cm		
Artemis Science Objective 2b: Determine the source(s) for lunar polar volatile deposits.	Determine the temperature of Amundsen A PSR, within the top 1 meter of regolith.	Measure the temperature (in Kelvin) of 10cm regolith samples at a time, up until the 1m depth.	Collect a regolith sample in 10cm bits until the full 1m depth is exacted. Analyze and record the temperature of each 10 cm sample.	Sensitivity	Observe temperature to 4 decimal points	Observes temperature to 4 or more decimal places	TRIDENT Drill	Instrument shall collect an augured 1meter's worth of samples in 10cm bit increments. The instrument shall then record the mass and strength of each 10 bit increment.
				Units	Kelvin	Kelvin		
				In situ calibration/validation	Capable of assessing whether its measurements are accurate and adjusting itself accordingly	Capable of assessing whether its measurements are accurate and adjusts accordingly		
				Functional Temperature Range	~20-100K	~20-100K		
	Determine D/H stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.	Measure the relative abundance of H2+ and HD+ and calculate the D/H ratio.	Collect a regolith sample in 10cm bits until the full 1m depth is extracted. Use a laser (or heat) to release gas from the sample. Separate Hydrogen from this gas using	Wavelength Range (Deuterium)	2.6-2.7 µm	1-12 µm	Tunable Laser Spectrometer	Instrument shall take and heat augured 1 meter regolith sample to sublimate samples, then utilize a wavelength between 2.6-2.7µm to identify the
				Wavelength Range (Protium)	2.6-2.7 µm	1-12 µm		

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
			gas chromatography. Measure H2+ and HD+ ratios and calculate D/H ratio.	Integration Range	Needs to assess each sample individually; sample collection time and relocation estimated to be 10 minutes	Capable of processing, assessing, and recording the results of the D/H ratio within 10 minutes (measurement takes less than a minute)		abundance (amount) of Deuterium and Protium in the sample. It will then use these measurements to calculate the D/H ratio.
				Sensitivity	~1 parts per billion	1 parts per billion - 1 parts per trillion		
	Determine ^{18}O/^{16}O stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.	Measure the relative abundance of ^{18}O and ^{16}O isotopes and calculate the ^{18}O/^{16}O ratio.	Collect a regolith sample in 10cm bits until the full 1m depth is extracted. Use a laser (or heat) to release gas from the sample. Separate Oxygen from this gas using gas chromatography. Measure ^{18}O and ^{16}O ratios and calculate ^{18}O/^{16}O ratio.	Wavelength Range (^{18}O)	2.7 µm	1-12 µm	Tunable Laser Spectrometer	Instrument shall take and heat augured 1 meter regolith sample to sublimate samples, then utilize a wavelength between 2.6-6.3µm to identify the abundance (amount) of ^{18}O and ^{16}O in the sample. It will then use these measurements to calculate the ^{18}O/^{16}O ratio.
				Wavelength Range (^{16}O)	6.3 µm	1-12 µm		
				Integration Range	Needs to assess each sample individually; sample collection time and relocation estimated to be 10 minutes	Capable of processing, assessing, and recording the results of the ^{18}O/^{16}O ratio within 10 minutes (measurement takes less than a minute)		
				Sensitivity	~1 parts per billion	1 parts per billion - 1 parts per trillion		
	Determine ^{13}C/^{12}C stable isotopic ratio	Measure the relative abundance	Collect a regolith sample in 10cm bits	Wavelength Range (^{13}C)	4.38 µm	1-12 µm	Tunable Laser Spectrometer	Instrument shall take and heat

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
	of Amundsen A PSR, within the top 1 meter of regolith.	of ^{13}C and ^{12}C isotopes and calculate the $^{13}C/^{12}C$ ratio.	until the full 1m depth is extracted. Use a laser (or heat) to release gas from the sample. Separate Carbon from this gas using gas chromatography. Measure ^{13}C and ^{12}C ratios and calculate $^{13}C/^{12}C$ ratio.	Wavelength Range (^{12}C)	4.32 μm	1-12 μm		augured 1 meter regolith sample to sublimate samples, then utilize a wavelength between 4.32-4.38μm to identify the abundance (amount) of ^{13}C and ^{12}C in the sample. It will then use these measurements to calculate the $^{13}C/^{12}C$ ratio.
				Integration Range	Needs to assess each sample individually; sample collection time and relocation estimated to be 10 minutes	Capable of processing, assessing, and recording the results of the $^{13}C/^{12}C$ ratio within 10 minutes (measurement takes less than a minute)		
				Sensitivity	~1 parts per billion	1 parts per billion - 1 parts per trillion		
	Determine $^{15}N/^{14}N$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.	Measure the relative abundance of ^{15}N and ^{14}N isotopes and calculate the $^{15}N/^{14}N$ ratio.	Collect a regolith sample in 10cm bits until the full 1m depth is extracted. Use a laser (or heat) to release gas from the sample. Separate Nitrogen from this gas using gas chromatography. Measure ^{15}N and ^{14}N ratios and calculate $^{15}N/^{14}N$ ratio.	Wavelength Range (^{15}N)	2.3-2.4 μm	1-12 μm	Tunable Laser Spectrometer	Instrument shall take and heat augured 1 meter regolith sample to sublimate samples, then utilize a wavelength between 2.3-2.4μm to identify the abundance (amount) of ^{15}N and ^{14}N in the sample. It will then use these measurements to calculate the $^{15}N/^{14}N$ ratio.
				Wavelength Range (^{14}N)	2.3-2.4 μm	1-12 μm		
				Integration Range	Needs to assess each sample individually; sample collection time and relocation estimated to be 10 minutes	Capable of processing, assessing, and recording the results of the $^{15}N/^{14}N$ ratio within 10 minutes (measurement takes less than a minute)		

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
				Sensitivity	~1 parts per billion	1 parts per billion - 1 parts per trillion		

1.3. Summary of Mission Location

The Lunar Vanguard rover will be landing on the Amundsen Rim, a ridge located along the southern edge of the Amundsen crater. This landing site was selected for its proximity to Amundsen A, a section of the Amundsen crater which has a <15° slope, average temperatures of around 40-50 K with an overall temperature range of 23-100 K, and high levels of hydrogen around 100-123 ppm (Runyon et al. 2012).

In terms of transversability, the site features areas with gentle slopes and elevation levels, especially on flat-topped rim segments. Although, these are surrounded by steeper slopes that may limit mobility (Wueller et al. 2024). The Lunar Vanguard rover should easily be able to maneuver to its target–Amundsen A–and back. In addition, the rim itself receives sunlight during TBD dates and should be able to support the use of solar panels (Runyon et al. 2012). The region benefits from sun visibility values of 0.4-0.5, meaning it receives sunlight 40% to 50% of the lunar day (Wueller et al. 2024). This means that the landing site can double as a charging location for the rover and allow moments of less extreme temperature.

Moonquakes on the Moon are driven by tectonic activity and global stresses from interior cooling and tidal forces; they occur with varying frequencies and intensities. The Apollo Passive Seismic Experiment (1969-1977) recorded 28 significant shallow moonquakes with magnitudes ranging from 1.5 to over 5.5. These quakes, associated with thrust faults, indicate ongoing seismic activity and can pose a potential hazard for the Lunar Vanguard rover due to the risk of strong ground shaking, regolith landslides, and terrain alterations (Watters et al. 2024).

Amundsen A's high hydrogen levels have been confirmed by LEND, and LAMP (Colaprete et al. 2016). This, in combination with its low temperatures, leads to a high likelihood of extracting samples of volatiles for analysis.

Despite both LEND and LAMP agreeing on hydrogen presence in the area, LAMP seems to indicate a lack of surface frost, due to low albedo (Colaprete et al. 2016). Since Amundsen A has a high hydrogen concentration but low albedo, there is a high likelihood that its volatiles are not spread out in a contiguous manner on its surface, but are scattered throughout the regolith in a heterogeneous manner (Colaprete et al.

2016). This means that Amundsen A provides unique insight into the composition of volatiles in the absence of surface frost within 1-meter depth of the surface.

The purity of water in lunar ice is not fully determined yet. While ice has been detected, it is often mixed with lunar regolith (soil). The term "dirty ice" is used to describe this mixture. Detailed in situ analysis is needed to assess the purity and potability (drinkability) of the water (Lawrence 2017). These volatiles are a critical resource for sustainable human presence on the Moon. It can be used for drinking water, oxygen production, and fuel (by splitting water into hydrogen and oxygen). There is also potential economic value in extracting and utilizing lunar resources. The knowledge gained from lunar exploration can be applied to other celestial bodies

Another reason is the special history of the Amundsen crater. Much of the crater was formed during the Nectarian era (around 3.92-3.85 Ga), but the floor of the crater developed during the Imbrian era (around 3.85-3.8 Ga) (Runyon et al. 2012). Since the area contains a multitude of rocks and minerals from various ages, it can provide key information about the formation of volatiles on the moon. For example, are the volatiles primarily found in older rocks? Are newer rocks more capable of retaining this ice? Amundsen Rim and Amundsen A could hold the answers to these questions.

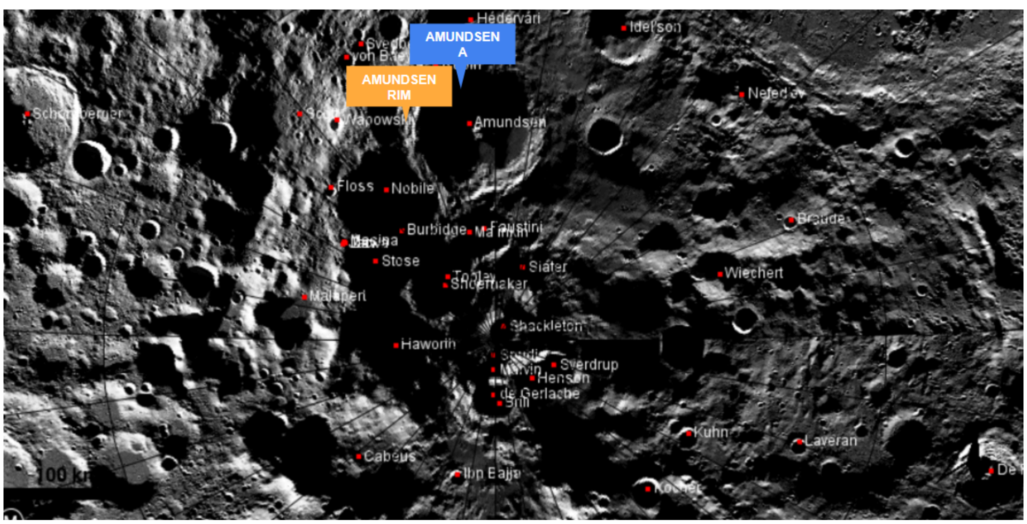


Figure 1. Map of Amundsen Crater showing Amundsen Rim and Amundsen A (Christensen 2009)

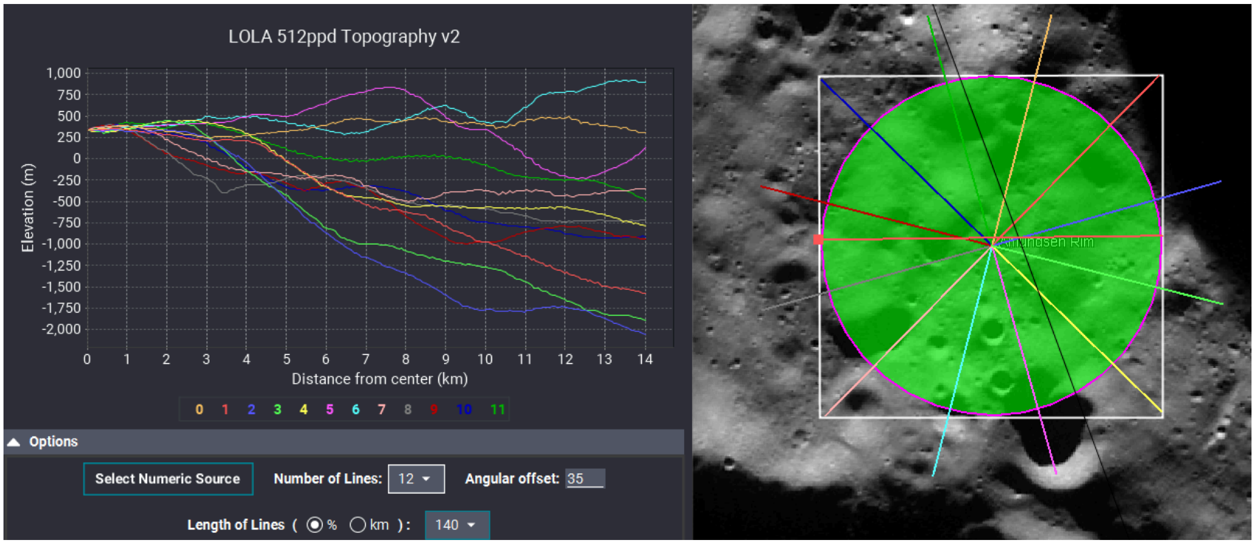


Figure 2. Crater Counting - Elevation levels 12 profile lines
(Christensen 2009)

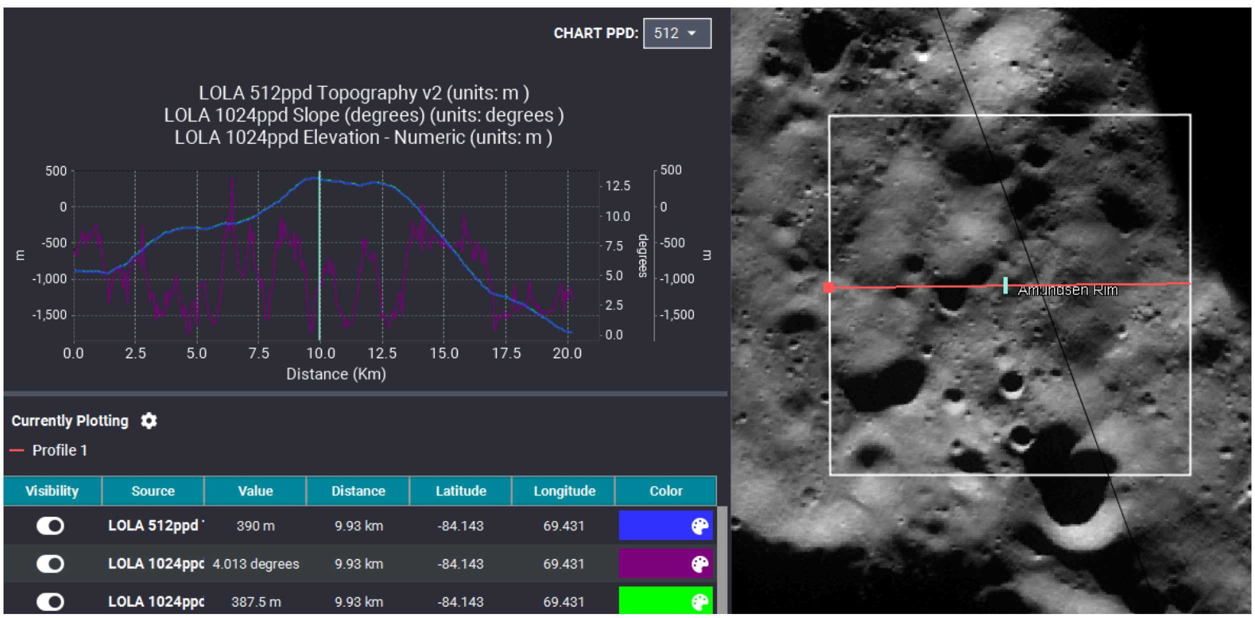


Figure 3. Profile Line - Slope, Elevation, Topography
(Christensen 2009)

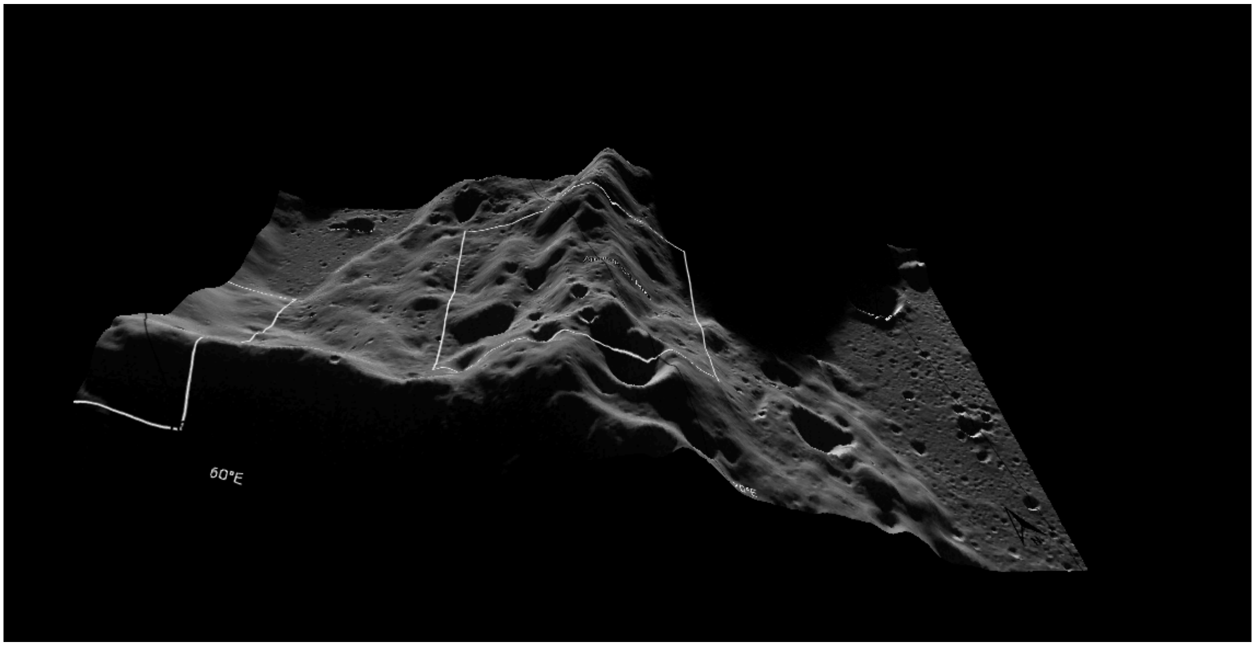


Figure 4. 3D View of Amundsen Rim - Range of Values | 3 vertical exaggeration | 54.181 Total Exaggeration (Christensen 2009)

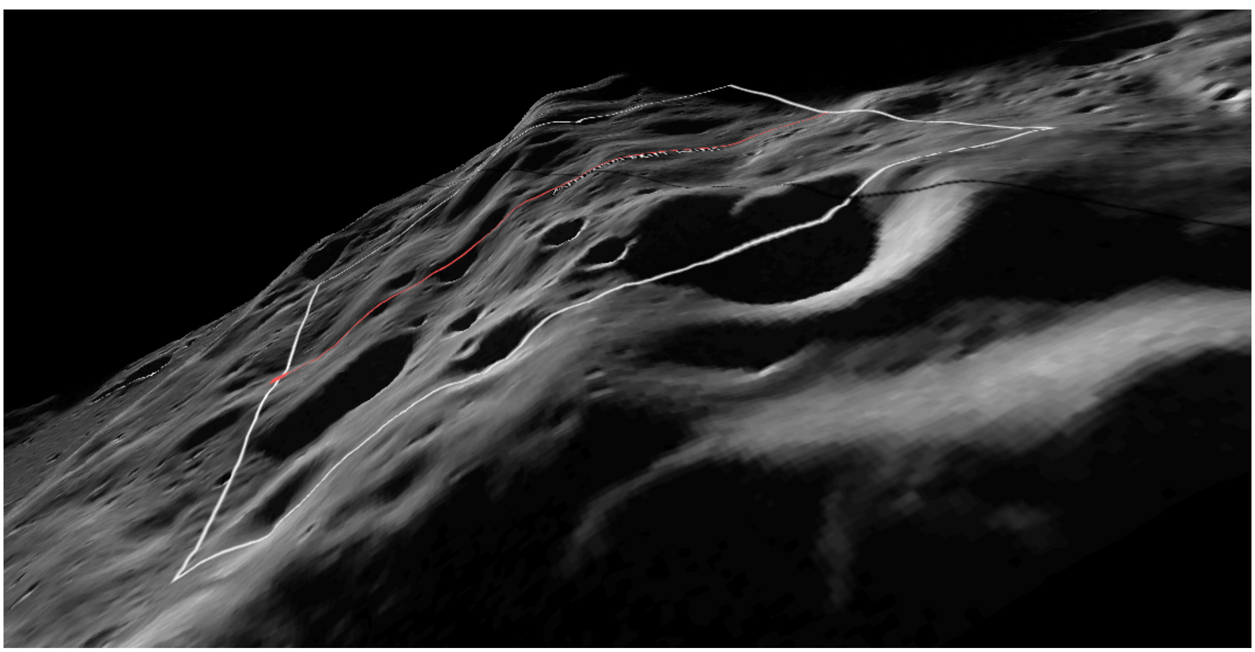


Figure 5. 3D View of Amundsen Rim - Range of Values | 1 vertical exaggeration (aka true scale) | 17.013 Total Exaggeration (Christensen 2009)

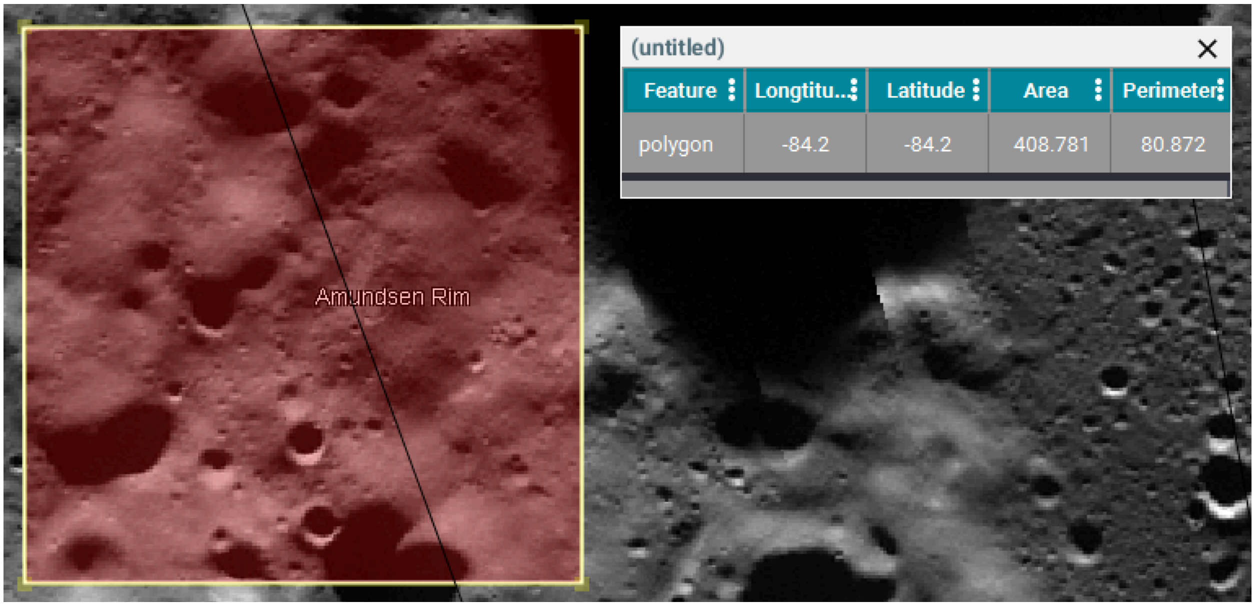


Figure 6. Amundsen Rim Parameters:
Area: 408.781 km^2 | Perimeter: 80.872 km | Longitude: -84.2 | Latitude: -84.2
(Christensen 2009)

1.4. Mission Requirements

In order to organize component selection of the Rover subsystems, requirements sorted in a hierarchical format are created. This section describes the highest level of mission requirements. System specific child requirements will be further elaborated upon in their sections.

These are the following customer-provided constraints, from the provided Mission Task document.

Mass Constraint: The lunar rover's payload (including all instruments) shall not exceed a mass of 85 kg.

Volume Constraint: The stored configuration of the lunar rover shall not exceed a volume of 1.5 m x 1.5 m x 1.5 m It can expand to a larger volume after deployment.

Cost Constraint: The total expense of the lunar rover shall not exceed $225 million, this does not include the rocket launch.

Launch Constraint: Readiness for the launch shall be achieved by September 1st, 2028.

Instrument Constraints: The science objectives shall be achieved with no more than two science instruments, including duplicates & multiple integrated instruments. Supplemental instruments require review & approval from the CCB.

Restricted materials: Shall not incorporate an RTG or any derivative thereof and the use of radioactive material in lunar rover systems shall not exceed a total mass of 5g.

Table 2. Top-Level Mission Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
MR 1	The system shall determine compositional state & distribution of volatiles in polar lunar sites.	Primary Science Goal	Customer		Demonstration	PAY, CDH	Not Met
MR 2	The system shall determine source(s) of the volatile deposits in lunar polar regions.	Secondary Science Goal	Customer		Demonstration	PAY, CDH	Not Met
MR 3	The system shall not exceed a net mass of 85kg	Customer Constraint	Customer		Inspection	All	Met
MR 4	The system's stored configuration shall not exceed a volume of 1.5m x 1.5m x 1.5m	Customer Constraint	Customer		Inspection	All	Met
MR 5	The total cost of the system shall not exceed $225 million	Customer Constraint	Customer		Inspection	All	Met

MR 6	The mission shall be ready for launch by September 1st, 2028	Customer Constraint	Customer		Inspection	All	Met
MR 7	The system will be able to traverse through the lunar surface.	In order to fulfill the science objectives, the rover must be able to take samples from different locations.	MR1 MR2		Demonstration	ME, EPS, CDH, TCS	Not Met
MR 8	The system shall survive the lunar environment for 90 days.	The lunar rover must endure rough lunar environments to capture data for the science goals.	MR 1 MR 2 MR 7		Demonstration	All	Not Met

1.5 Concept of Operations (ConOps)

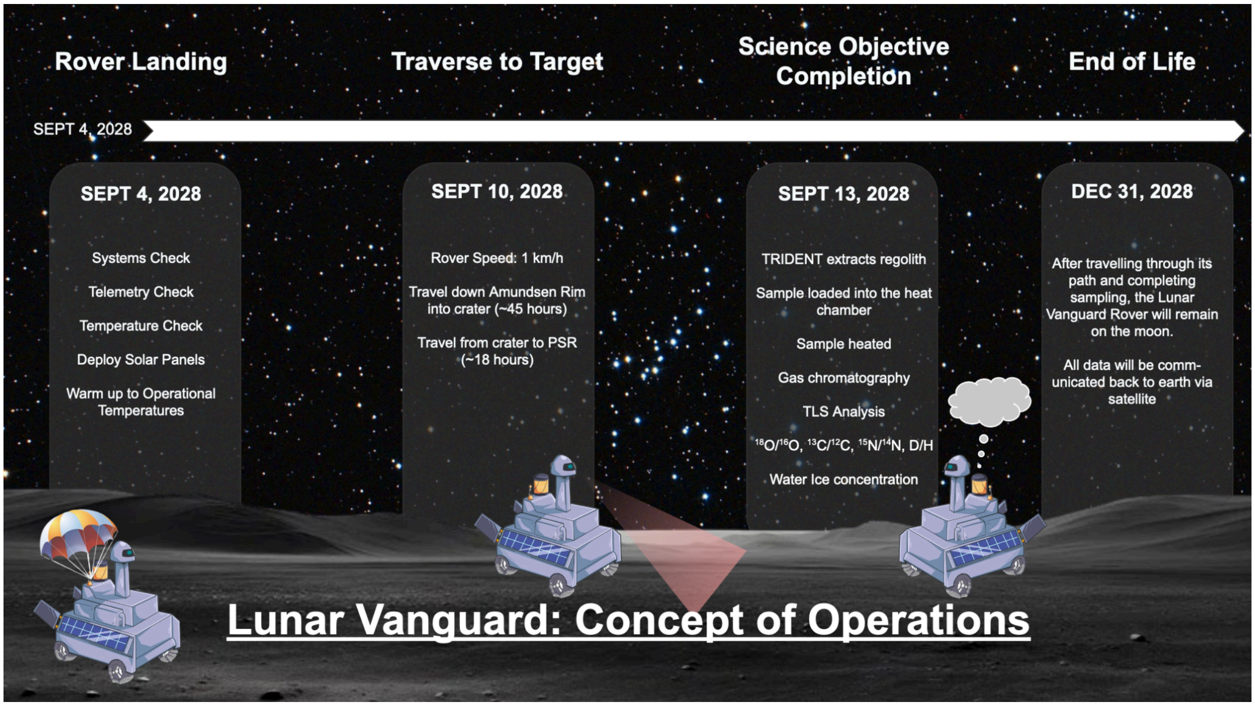


Figure 7. Lunar Vanguard: Concept of Operations

Assumptions

1) Rover movement will be capped at 1 km/h.
2) Rover will require light areas to allow for solar recharge of batteries in case of emergency.
3) Any path with a slope of 15 degrees or higher should be avoided.
4) Rover will not be returning to Earth. All sample collection must be done *in situ*.
5) Only two scientific instruments may be used. These will be (A) TRIDENT drill and (b) Spectrometry Suite.
6) Since this does not allow for a hydrogen sensor, we must use an alternative method for sample collection.

1.5.1 Rover Landing

Launch for the Lunar Rover mission is scheduled for September 1, 2028. If everything goes according to schedule, the rover will touch down at the Amundsen Rim landing site around September 4, 2028. After landing, the rover will need to perform checks of systems, telemetry, and temperature. It will need to deploy its solar panels and acclimate to the temperature of the environment around it. Further tests will need to be conducted to ensure mission critical instruments and components (such as the TRIDENT drill, GS-MS spectrometry suite, sampling arm, and antenna). To allow time for debugging, a timespan of six days has been allotted.

1.5.2 Launch Site to PSR

After conducting initial tests in the Amundsen Rim landing site, the Lunar Vanguard rover will navigate its way to Amundsen A PSR at a speed of 1 km/h. Traversal from landing to sampling site will take an estimated 63 hours (roughly 3 days, rounded up to allow for margin). All slopes along this path have been assessed to ensure the rover is never traveling along a slope higher than 15 degrees. The maximum angle the rover must traverse is 10 degrees and occurs on the way down from Amundsen Rim into the crater.

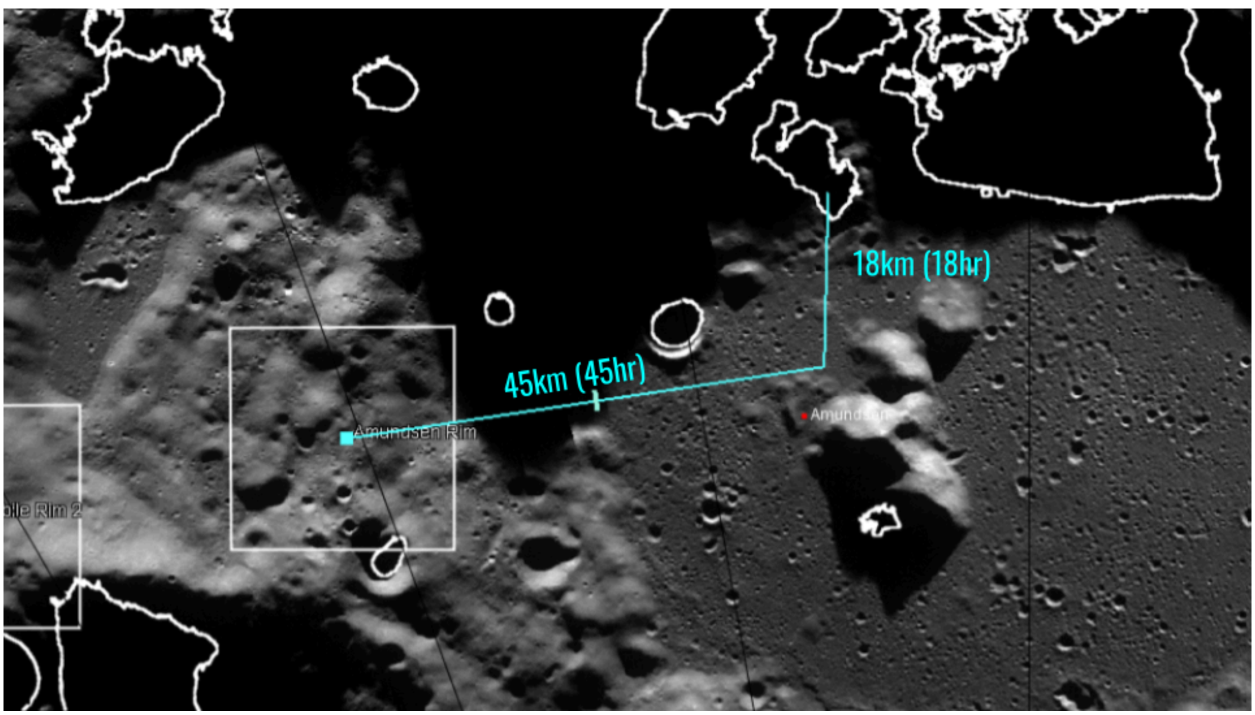


Figure 8. Top-down map of Lunar Vanguard traversal

(Christensen 2009)

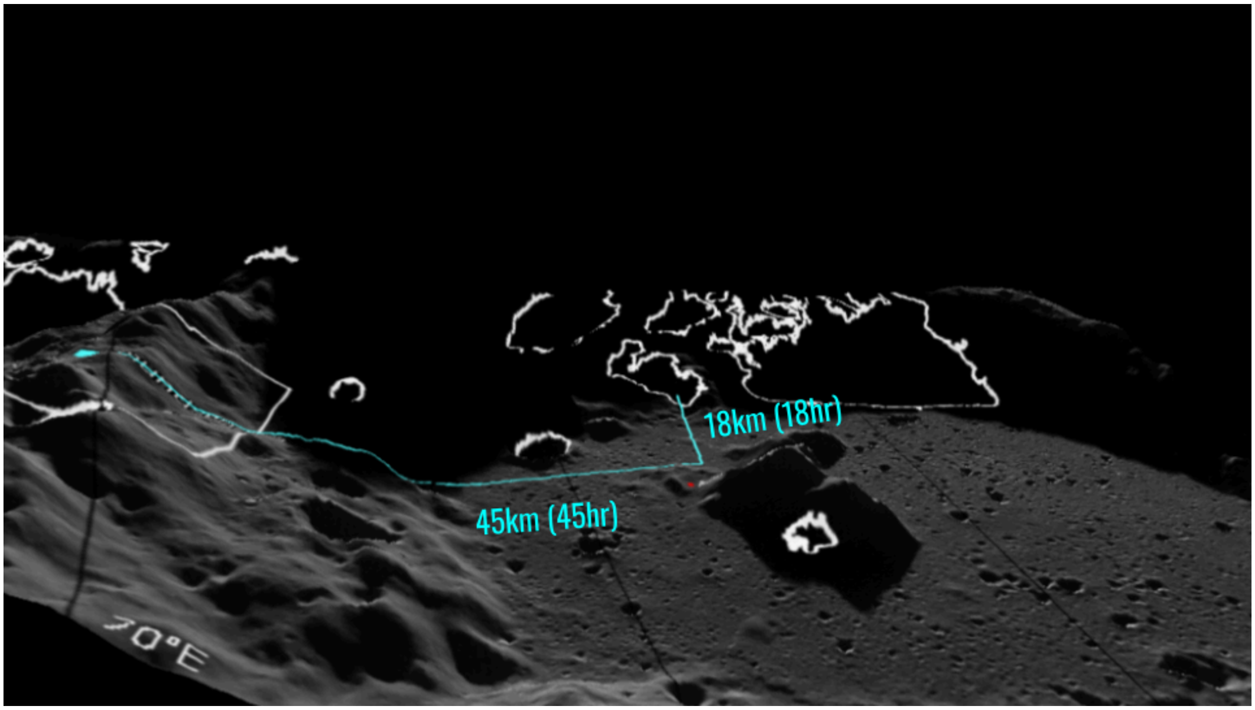


Figure 9. Side view Lunar Vanguard traversal

(Christensen 2009)

1.5.3 PSR Sampling

The Lunar Vanguard Electrical and Science team are assessing the Amundsen A PSR to ensure the rover is sampling a perimeter of the PSR that allows for the rover to dip out of the shadows to recharge its battery using the sun. Initial plans to utilize reflective technology to redirect sunlight to the rover as it navigates the PSR were put on hold due to unexpected cuts in budget.

1.5.4 Sample Collection Methodology

After navigating to a grid in the PSR, the rover will begin its sampling sequence. The steps and durations are as follows:

1) **(5 hour)** Rover drives to the grid.

2) **(30 minutes)** TRIDENT drill extracts regolith to ~1m of depth.

3) **(10 minutes)** Robotic arm takes the sample from the drill and loads it into the heating chamber for sample analysis.

4) **(30 minutes)** Heating chamber takes in lunar soil, heats it up, and creates gasses from volatiles.

5) **(60 minutes)** After heated in the chamber, released gasses enter the gas chromatography chamber for further breakdown.

6) **(60 minutes)** From gas chromatography, gas is released into TLS for analysis.

7) **(10 minutes)** Results are recorded into the rover's software and sent to earth via antenna. Transference and integrity of this data is further checked by software.

1.6. Vehicle Design Summary

The overall design of our rover was intended to outlast our mission expectations, from having a sufficient amount of power through traversing the lunar landscape, to keeping in contact with the team on earth. After many dedicated trade studies to optimizing the rover design in categories that can effect the outcome of the mission. Primary categories like cost, weight and power consumption were put in thought for selecting every component onboard the rover.

While each subsystem of the rover ranging from mechanical to payload had their own unique criteria, the team desired a quality rover that could still meet customer constraints and abide by their respected subsystem requirements. To verify these requirements the team implemented techniques across the board showing whether or not the requirement is met from either putting the system through analyzation, various testing methods, inspection through measurement, and lastly demonstration through the actual mission itself.

Taking into consideration the missions Con Op's the rover was designed for multiple stages, and to traverse through those stages efficiently. Having our first stage being the system check to ensure the functionality of all the components will be crucial in starting the mission on the right foot, and that's where EPS and CDH will shine prepping the rover for its first venture. While on the trek to excavate volatiles in the PSR all systems play a big role, with our design taking into consideration risks and backup systems is important for any mishap along the journey.

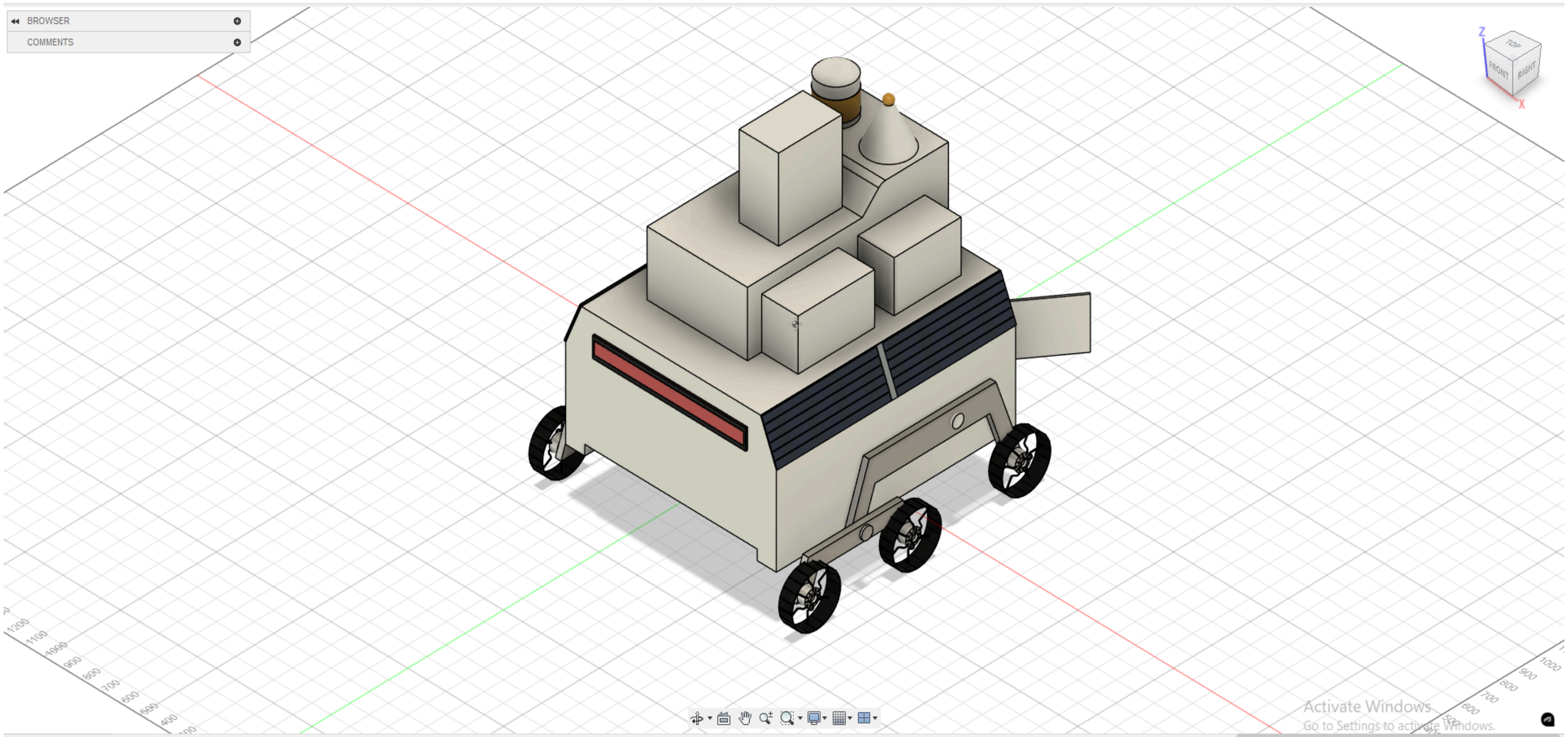


Figure 10. Overall Rover Design

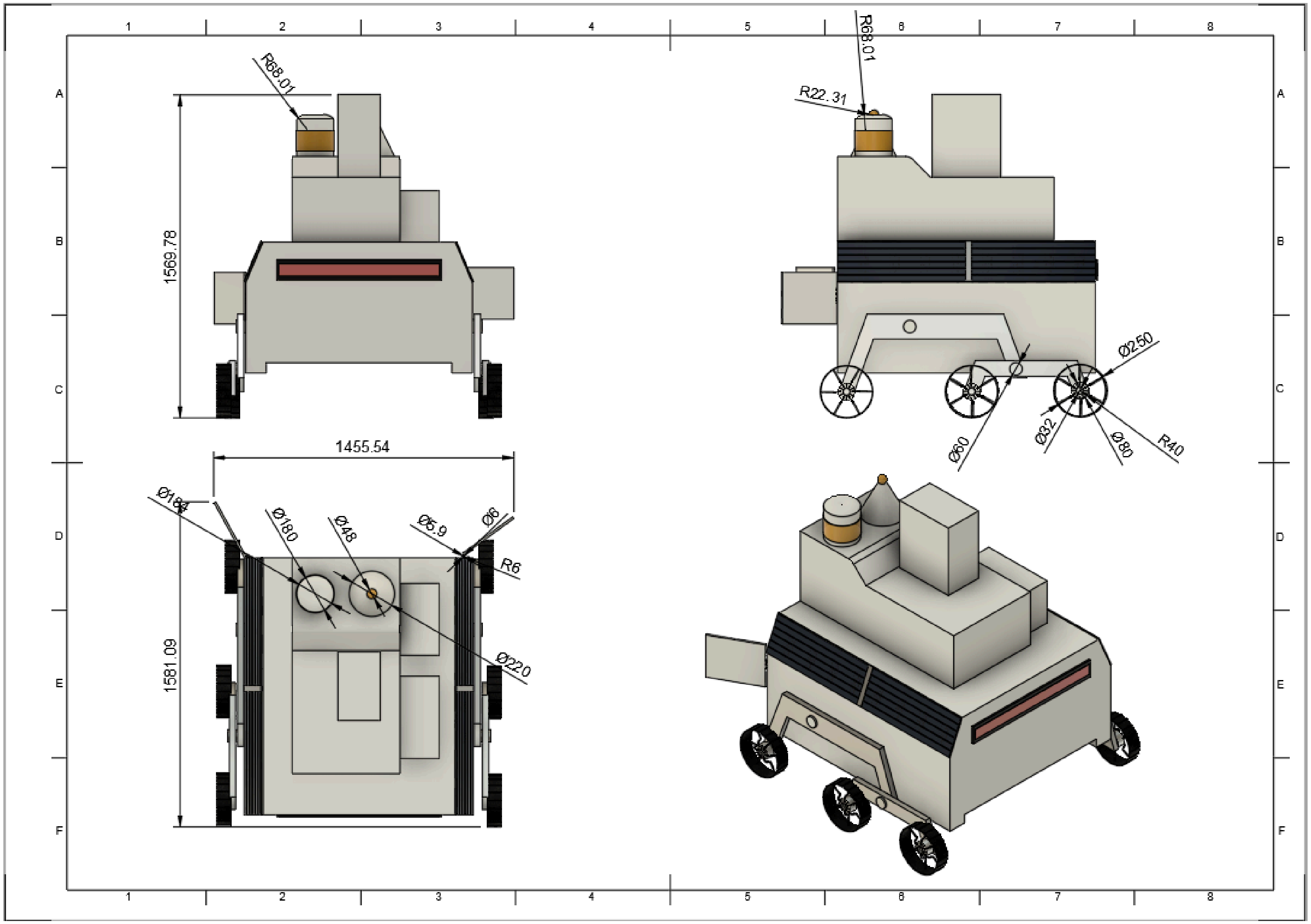


Figure 11 Rover Drawing

1.7. Science Instrumentation Summary

The Lunar Vanguard rover is equipped with high tech instruments that are built to handle the uncommon and extreme atmosphere of the Amundsen ridge. These instruments include the TRIDENT Drill and two Tunable Laser Spectrometers (one primary, and one secondary). A robotic arm, a pyrolytic cell, and two gas chromatography instruments (one primary, and one secondary) have also been included to facilitate the sample collection process. Two SQRLi cameras (one for the front, and one for the back) are included to assist the rover in navigating the PSR. Each instrument was strategically picked for this specific mission in order to successfully complete the overall objective.

The TRIDENT Drill is designed to collect samples up to a depth of one meter in 10-centimeter increments. Each collected sample's mass and strength will be recorded. The drill has been resized from its initial mass of 22 kilograms and volume of 11,244.64 cubic centimeters to fit the Lunar Vanguard rover. It now has a mass of 7.067 kilograms and a volume of 37,042.92 cubic centimeters. It also has a maximum power draw of 200 watts. The total cost of the TRIDENT Drill is $4.8 million, which is considered relatively economical.

The team has also included a Tunable Laser Spectrometer (TLS) among the essential instruments required for this mission. The primary TLS will be accompanied by a backup to ensure operational continuity in the event of a malfunction. The objective of the TLS is to identify a variety of gasses, such as stable isotopes of carbon, hydrogen, and oxygen, water vapor, carbon dioxide, and methane. They can also be used to record vertical mixing ratio profiles, calculate isotope ratios, and distinguish between contributions from simple gasses (Webster, 2014). The same specifications apply to both the primary and secondary TLS. Each spectrometer has a mass of approximately 5 kilograms and a volume of 3 cubic centimeters. The power draw for both spectrometers is 10 watts, and the total cost for each is approximately $3.9 million.

To transport filled sample containers for sealing and storage, as well as to deliver fresh sample tubes to the drill, Lunar Vanguard's rover will be equipped with a robotic arm. The arm is projected to have a power draw of 30 watts and a total cost of $1 million. The 6 DoF RO1 Robotic Arm typically costs around $37 thousand (Standard Bots 2024), but additional funds are being allocated to enhance the arm's durability for the space environment.

The pyrolytic cell of the rover is tasked with determining the chemical composition of collected volatiles. This process involves heating the samples to convert them into gaseous form, which are subsequently analyzed using chromatography and mass spectrometry instruments. This method facilitates a comprehensive understanding of the chemical makeup of each collected sample.The oven has a capacity of around 21 cubic centimeters and a mass of 5 kg. With a maximum power draw of approximately 36 Watts, the entire cost comes to nearly $30,000.

In addition to the previously mentioned instruments, Lunar Vanguard has incorporated a gas chromatograph. This gas chromatograph will enable the rover to trace organic compounds and analyze the major constituents of the cabin air with high precision (Kusch, 2012) . In the event of a malfunction or breakdown, the rover will be equipped with a secondary instrument to ensure mission continuity. Both instruments are identical, each with a mass of approximately 9.5 kilograms and a volume of 3 cubic centimeters. They have a maximum power draw of 10 watts, and each instrument costs approximately $3.9 million.

Lastly, the rover will be equipped with an advanced derivative of the LiDAR camera known as SQRLi. This system includes a camera mounted at the front and back of the rover to capture comprehensive visual data. While the physical characteristics of this specific camera system are unknown, Lunar Vanguard has conducted brief research in order to come up with an analogue for it. The analogue for SQRLi is the Compact LED Lidar System that has a mass of 1.7 kilograms and a volume of 11,109 cm^3 (Shiina, 2019). Each camera has a power draw of approximately 10 watts. The total cost for both cameras is $855,336.

1.8. Programmatic Summary

1.8.1 Team Introduction

Table 3: Team Biographies

Member Name	University Name/Location/Major	Bio
Aiden Deffner *Primary*: CDH *Secondary*: Electrical Engineer	Johns Hopkins University Baltimore, MD *Major*: Computer Science	• Currently a member of the Software Engineering Club at JHU • Currently a member of the varsity cross country and track and field teams at JHU • Previously involved with UC Santa Cruz to process and analyze spectroscopic data from the Keck II telescope • Previously worked with Looma Education to create technology and curriculum for students in Nepal
Amani Salamah *Primary*: Science (Astrophysicist) *Secondary*: Program Analyst	Mount San Antonio College Walnut, CA *Major*: Aerospace Engineering	• Currently the ICC Rep for the engineering club at Mt. San Antonio College • Completion of a research project with Stanford University on String Theory • Active collaboration and event planning with "Society of Women Engineers" club
Brandon Ta *Primary:* Lead Systems Engineer *Secondary:* CDH	University of California, Riverside Riverside, CA *Major*: Computer Science	• Currently a part of the executive board as the Treasurer of a professional engineering organization on campus • Project lead for performing an exploratory data analysis on motor vehicle collisions in New York City • Project lead for designing a software for helping students at UCR discover dining options that fit their budget, nutritional needs, and schedule on campus
Jay Beesla *Primary:* Thermal Engineer *Secondary:* Mechanical Engineer	University of Washington Tacoma Tacoma, WA *Major*: Mechanical Engineering	• Currently University of Washington Tacoma IEEE Branch Secretary • Currently researching and implementing PID (Proportional Integral & Derivative) control into various projects; drones and reaction wheels.

		• Previous Production Intern at Kenworth Truck Co. • Recently involved in a research project for Boeing, coming up ideas with AI & ML for predictive maintenance.
Mark Foley *Primary:* Chief Science Officer *Secondary:* Thermal Engineer	College of the Canyons Santa Clarita, CA *Major:* Environmental Engineering, Machine Learning, and GIS / Manufacturing Certification	• Project Manager and Environmental Science Lead for NASA RockSat-X sounding rocket payload • Project Manager, Chief Science, and Safety Engineer for NCAS 1, 2, and 3 • College of the Canyons Astronomy and Physics club secretary • Biodiversity Initiative Intern - Analyzed resource use of ChatGPT, Researched school waste management system • Data Engineering intern
Nasa Tan *Primary:* Mission Assurance *Secondary:* Mechanical Engineer	California State University of Long Beach Long Beach, CA *Major:* Aerospace Engineering, Astronautics	• Team Lead Mechanical Engineer and Operations Team Member on the University Rover Challenge Competition Club Team during second year of university • Lead Structural Engineer during third and fourth year of university in Long Beach Rocketry (club) • Presently an Additive/Hybrid Manufacturing Lab Research Assistant at Long Beach State
Nathan Panyangnoi *Primary:* Program Analyst *Secondary:* CDH	San Jose State University San Jose, CA *Major:* Computer Engineering, Computer Science	• Currently a member of Tau Beta Pi Honor Society • Currently join Machine Learning researcher at San Jose State University involves with facial recognition project. • Software Engineer club member and IEEE member at SJSU • Proviously interned and work as IT manager and Front-end Software Developer
Rana Eyit	Clovis Community College Fresno, CA	• Currently president of the engineering club at Clovis

Primary: Deputy Project Manager of Resources *Secondary:* Outreach Manager	*Major:* Mechanical Engineer, Aerospace Engineer	Community • Co-president and mechanical engineer for college ROV team during first year of college • Mentor of two First Robotics Competition team one in Fresno and one in Ankara, Turkiye
Rowan Nag *Primary:* Project Manager *Secondary:* Mission Assurance Officer	Purdue University West Lafayette, IN *Major:* Planetary Science, Honors Applied Physics	• Ground Station Director at Purdue Space Program - Satellites, a SEDS Chapter • Researching Reflected exoplanet atmospheres in preparation for the Nancy Roman Space Telescope! (Johnson Cloud Lab) • Amateur Astrophotographer
Sarina Filipinas *Primary:* Science (Researcher) *Primary:* Electrical Engineer	University of California Merced - Merced, CA *Major:* Mechanical Engineer	• Engineer and driver for First Tech Challenge from 2021-2023 • Active member of Roteract, UCM Code, and Society of Women Engineers • Interned for Gudgel Structural Engineering

1.8.2. Team Management Overview

To ensure the mission's success, the team has been divided into three specialized subteams; science, engineering, and programmatics. Each subteam is led by a team lead who facilitates communication within the subteam and liaises with the Project Manager and mentors. All tasks are assigned to subteams during general meetings and communicated by their respective team leads. Each subteam is responsible for specific sections of the deliverables, with individuals and groups taking on tasks based on their expertise and experience. Lunar Vanguard's organizational chart is illustrated in Figure 10.

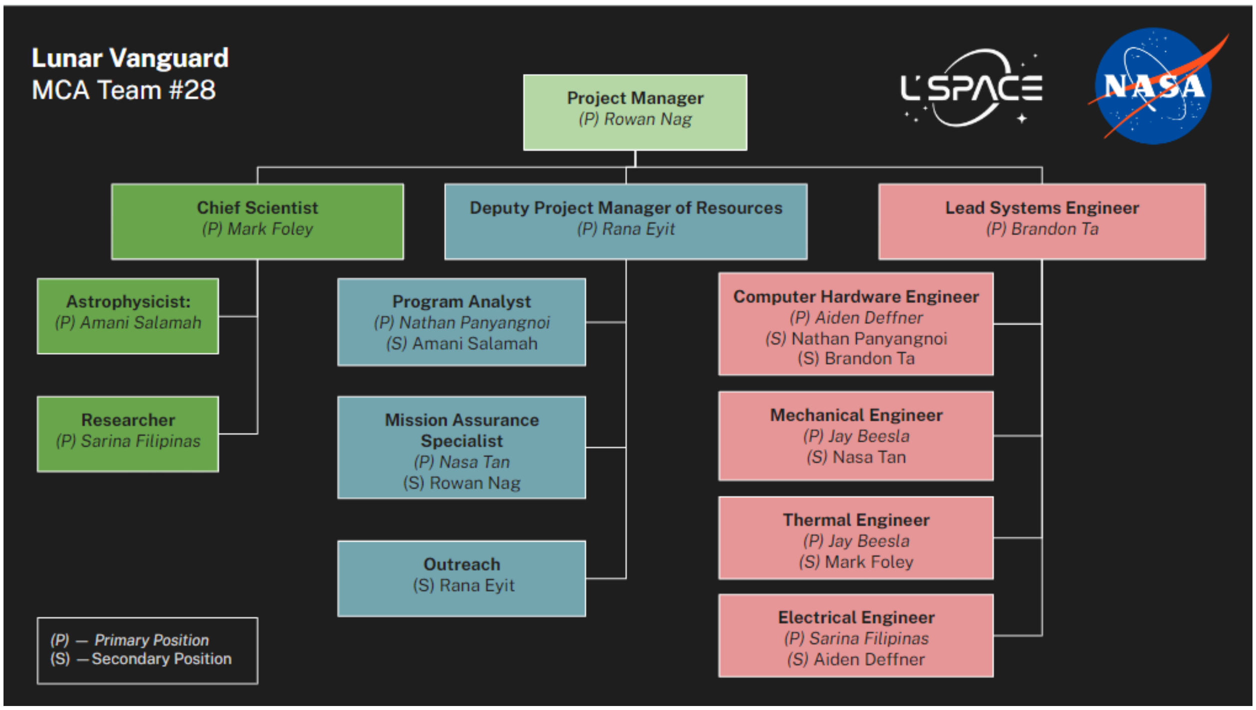


Figure 12. Lunar Vanguard Org Chart

To effectively manage tasks and adhere to the mission timeline, the team will utilize Gantt charts. These charts are developed based on the information provided by the Project Manager and team leads, incorporating feedback from all team members. The team conducts regular weekly meetings via Discord, consisting of one general meeting and separate meetings for each subteam. In the general meetings, the progress of each subteam is discussed. The team is then divided into sub teams to work on the necessary tasks determined by the Lead Systems Engineer, Chief Scientist, and DPMR. These tasks are overseen by the Project Manager, who communicates them to everyone through Discord and meeting minutes including deadlines. Each member will initially focus on their primary role before transitioning to their secondary role. Subteam meetings follow a similar structure to ensure the completion of their assigned tasks.

Depending on the task, team members decide how they work. For tasks that required research and writing most of the members prefer to work individually. In discussion to satisfy the science objectives and work on the rover, members usually communicate through discord to have a meeting on the specific subject.

The team consists of members from different backgrounds, educations, and experiences in and outside the fields of the mission. This variety of experience and knowledge contributes to the overall mission. The team utilizes online sources to learn and research the topics that the team has limited knowledge about. Knowledge and experience are shared among team members through voice calls and chat discussions. In addition to these sources, the team acknowledges the mentors and individuals of their field of expertise by connecting with them and asking questions to be better equipped with the information to handle the project.

Most mission-related decisions are made democratically, ensuring that all voices are heard. The team understands that teammates might have differences of opinions or ideas during the decision process. Differences in opinions are handled democratically, including debates on the opinion or idea. Trade studies are another decision-making process available to the team. Urgent, but non-critical decisions can also be made autocratically by the project manager. Schedule conflicts, for example, may prevent team members from finishing the assigned responsibilities. The PM has the power to give new tasks in certain situations. The PM may assume leadership of the subteam in circumstances where the leaders are not present. If the deliverable is not being completed within the anticipated time frame, the PM may choose to request an extension and implement a plan to finish the work as soon as feasible.

Although the team did not have any conflict, the team has implemented conflict resolution strategies to create a better working environment. Acknowledging the possible prejudices, everyone has their time to state their ideas. The team has set their expectations and management in the early phases of the MCA. In any conflict situation the team utilizes communication to address the conflict. During the addressing, both parties are involved as well as the PM and/or a supervisor to talk about the conflict and bring up any solutions regarding it. After identifying the solution, there are follow-ups after the conflict to view the results.

Having members from diverse regions and backgrounds occasionally results in real-life situations that might prevent a member from meeting their deadlines. To manage this, Lunar Vanguard uses Discord messages to update everyone on their circumstances, enabling the team to adjust and support each other as needed. This approach fosters a well-organized team environment, ensuring that all requirements are met efficiently.

The team structure was created according to availability and willingness to learn. In introductions, every member of the team indicated which role they felt best ed for based on their past experiences whether that be in academics, work, internships, or anything else related. Depending on a member's given skills and experiences, votes were casted and thus the team structure was created. Although some team members have more responsibility than others, everyone on the team does their part in the overall project.

Due to several team members traveling, the team thought it best to request an extension for the MDR, this affected the project schedule. Following the request, the team leaders held a meeting to create a revised schedule for completing all remaining tasks. Each item was delivered according to the availability of members. Throughout the process team members supported one another via Discord to complete their assigned sections.

1.8.3. Major Milestones Schedule

The team has created an outline after researching similar lunar missions. The timeline is then established with the limitations of the budget, personnel, and different aspects of the mission to satisfy the scientific objectives and the goals. The team illustrated the timeline and major milestones for the mission in Table 5, and Table 6.

Table 4. Estimated Mission Timeline (Phases C-F)

Phases	Phase C	Phase C	Phase D	Phase D	Phase E	Phase F
Schedule	Q3 2024	Q3 2025	Q4 2027	Q3 2028	Q4 2028	Q1 2030
Description	Final Design	Fabrication	System Assembly	Test Launch	Operation and Sustainment	Closeout
	Verify Design		System Integration	Official Launch		
			System check verification			

Table 5. Major Milestone Dates

Expected Phase C Start	Q3 2024
Expected Launch Date	September 1st, 2028
Expected Arrival Date	October 1st, 2028
Expected Closeout	Q1 2030

Major milestones are separated into phases and illustrated in Table 6.

Table 6. Major Milestones Separated into Phases

Phase C	Critical Design Review (CDR) System Integration Review (SIR) Phase-C Margin KDP-D	11/12/24 - 12/12/24 05/26/27 - 07/19/27 07/19/27 - 09/30/27 09/29/27 - 09/30/27
Phase D	Test Readiness Reviews (TRRs) Operational Readiness Review (ORR) Launch Post-Launch Assessment Review (PLAR) KDP-E	03/23/28 - 06/30/28 07/03/28 - 08/18/28 09/01/28 09/01/28 - 01/25/29 09/28/28 - 09/29/28
Phase E	Conduct the intended prime mission Process and analyze mission data Critical Event Readiness Review (CERR) Develop final mission report Decommissioning Review (DR) KDP-F	10/02/28 - 11/21/28 11/22/28 - 01/23/29 01/24/29 - 02/28/29 03/31/29 - 08/08/29 08/09/29 - 10/19/29 12/28/29 - 12/31/29
Phase F	Disposal Readiness Review (DRR) Final mission Phase F review Final Archival of Data	01/28/30 - 03/25/30 02/26/30 - 03/18/30 03/28/30 - 03/29/30

1.8.4. Budget Overview

The budget was determined to be $225 million at the start of the mission. A budget cut was established by the customer. The ‘new’ budget is adjusted for the budget cut of $50 million.

Table 7. Budget Overview

Direct Costs (Budget update)				
Subsystem	**New Budget Allocation Estimate (%)**	**New Budget Allocation Estimate (Dollars)**	**Current budget from new budget Estimate(Dollars)**	**Break Down Current budget from new budget Estimate(Dollars)**
Mechanical	58.25%	≈$101.9 million	$ 96,224,761	$ 2,195,880
Power				$ 1,827,435
Thermal				$ 14,511,600
CDH				$ 1,435,500
Navigation				$ 462,092
Spacecraft cost margin				$ 12,080,552
Science Payload				$ 19,836,000
Total Facilities	25%	≈$43.75 million	$ 40,677,174	$ 40,677,174
Others Direct Cost				
Personnel	15%	≈$26.25 million	$ 26,242,168	$ 26,242,168
Travel	0.4%	≈$0.7 million	$ 760,857	$ 760,857
Outreach	1.25%	≈$2.19 million	$ 1,968,009	$ 1,968,009

The new updated estimate budget from the mission lasts 6 years from phase C to phase F which accounts for total MTDC, total other direct cost with F&A constant rate at 10%, ERE Staff constant rate at 28% and current inflation rate of 2024. Total final cost calculations are estimated at $160,421,685.

Table 8. Final Cost Overview

FINAL COST CALCULATIONS							
Total F&A	$ -	$ 267,504	$ 3,908,527	$ 2,740,349	$ -	$ -	**$ 6,916,380**
Total Projected Cost	$ 3,629,219	$ 9,345,817	$ 75,741,920	$ 55,196,510	$ 4,261,987	$ 3,416,801	**$ 151,592,254**
Total Cost Margin	$ 220,039	$ 1,098,415	$ 12,390,753	$ 8,639,843	$ 277,822	$ 217,690	**$ 22,844,562**
	6.1%	11.8%	16.4%	15.7%	6.5%	6.4%	
Total Project Cost	$ 3,849,257	$ 10,444,232	$ 88,132,672	$ 63,836,353	$ 4,539,809	$ 3,634,491	**$ 174,436,816**

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

Mechanical

The mechanical subsystem is responsible for protecting the rover from external forces, and supplying its movement capabilities. It does this through a protective yet lightweight metal chassis, and a mobility system consisting of wheels and durable suspension.

Power

The power subsystem is responsible for generating, storing and distributing power. The rover will do this using solar panels and lithium ion power cells. Due to the nature of solar panels, this subsystem is only able to generate power when outside of a PSR and when it is lunar day. Stored power can be distributed between subsystems any time.

CDH

The CDH (Command and Data Handling) subsystem is responsible for connecting all subsystems of the rover together through software and establishing telecommunications between the rover and the Earth. All commands and data go in and out of the subsystem during operation. It is also responsible for monitoring the conditions of each subsystem to ensure that the rover maintains optional functionality throughout the course of the mission. The CDH subsystem gives the rover “life.” It helps the rover move and execute the actions necessary in pursuit of the mission’s goals.

Thermal

The thermal subsystem is responsible for regulating temperatures throughout the rover to maintain operations on the lunar surface. The rovers systems will require components to function in the harsh sun and the below freezing PSR. Taking into account both the worst case scenario in cold and hot environments the Thermal Control System (TCS) will use vital components for dissipating and creating heat to actively and passively optimize temperatures in the warmbox for vital components.

Payload

The payload subsystem contains the scientific instruments and sample collection devices used to accomplish mission objectives. For the Lunar Vanguard rover, the primary scientific instruments are the TRIDENT drill and TLS (Tunable Laser Spectrometer) and the sample collection devices include a robotic arm and spectrometry suite components like tubing, scrubbers, and getters. It also includes the rover's navigational method: SQRLi.

Table 9. Mass, Volume & Power Overview

Lunar Vanguard Rover			
Subsystem	Mass	Volume	Max Power Draw
Mechanical	29.6 kg	1.84 m^3	100W
Power	17.33 kg	0.02 m^3	40W
CDH	9.95 kg	0.22 m^3	126.3 W
Thermal	16.1 kg	0.97 m^3	125 W
Payload	53.467 kg	0.13 m^3	316 W
Total	126.45 kg	3.18 m^3	707.3 W

2.1.1. Mechanical Subsystem Overview

The mechanical subsystem is broken down to two main categories that are essential to the Lunar Vanguard mission which are mobility and structural. These categories sum up the basis for things like material properties, motor torque and axial/radial loads.This analysis allows the rover to traverse through the harsh terrain in the lunar south pole by using its sturdy components, while also protecting internal components from the environment through its chassis.

The chassis will be constructed of aluminum 7075, a lightweight and durable metal. The resistance to breaking under tension has a max tensile load of 572 MPa (ASM n.d.) which is more than enough for the Lunar Vanguard missions expected loads experienced. The thermal properties of the chassis for the rover can withstand temperatures up to 750K, thus should impose no risk of the chassis melting or deforming while in lunar daytime because of temperatures only reaching up to 400K.

Traversing around Amundsen Crater will require a reliable and efficient drivetrain system to provide a prospecting speed of 1 Km/hr during its traverse mode. In addition to navigating possible rough terrain, the drivetrain should be fully functional in both directions, along with individual control of each wheel on the rover. With a max radial load capacity of 900N (MAXON n.d.) it's sufficient enough for the Lunar Vanguard rover that will weigh about 138N on the moon's surface.

Furthermore the mobility portion of the rover will be a suspension system that is capable of climbing slopes of ±20°, while also clearing obstacles that stand at the 20 cm range. With simplicity and great reliability the 6 wheel rocker bogie suspension will help traverse over debris while en route to sampling locations in the PSR.
Emphasizing the need for agility throughout the whole subsystem, The wheels will be an aluminum 7075 base with aluminum spokes for structural integrity of the wheels. Adding on to the grip of the wheels the exterior facing portion of the wheel will have treads/grousers patterns that will improve the lifetime of the wheels while deployed to the lunar surface.

2.1.1.1. Mechanical Subsystem Requirements

Table 10. Mechanical Subsystems Requirements

WBS Level	Req ID	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
Level 1	ME 1.0	The System will be able to survive the lunar surface for 90 days.	Derived from the top-level mission requirements	MR 1 MR 2 MR 7	ME 1.1	Demonstration	All	Not Met
Level 1	ME 2.0	The system shall be able to traverse the lunar south pole	Derived from the top-level mission requirements	MR1 MR2	ME 1.1	Demonstration	All	Not Met
Level 2	ME 1.1	The system shall have a mechanical subsystem that provides protection and allows for traversal on the lunar south pole.	Mechanical system is responsible for mobility and protection of the rover.	ME 0.2	ME 1.1.1 ME 1.1.2	Demonstration	ME	Met
Level 3	ME 1.1.1	The mechanical subsystem shall have a chassis which encloses and protects internal components	The chassis subsystem of the mechanical system.	MR 4	ME 1.1.1.1 ME 1.1.1.1.1	Inspection	ME	Met

Level 4	ME 1.1.1.1	The chassis will shield internal components from radiation	The chassis subassembly of the entire mechanical system.	ME 0.2		Inspection	ME, TCS	Met
Level 5	ME 1.1.1.1.1	The chassis should not impede the rover's mobility due to weight.	The chassis should remain lightweight for maneuverability.	MR 3		Inspection	ME	Met
Level 3	ME 1.1.2	The mechanical subsystem shall have a mobility system which allows for efficient and safe traversal of the lunar south pole.	The chassis subsystem of the mechanical system.	ME 0.1	ME 1.1.2.1 ME 1.1.2.1.1 ME 1.1.2.2 ME 1.1.2.1	Demonstration	ME, CDH, EPS	Not Met
Level 4	ME 1.1.2.1	The mobility system should allow the rover to safely traverse slopes of 15° or less.	Mobility system allows the rover to traverse the lunar surface.	ME 0.1 ME 1.1.2	ME 1.1.2.1.1	Test	ME	Met
Level 5	ME 1.1.2.1.1	The mobility system should have wheels with sufficient traction to not slip on lunar regolith	Parts that form the mobility system.	ME 0.1 ME 1.1.2		Test	ME	Met
Level 4	ME 1.1.2.	The mobility system should allow the	Mobility system allows the rover to traverse the lunar surface.	ME 0.1 ME 1.1.2	ME 1.1.2.2.1	Test	ME	Met

	2	rover to traverse over bumps and uneven surfaces.						
Level 5	ME 1.1.2.2.1	The mobility system should have a suspension system that can provide stable and safe traversal over small outcroppings or holes.	Parts that form the mobility system.	ME 0.1 ME 1.1.2		Demonstration	ME	Met

2.1.1.2. Mechanical Sub-Assembly Overview

Chassis

The chassis is a critical component of the rover. It's effectively a metal box that encompasses most of the rover's components, while also allowing external access to certain components (antenna, solar panels, science instruments). The chassis must be physically durable, as to be resistant to any wear, deformation, or impacts it may experience throughout the mission. Additionally, it must be ductile enough to deform or bend before breaking. Due to how much material is used for the chassis, as it must encompass the entire rover, it can be extremely heavy. Therefore, picking a lighter material is also important to ensure chassis feasibility.

While conducting trade studies between aluminum 7075, steel, and galvanized steel the criteria was able to pull the team to a decision of using the highly reliable aluminum 7075. The chassis will be an aluminum fabricated box to hold the precious components such as the power system, communication and data handling, and lastly the vital thermal system. The chassis is like the armor of the rover while encompassing the major components of the rover it will also be holding various necessities science tools such as the modified trident drill, solar panels, radiators, antennas,etc. so taking into account the the rovers center of mass is crucial while trekking over obstacles.

Because the Lunar Vanguard rover must have a chassis suited to its own components and instruments, even if the material has been used on other missions to the lunar surface, the TRL of the chassis will be relatively low - TRL 4.

Wheels

Wheels are fundamental components for transportation, optimized for traversing relatively flat terrain on the lunar surface. Various types of wheels such as Mecanum wheels, aluminum wheels, and omni wheels can be considered depending on specific mission requirements.

When selecting wheels for a lunar rover, several criteria must be taken into account. Transport mass and volume, the weight and size of the wheels must be minimized to ensure efficient transport and integration with the rover. This is particularly critical for missions where payload capacity is limited. Operating temperature range, the wheels must be able to function reliably within the extreme temperature variations found on the lunar surface. This includes withstanding both the intense heat of lunar days and the frigid cold of lunar nights. Lunar regolith traction, traction is crucial for maintaining mobility on the lunar regolith, which is known for being soft and loose. Wheels must be designed to prevent getting stuck during forward movement or turning actions, a challenge noted in Asnani (2009).

Selecting the appropriate wheel type involves balancing these considerations to ensure the lunar rover can navigate effectively, perform its mission tasks, and return valuable data from the lunar environment. For the Lunar Vanguard Mission, the aluminum wheels will be the most effective. Aluminum wheels were used for the Curiosity rover. TRL - 6

Drive Train

The Drivetrain is the oil for the machine, when moving the whole rover through the lifetime of this mission having a efficient motor is going to be vital for durability. The mobility and weight of the drivetrain assemblies are the main criterias to be cautious about when selecting a benefitting combination of components. The rover must have brakes to slow down or come to a stop when drilling into the lunar surface, and also the ability to reverse its direction when opposed with an obstacle or the chance it may get stuck in uneven terrain.

For the Lunar mission deciding on the drivetrain system came to a couple of criteria that were all essential but the most important was the torque efficiency. Since the Maxon DC GPX52 Planetary Gearbox & IDX56 Motor has a complementary gearbox to help with torque and speed characteristics with the motor. This will ideally help in rougher terrain that may come across the rovers' way to important testing sites. Also with the built in brake system of the drivetrain system from Maxon it will allow for integration to be simple with this drivetrain and wheel setup.

For the Lunar Vanguard mission the drivetrain subsystem will be at a TRL 5 since Maxon’s motors have been used in the past on Mars missions (Maxon n.d.), but haven’t seen temperature fluctuations such as the south pole of the moon and lunar regolith.

Suspension

Suspension is necessary to reduce damage to components when traversing uneven or bumpy surfaces. Similar to the wheels, it can be expensive and very heavy. The rover must have a suspension able to handle the variety of heights on the lunar surface, and allow the rover to maintain stability while navigating to a target. It’s also a system at risk of dust, which can corrode the suspension. The team ended up considering Rocker-Bogie, Torsion bar, and coil spring based suspension systems.

For the Lunar Vanguard Mission the selection of the suspension was assessed over several criteria. One of the most essential criteria that affected the decision for a rocker bogie suspension system was the adaptability to the terrain. Since the rocker bogie suspension has a main drive wheel and the other end with a pivot to passively adapt to terrain via smaller linkages.It can overcome most surface inclinations that are up to slopes of 15°. The differential gear system is pivotal for the rocker bogie suspension with it being the mechanism that adjusts and controls the rocker arms on both sides of the rover.

For the Lunar Vanguard Mission the suspension system will be at a TRL4 because the system hasn't been implemented on the lunar surface yet. But there have been suspension tests through simulations and also the well known history with both of the Mars rover missions Perseverance and Curiosity both using three wheel rocker bogie systems. In its entirety the mechanical subsystem will be given a TRL 4 because of the lowest components holding these ranking's, the team doesn't want to go above this as it will increase risks for the mission the further it continues.

Table 11 Mechanical Subsystem Overview

Mechanical Components	Mass	Volume/Density	Max Power Draw
Al Chassis	10 kg	.037m^3	0 W
Maxon Drivetrain	8 kg	.901m^3	100 W
Rocker Bogie Suspension	8.6 kg	.025m^3	0 W
Al Wheels	3 kg	.078m^3	0 W
Total	29.6 kg	0.97m^3	100 W

2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans

The mechanical subsystem does not have any redundant components included. This is acceptable due to the high reliability and durability of the components that are used in the subsystem. It is also not feasible to use redundant components for the mechanical subsystem due to the mass and overall bulk of chassis & mobility systems.

One case of failure for the mechanical subsystem is a navigation failure. This could happen for many reasons, but generally, it results in the Rover having incorrect or a lack of knowledge in terms of how far it has traveled, or its location on the moon. In this case, the navigation components can be rebooted. Next, they can be recalibrated based on available landmarks or positioning systems. If all else fails, the rover can send an image from its guidance systems to the ground segment, then standby for manual command.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans

Chassis

Primary Supplier: JPL
Secondary Supplier: Airbus Defence & Space
Lead Time: 1 year 6 months

The Lunar Vanguard team has selected the Jet Propulsion Laboratory (JPL) as the primary supplier for manufacturing the mission's chassis. Utilizing Aluminum 7075 as the main material, JPL brings extensive experience in chassis design, notably from their work on the Mars missions. However, the unique dimension constraints of the Lunar Vanguard mission present a significant challenge.

JPL anticipates a lead time of 18 months to deliver the chassis, since it will need to go through specific heat treatment testing, because of the fluctuations of temperature on the lunar surface. Also, customizing the chassis will take days of analysis and pre modeling based on what components will be stored inside of the chassis. But drawing on their expertise in design and research. The necessary modifications to ensure the chassis' quality and reliability for the lunar environment will require additional time.

If JPL is unavailable to manufacture the chassis, Airbus is the next preferred option. Airbus has a proven track record, having collaborated with the ESA on various components for the ISS and currently working on the chassis design for the ExoMars rover "Rosalind Franklin," set for launch in 2028.

Drivetrain

Primary Supplier: Maxon

Secondary Supplier: JPL
Lead Time: 1 year

The Lunar Vanguard team has selected Maxon Group as the primary supplier for the rover's critical drive system. Maxon has a proven track record, having previously collaborated with NASA on brushless motors for the Curiosity rover and the 2020 Perseverance rover, supplying various motors for the drivetrain and robotic arms (Maxon 2024). Given their extensive experience with rover drivetrains and NASA missions, the manufacturing and testing of the motors under load conditions are expected to proceed smoothly.

Maxon will be allocated a lead time of one year, because the required modifications for the drivetrain system will be heavily dependent on the up sizing of the motors and drivetrain system. Furthermore modifications will lead to more testing, requiring proper torque and revs for the load given. Risk wise it'll be important to check dust collection if any within the drivetrain systems seals while that can impose a big issue on the lunar surface.

If Maxon is unavailable to take on the Lunar Vanguard drivetrain contract, the team will engage JPL for this work. Having previously collaborated with Maxon, JPL's expertise in building and researching components makes them the best secondary supplier for the mission.

Locomotion Bogie Suspension

Primary Supplier: JPL
Lead Time: 1 year 3 months

JPL has extensive experience with rocker-bogie suspension systems, having developed them for Mars missions. Given that the Lunar Vanguard mission will encounter terrain similar to that of Mars, this system remains ideal and durable for planetary exploration.

The primary challenge will be resizing the suspension system to fit within the payload and dimensional constraints for launch. Despite this, a lead time of 15 months is expected from JPL. Because of the modification to the suspension system, building mock terrains that will be similar to the moon's surface to test where the suspension will be the weakest and what obstacles to avoid and maneuver around will need time. Also being able to model and design the new differential system that will function separately with the main drive wheels followed by other wheels that pivot independently will need to fit in the constraints of the Lunar Vanguard rover.

Wheels

Primary Supplier: JPL
Secondary Supplier: IACMI
Lead Time: 1 year

The Lunar Vanguard team has entrusted JPL with the development of the rover's wheels, given their expertise in designing wheels for rigorous terrain. JPL has incorporated design enhancements since the first Mars mission, such as adding grousers to the wheels for improved traction and longevity, and reducing surface contact.

JPL has been allocated a lead time of six months for the wheels. This timeframe is deemed sufficient due to the smaller scale of the Lunar Vanguard mission compared to previous Mars missions, necessitating fewer modifications during the manufacturing process.

If JPL is unavailable, the team's secondary supplier will be IACMI (The Composites Institute). IACMI has been selected for their proficiency in material selection and manufacturing for conventional vehicles. However, this may require a longer lead time to design, test, and produce a high-quality set of wheels for the Lunar Vanguard mission.

2.1.1.5. Mechanical Subsystem Verification Plans

Table 12. Mechanical Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
ME 1.0	The System will be able to survive the lunar surface for 90 days.	Demonstration	Demonstration of surviving the harsh conditions of the lunar surface and observing and recording the functionality of the rovers operations during the mission will be a key factor for this method.	ensuring this verification method will be done through observing the actual mission itself and keeping up with any issues or risks that may pop up in the missions 90 day plan. Ultimately trying to avert those inevitable problems that can come up during a mission.
ME 2.0	The system shall be able to traverse the lunar south pole	Demonstration	Through raw observation of the mission in the lunar south pole, the team shall conclude whether or not the mission has the will to move on further. Ensuring the possibility of future updates and plans to upcoming missions.	Legitimately traversing through the lunar surface and facing the challenges the lunar regolith imposes will be important in how long the rover will take to a specific sampling site in the polar regions.
ME 1.1	The system shall have a mechanical subsystem that provides protection and allows for traversal on the lunar south pole.	Demonstration	Protection will be determined when the mission is active as the chassis of the mechanical system will be the armor for the components inside creating a warm box that will trap and release heat when necessary during the mission.	The observation of any leaks into the main box will be tracked down through various sensors onboard the rover.

ME 1.1.1	The mechanical subsystem shall have a chassis which encloses and protects internal components	Inspection	Direct physical examination will be conducted to see if specifications and dimensions are correct both from the mechanical side of the chassis, and the various components housed in the chassis.	Reviewing engineering drawings, and measuring the rover will be necessary to ensure that the mission is within customer constraints. This can be simply done with calipers or industrial 1D measuring tools.
ME 1.1.1.1.1	The chassis should not impede the rover's mobility due to weight.	Inspection	Inspection will be the most reliable method for checking on the mission's weight before launch readiness.	Using a measurement scale for the entire rover will be the most effective way to measure the weight of the rover, this can definitely be done with a industrial scale
ME 1.1.2	The mechanical subsystem shall have a mobility system which allows for efficient and safe traversal of the lunar south pole.	Demonstration	This will need to be shown during the mission to prove whether the mobility system will be efficient on the lunar surface.	This can be observed over a graph detailing the power used to measure the distance traveled, and how efficient the rover is.
ME 1.1.2.1	The mobility system should allow the rover to safely traverse slopes of 15° or less.	Test	Using mock tests to verify that the suspension system can hold its own without tipping or getting stuck will ensure the rover will strive in lunar conditions.	A terrain environment built with abrasive sand that will replicate the lunar surface, and modeling the lack of rain and wind in a controlled environment will be ideal for ensuring proper suspension testing and durability.
ME 1.1.2.1.1	The mobility system should have wheels with sufficient traction to not slip on lunar regolith	Test	Using extreme slopes with environments that are replicable to the lunar surface can help ensure which traction pattern is the most ideal for the lunar surface, disallow any slip within those 15-degree slopes.	The wheels similar to the suspension test can also be tested in a similar sand-like controlled environment chamber. That will mostly be done on slopes since slipping is more common in that type of scenario with faster speeds of the motor-controlled wheels.

ME 1.1.2.2	The mobility system should allow the rover to traverse over bumps and uneven surfaces.	Test	Similar to ME 1.1.2.1 mock testing using terrain similar to the lunar environment will be beneficial in ensuring the traversability of the rover in dire situations where the mission may need to go in a bigger crater or bumps that can hinder the mission.	With a controlled environment that will have similar sand-like features to mimic the lunar surface, the test can also add ditches and hills to push the limits of the overall body of the rover, and through this observation keep a limit to what specific heights the mission should climb over
ME 1.1.2.2.1	The mobility system should have a suspension system that can provide stable and safe traversal over small outcroppings or holes.	Demonstration	The operation of the mission is the only way to see if the suspension system will be able to last throughout the unforgiving lunar surface. and the observation of how the chassis is handling the lunar terrain is a vital way of proof for future-proofing upcoming missions to the lunar surface.	Some areas of the Amundsen PSR may have ditches and potholes that the rover will need to overcome and this will ideally be tracked through the camera system and the LRO. Ensuring the mobility and structural system are doing their intended responsibilities.

2.1.2. Power Subsystem Overview

The power subsystem is designed to ensure the efficient generation, storage, and distribution of electrical power to all onboard components. This subsystem is crucial for the rover's continuous operation during its mission on the lunar surface. The primary source of power generation is high-efficiency XTJ Prime solar cells, which are strategically placed on the spacecraft, with solar trackers to maximize sunlight exposure. These solar panels convert absorbed solar radiation into direct current (DC) electricity, which is subsequently used to recharge the lithium-ion batteries, specifically the EnerSys ABSL CM1040 model.

Solar power is renewable, eliminating the need for the rover to carry fuel. However, a significant downside is the reliance on sunlight, which can be minimal in the Permanently Shadowed Regions (PSRs) where the rover will conduct its science operations. This dependency requires careful planning to ensure the rover's continuous operation even during periods with limited sunlight.

The Pumpkin Space EPSM1 module plays a critical role in managing and distributing the generated power to various rover subsystems. The Moog Integrated Avionics Unit (IAU) oversees the control and regulation of power, ensuring that each subsystem receives the appropriate amount of energy based on the operational phase.

Alternative power generation methods, such as radioisotope thermoelectric generators and fuel cells, were considered but ultimately deemed unsuitable due to customer constraints and mission life cycle requirements. While solar panels offer renewable energy, they are dependent on surface area, which is limited by the rover’s volume constraints. Despite these limitations, solar panels were selected due to their proven functionality on the moon and at the lunar south pole.

See appendix for power vs time plot and power subsystem calculations.

2.1.2.1. Power Subsystem Requirements

Table 13. Power Subsystem Requirements

WBS Level	Req ID	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
Level 1	PWR 1.0	The system shall generate, store, and distribute power efficiently throughout the mission	Derived from the top-level mission requirements.	Mission req	PWR 1.1	Demonstration	All	Not Met
Level 2	PWR 1.1	The power subsystem shall ensure continuous operation of all spacecraft subsystems	Critical for maintaining mission continuity.	PWR 1.0	PWR 1.1.1 1.1.2 1.1.3	Demonstration	All	Not Met
Level 3	PWR 1.1.1	The power subsystem shall generate power using XTJ Prime solar cells	Solar panel sub assembly for power generation.	PWR 1.1	PWR 1.1.1.1 1.1.1.2	Inspection & Testing	PWR Thermal	Met
Level 4	PWR 1.1.1.1	The solar panels shall have a total surface area sufficient to generate the required power.	Solar panels specifications.	PWR 1.1.1	N/A	Inspection	PWR	Not Met

Level 4	PWR 1.1.1.2	The solar panels shall be mounted on adjustable brackets to maximize sunlight exposure.	Mounting and positioning of solar panels.	PWR 1.1.1	N/A	Testing	PWR	Not Met
Level 3	PWR 1.1.2	The power subsystem shall store energy in EnerSys ABSL CM1040 rechargeable batteries.	Battery subassembly for energy storage.	PWR 1.1	PWR 1.1.2.1	Testing	PWR Thermal	Not Met
Level 4	PWR 1.1.2.1	The batteries shall operate within a specified temperature range to ensure functionality.	Battery specifications.	PWR 1.1.2	PWR 1.1.2.1 .1	Testing	PWR Thermal	Not Met
Level 5	PWR 1.1.2.1 .1	The batteries shall include a thermal management system to maintain optimal operating temperatures.	Thermal management for batteries.	PWR 1.1.2. 1	N/A	Testing	PWR Thermal	Not Met
Level 3	PWR 1.1.3	The power subsystem shall distribute power using the Pumpkin Space EPSM1	Power distribution subassembly.	PWR 1.1	PWR 1.1.3.1	Testing	All	Not Met

		DC power unit.						
Level 4	PWR 1.1.3.1	The DC power distribution unit shall include overcurrent protection and voltage regulation.	Specifications for power distribution unit.	PWR 1.1.3	PWR 1.1.3.1 .1	Testing	PWR	Not Met
Level 5	PWR 1.1.3.1 .1	The power distribution unit and integrated avionic unit shall monitor and log power usage of all subsystems.	Monitoring and logging power usage.	PWR 1.1.3. 1	N/A	Testing	All	Not Met

2.1.2.2. Power Sub-Assembly Overview

Power Sub-Assembly Overview

The power subsystem of the Lunar Vanguard rover is a critical component that ensures the rover's operational efficiency and reliability during the mission. This subsystem comprises four main subassemblies: the XTJ Prime solar panels for power generation, EnerSys-ASBL CM1040 lithium-ion batteries for power storage, Pumpkin Space EPSM 1 Power Distribution Unit (PDU) for power distribution, and the Moog Integrated Avionics Unit (IAU) for overall system control. Each of these subassemblies has been selected for its proven performance in space applications, with consideration of the specific challenges posed by the lunar south pole environment.

Power Generation Subassembly

The power generation subassembly uses XTJ Prime solar panels to convert solar radiation into direct current (DC) electricity, which powers the rover. These high-efficiency solar panels are mounted on solar cells that allow them to optimize sunlight exposure by tracking the sun’s movement. This feature is crucial since Amundsen Rim only receives 40-50% of sunlight throughout a lunar day.

The XTJ Prime solar panels are made of advanced triple-junction cells that can capture a broader spectrum of sunlight compared to traditional solar cells. This capability enhances their efficiency, ensuring that the rover generates sufficient power even in low-light conditions. The panels' durability has been demonstrated in missions like the Mars Rovers (Spirit, Opportunity, and Curiosity) and the International Space Station (ISS), where they have withstood harsh space conditions. However, the unique challenges of the lunar environment, particularly the Permanently Shadowed Regions (PSRs), require further testing to fully validate their performance. As a result, these panels are currently rated at a Technology Readiness Level (TRL) of 6 to 7.

The system also includes protective coatings to shield the solar cells from micrometeoroids and cosmic rays, further enhancing their longevity. During the lunar day, when sunlight is available, the panels generate electricity that powers the rover's systems directly. Any excess energy is stored in the onboard batteries for use during the lunar night or when the rover is in shadow. This is essential for maintaining the rover’s continuous operation throughout its mission, regardless of the lighting conditions.

The adjustable brackets are controlled by the rover’s onboard computer, which uses real-time data from sun-tracking sensors to adjust the panels' orientation for maximum energy capture. This integration ensures that the rover can remain powered throughout its mission, even as environmental conditions change.

Power Storage Subassembly

The EnerSys-ASBL CM1040 lithium-ion batteries are the core of the power storage subassembly, selected for their high energy density, efficiency, and reliability. These batteries store the energy generated by the solar panels during the lunar day and release it during the lunar night or when the rover operates in PSR’s. The ability to store large amounts of energy compactly is crucial, given the mission's weight and volume constraints.

The design of the EnerSys-ASBL CM1040 batteries includes an integrated thermal management system, this is essential for maintaining their performance in the extreme conditions of the lunar environment. Amundsen Rim experiences significant temperature fluctuations, with an overall range of 23-100 K. The thermal management system ensures that the batteries remain within their optimal operating temperature range, protecting them from freezing or overheating. This system includes both passive and active thermal control elements, such as insulation layers and heating elements, which are controlled by the rover’s onboard computer.

The EnerSys-ASBL CM1040 batteries have been successfully deployed in several high-profile space missions, including JAXA’s and NASA’s GMP Core 2014 mission and the Proba-1 Satellite Mission. The Proba-1 Mission has remained operational for over two decades, far exceeding its expected lifespan. This demonstrates the batteries' durability and reliability under demanding conditions. However, because the lunar environment presents unique thermal challenges, further validation under these conditions is necessary, resulting in a TRL of 6.

The batteries' high energy density (1066Wh) allows the rover to store enough power to sustain operations during extended periods of darkness or in shadowed regions. This capability is essential for ensuring that the rover can continue to function even when solar power is unavailable. The batteries also have a long cycle life, capable of enduring up to 300-1000 charge-discharge cycles depending on the temperature.

The batteries are integrated into the rover's power distribution system, managed by the Moog IAU. The batteries store excess energy generated by the solar panels and release it as needed to power the rover's systems. The thermal management system is also controlled by the IAU, which monitors the batteries' temperature and adjusts the heating and cooling elements to maintain optimal conditions. This integration ensures that the batteries can provide reliable power throughout the mission, even in the harsh lunar environment.

Power Distribution Subassembly

The Pumpkin Space EPSM 1 Power Distribution Unit (PDU) is responsible for distributing power efficiently across all rover subsystems. This subassembly ensures that the energy generated by the solar panels and stored in the batteries is delivered to the rover's systems as needed, maintaining a stable and safe power supply.

The EPSM 1 PDU provides overcurrent protection and voltage regulation, which are critical for safeguarding the rover's electronic systems from power fluctuations. These features protect the subsystems from potential damage due to power surges or drops, which could otherwise disrupt the rover's operations. The PDU is also equipped with monitoring and logging capabilities, allowing the rover’s computer to track power usage in real-time and adjust the distribution of power accordingly.

The PDUs robust design ensures that it can withstand the extreme conditions of the lunar environment, including temperature extremes, radiation, and potential mechanical shocks from landing or surface operations. The PDU has proven its capabilities in other space applications, such as NASA’s IceCube Mission, where it successfully managed varying power levels and ensured stable power distribution. Despite its performance, it’s current TRL is 6, additional testing is required to validate its functionality under lunar-specific conditions for the Lunar Vanguard.

The EPSM 1 PDU is integrated into the rover's power management system, distributing energy to all subsystems. The PDU works in conjunction with the Moog IAU, which provides overall control and coordination of power distribution. The PDUs data logging capabilities provide valuable insights into the rover's power consumption patterns, enabling the mission team to optimize power management and ensure that the rover operates efficiently throughout its mission.

Integrated Avionics Unit (IAU) Subassembly

The Moog Integrated Avionics Unit (IAU) is the central control unit for the rover's power subsystem, responsible for coordinating the distribution of power across all subsystems. The IAU dynamically allocates power based on the rover's operational phase, ensuring that critical systems receive the necessary energy while conserving power in non-essential areas.

The IAU's ability to efficiently manage power distribution is critical for the rover’s success. The unit can prioritize power delivery to systems that require it most during specific mission phases, while reducing power to other systems during periods of low activity. For example, allocating power towards the mechanical and CDH subsystems, and turning off power for the payload instruments during the transversal phase.

The Moog IAU is also equipped with radiation-hardened components and low-power hibernation modes, which are essential for maintaining reliable operation in the harsh lunar environment. These features help to protect the unit from the damaging effects of radiation and allow the rover to conserve energy during periods of inactivity. The IAU has been successfully used in various space missions, including NASA's VIPER project and Artemis 1 mission, where it demonstrated its reliability and capability. However, further testing is needed to confirm its performance under the specific conditions of the lunar South Pole, the IAU has a TRL of 6.

Overall Technology Readiness Level (TRL)

The overall TRL of the power subsystem is 6. Each subassembly has been tested and proven in space missions, but additional testing under lunar-specific conditions, specifically in PSRs, is necessary.

Table 14. Power Subsystem Estimates Overview

	Mass (kg)	Volume (m^3)	Max Power Draw (W)
Battery	8.8 kg	0.0099112 m^3	1066Wh (energy stored)
IAU	Up to 8.3 kg	0.0063 m^3	37W
PDU	0.23 kg	1.3167×10^{-4} m^3	3W
Solar Cells	84 mg/cm^2	3.78×10^{-4} m^3	Generates 612.3W w/82 cells

2.1.2.3. Power Subsystem Recovery and Redundancy Plans

The power subsystem utilizes multiple power cells within the battery, which can act as backups for each other. Power can be redistributed to functioning cells, and although this reduces total battery capacity for the rover's operations, components should still be operable within this additional margin. There are no redundant solar panels in the rover. This is because the risk of solar panels being damaged or power production capabilities being reduced beyond a reasonable measure is unlikely. A likely risk for solar panels is that lunar regolith could partially cover them, but they should still be able to produce sufficient power for the rover's nominal operations. Also, solar panels have too much mass and general bulk for the rover to carry a duplicate set.

The power subsystem has multiple recovery modes. First, if the power usage of components is high, the rover will reduce the usage of power-consuming components to conserve energy. This is to reduce the chances of the subsystem entering low power mode. Low power mode is more critical and is a result of current battery levels dropping below suitable levels. Non-critical components shall be disabled, and the rover will prioritize recharging. This may include navigation out of a PSR, deployment of solar panels, or other measures.

2.1.2.4. Power Subsystem Manufacturing and Procurement Plans

Lithium-ion Batteries

PRIMARY SUPPLIER: EnerSys ABSL

SECONDARY SUPPLIER: Saft Batteries

LEAD TIME: 6 Months

EnerSys-ABSL will be the primary supplier of the CM1040 Lithium-ion batteries. These batteries are known for their high energy density, reliability, and long operational life. They've been selected due to their success in missions such as JAXA's and NASA's GMP Core 2014 mission and the Proba-1 Satellite Mission. The Proba-1 satellite launched in October 2001, and has exceeded its two year expected lifespan, it's still active and holds the record as the longest lithium-ion battery powered mission.

Saft Batteries were selected as the secondary supplier due to their strong reputation, energy efficiency, and reduced sensitivity to Lunar Temperatures. However, EnerSys-ASBL was chosen as the primary since they have more documented space mission usage and would better adapt to the Lunar Vanguards requirements.

A lead time of about 6 months is expected for both suppliers. About 1 to 1.5 months will be dedicated to each phase of testing, this involves thermal, electrical performance, customization/integration, and certification testing. The batteries should have trials with high and low extreme temperatures to simulate lunar conditions. The batteries should demonstrate their ability to function reliably within the operating temperature range of 0°C to 40°C. The batteries should demonstrate the ability to supply constant power under various loads. Additionally, integration and customization to ensure that the battery works properly with the thermal management system. For certification, they should go through a full test, simulating sample collection and traversing.

Integrated Avionic Unit (IAU)

PRIMARY SUPPLIER: Moog Inc.

SECONDARY SUPPLIER: Honeywell Aerospace

LEAD TIME: 6 Months

Moog’s IAU was selected for the NASA VIPER project, which gives credibility to its capabilities and should be considered for the primary supplier for the IAU. Moog's avionic units have been used in various other spacecraft missions like Artemis 1 where they provided thrust vector control actuators and various other low earth orbit satellite missions. They’ve been proven to have high reliability, radiation tolerance, and low-power hibernation modes, which makes it suitable for lunar environments.

As the backup supplier, Honeywell Aerospace is a reliable alternative if Moog is unavailable. Honeywell provided avionic components for the Mars rover and proved to provide consistent performance.

The expected lead time is about 6 months to ensure that specifications are tailored to the Lunar Vanguard. About 1 to 2 months should be dedicated to each testing phase: radiation, low power mode, integration/customization, and environmental testing. During these tests, the IAU should undergo radiation exposure tests, to ensure it doesn’t degrade too much during the mission’s lifespan, ensure that the IAU manage’s power consumption effectively without error, and is able to work with CDH and thermal subsystems seamlessly. For final validation, its performance should be tested through a mission simulation such as, can it handle the stress of the launch, extreme temperatures, possible moonquake vibrations, etc.

Power Distribution Unit (PDU)

PRIMARY SUPPLIER: Pumpkin Space Systems

SECONDARY SUPPLIER: GomSpace

LEAD TIME: 6 Months

Pumpkin Space Systems EPSM 1 module would be an ideal pairing with Moog’s IAU for distributing power to various subsystems of the rover. The modularity and scalability of the Pumpkin Space Systems module makes it the primary choice. NASA’s IceCube Mission utilized this same supplier and product, highlighting its ability to handle varying power levels in space.

If Pumpkin Space Systems is unavailable, GomSpace would be the secondary supplier due to their range of power for small spacecraft and similarity in efficiency. Pumpkin offers higher integration and customization options.

The expected lead time is about 6 months for modular configuration. About 1 to 2 months will be dedicated to each testing phase of this subsystem as well. The unit needs to be customized to fit the specific voltage levels needed by different subsystems and integrate overcurrent protection mechanisms as well. Like the other power subsystems, it needs to be able to withstand the harsh lunar conditions. During testing, the goal is to ensure that the ESPM 1 can efficiently manage and distribute power without instability. For its final phase of development, it should endure stress tests to make sure it can handle unexpected events, and its compatibility with the Lunar Vanguard's other subsystems.

Solar Cells

PRIMARY SUPPLIER: Spectrolab

SECONDARY SUPPLIER: Azur Space

LEAD TIME: 6 Months

Spectrolab solar cells provide reliable and efficient energy, as proven in the Spirit, Opportunity, and Curiosity rovers. They have a robust design capable of surviving the harsh lunar environment, this makes them the ideal choice for powering the Lunar Vanguard rover.

If unavailable, Azur Space is the secondary supplier. They provide high-efficiency multi-junction solar cells and have been used in NASA's Europa Clipper Mission. Spectrolab's solar cells have a slightly better efficiency and more extensive use in space missions.

The lead time is estimated to be about 6 months and possibly more depending on testing and the Lunar Vanguard's power generation requirements. Each phase of testing should take about 1 to 2.5 months. The bulk of the process is customization; the cell size, configuration, and mounting mechanisms need to be optimized to the rover's constraints and power needs. The cell's efficiency should be evaluated under various different lighting conditions like partial shading, dust on the panels, etc. Lunar conditions and mechanical stress tests will also be needed to verify that the solar panels can withstand operation on the lunar surface.

2.1.2.5. Power Subsystem Verification Plans

Table 15. Power Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PWR 1.0	The system shall generate, store, and distribute power efficiently throughout the mission.	Demonstration	Demonstrating the system's ability to generate, store, and distribute power under mission conditions validates its readiness.	A full-scale demonstration under simulated mission conditions, including the lunar surface environment, will be conducted. The system will be monitored to ensure continuous power availability throughout the mission phases.
PWR 1.1	The power subsystem shall ensure continuous operation of all spacecraft subsystems	Demonstration	Continuous operation is critical; demonstration ensures that power is reliably supplied to all subsystems.	During a simulated mission, the power subsystem will be observed for uninterrupted power delivery to all critical subsystems over an extended period, including during peak loads and low-power phases.
PWR 1.1.1	The power subsystem shall generate power using XTJ Prime solar cells.	Test	Testing the solar cells under simulated lunar conditions ensures they meet power generation requirements.	Solar cells will undergo testing in a lunar environment simulator to assess their efficiency, output, and durability under various angles of sunlight exposure and shading. Output will be measured to confirm it meets design specifications.

PWR 1.1.2	The power subsystem shall store energy in EnerSys-ASBL CM1040 lithium-ion batteries.	Test	Testing ensures that the batteries can store and release energy reliably under mission-specific conditions.	Batteries will be tested for charge and discharge cycles, thermal performance, and storage capacity under conditions mimicking the lunar environment. Data will be collected to verify that energy storage meets mission requirements.
PWR 1.1.3	The power subsystem shall distribute power using the Pumpkin Space EPSM 1 DC power unit.	Test	Testing the PDU ensures that it can distribute power reliably and safely across all subsystems.	The PDU will undergo testing in a controlled environment to simulate the lunar conditions. Tests will focus on the PDUs ability to manage power loads, provide overcurrent protection, and maintain voltage regulation within required parameters.
PWR 1.1.1.1	The solar panels shall have a total surface area sufficient to generate the required power.	Inspection	Inspecting the solar panels' surface area ensures they meet the required specifications for power generation.	Solar panels will be inspected to ensure that the total surface area aligns with design specifications. A detailed examination will confirm that the panels are mounted correctly and are capable of capturing the maximum possible sunlight exposure.
PWR 1.1.2.1	The batteries shall operate within a specified temperature range to ensure functionality.	Test	Testing the batteries under extreme temperatures ensures they can operate reliably on the lunar surface.	Thermal testing will be conducted to evaluate the batteries' performance across the expected temperature range on the lunar surface. Data will be gathered to verify that the batteries maintain their charge and discharge

				capabilities within specs.
PWR 1.1.3.1	The DC power distribution unit shall include overcurrent protection and voltage regulation.	Inspection & Test	Inspection and testing confirm that the PDUs safety features are operational and meet design requirements.	The PDU will be inspected for correct installation of overcurrent protection devices and voltage regulation components. Subsequent testing will verify that these features function correctly under simulated lunar operational conditions.
PWR 1.1.3.1.1	The power distribution unit and IAU shall monitor and log power usage of all subsystems.	Test	Testing ensures that the power usage logging capabilities of the PDU and IAU are accurate and reliable.	The PDU and IAU's monitoring and logging systems will be tested by simulating various power consumption scenarios. Data accuracy and logging reliability will be assessed to ensure that they can provide critical power usage data throughout the mission.

2.1.3. CDH Subsystem Overview

The CDH subsystem of the Lunar Vanguard rover is primarily responsible for linking all other subsystems together in order to carry out its tasks successfully throughout the mission. The subsystem is also responsible for telecommunications, data computing, and software architecture of the rover to ensure the mission's science objectives and success criteria are being fulfilled. In order to carry out these responsibilities, the subsystem is made up of four subassemblies including the CPU, the storage devices, the antennas, and the transceivers.

The CPU and storage device subassemblies will need sequence file, command, and patch file data in order to receive and process new commands and software updates from mission control. Antenna and transceiver subassemblies require commands from the rover software to transmit data and messages.

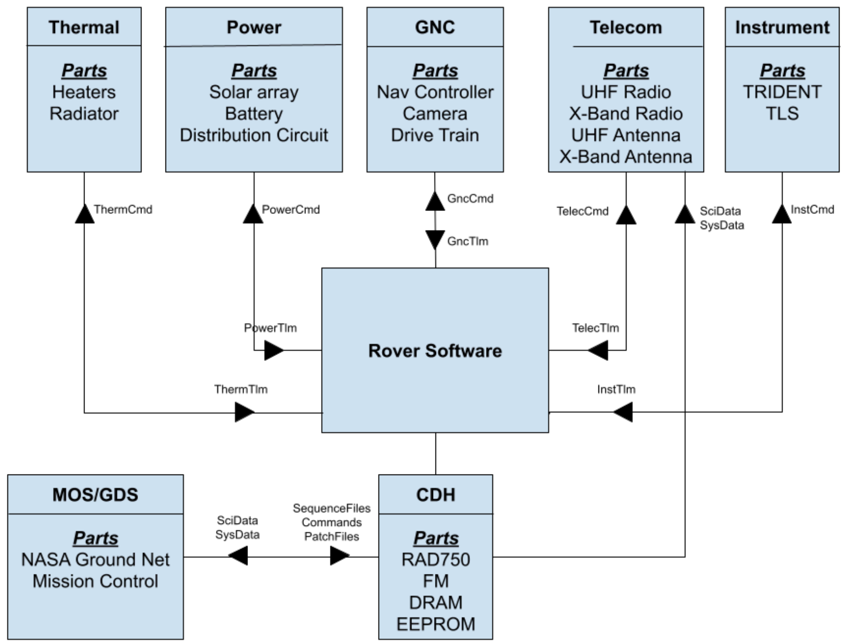


Figure #13. Software Architecture Flowchart.

2.1.3.1. CDH Subsystem Requirements

Table 16. CDH Subsystem Requirement

WBS Level	Requirement ID	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
Level 1	CDH 1.0	The system shall determine the compositional state & distribution of volatiles in polar lunar sites.	Derived from the Top-Level Mission Requirements	MR 1	CDH 1.1	Demonstration	All	Not Met
Level 1	CDH 2.0	The system shall determine the source(s) of the volatile deposits in lunar polar regions.	Derived from the Top-Level Mission Requirements	MR 2	CDH 1.1	Demonstration	All	Not Met
Level 2	CDH 1.1	The system shall have a subsystem that is responsible for collecting, processing, storing, and sending scientific and system data efficiently.	The responsibilities the subsystem is in charge of.	CDH 1.0 CDH 2.0	CDH 1.1.1 CDH 1.1.2 CDH 1.1.3 CDH 1.1.4 CDH 1.1.5 CDH 1.1.6	Demonstration	CDH	Met
Level 3	CDH 1.1.1	The subsystem shall contain a CPU that will facilitate all actions of the rover while monitoring its health.	A component of the subsystem.	CDH 1.1	CDH 1.1.1.1	Inspection	All	Met
Level 4	CDH 1.1.1.1	The system shall log and manage	How the CPU keeps itself in proper	CDH 1.1.1		Test	All	Met

		environmental and system health data including temperatures, power generation, and structural condition.	working conditions.					
Level 3	CDH 1.1.2	The subsystem shall contain storage devices that allow the rover to store all kinds of data it receives.	A component of the subsystem.	CDH 1.1	CDH 1.1.2.1	Inspection	CDH	Met
Level 4	CDH 1.1.2.1	There shall be multiple kinds of storage devices so that memory is processed and stored in the most efficient way.	Storage devices such as flash memory, RAM, or ROM can be used.	CDH 1.1.2		Inspection	CDH	Met
Level 3	CDH 1.1.3	The subsystem shall contain at least one transceiver that processes radio signals for the rover to receive and transmit.	A component of the subsystem.	CDH 1.1	CDH 1.1.3.1	Inspection	CDH	Met
Level 4	CDH 1.1.3.1	The transceiver(s)/transmitter(s) shall be compatible with the frequencies of the antenna(s).	Ensures compatibility between the telecommunication components.	CDH 1.1.3		Inspection	CDH	Met
Level 3	CDH 1.1.4	The subsystem shall contain at least one	A component of the subsystem.	CDH 1.1		Inspection	CDH	Met

		antenna that allows the rover to send and receive radio signals between the rover and the flight team.						
Level 3	CDH 1.1.5	The subsystem shall support software updates and patches.	How the system maintains optimal functionality.	CDH 1.1		Test	CDH	Met
Level 3	CDH 1.1.6	The electronic components of the subsystem shall be radiation-hardened to resist radiation exposure of 100 krads and extreme temperatures of -55°C to 125°C	Allows the components to maintain functionality in space.	CDH 1.1		Test	CDH	Met

2.1.3.2. CDH Sub-Assembly Overview

CPU

The CPU is responsible for linking all the subsystems of the rover together acting as the "brain" of the spacecraft. The CPU processes, interprets, and executes instructions using its software programs through its hardware components in order to carry out the rover's tasks throughout the mission. It must always be running, constantly monitoring its health including its temperatures, power levels, durability, and other features that help keep the rover alive. It checks and adjusts temperature controls in the rover's body then records power generation and storage data to decide which new activities to start or finish. This way, the CPU can ensure that the rover maintains optimal conditions for functionality. The CPU also utilizes the rover's telecommunications along with Earth's orbiters to effectively communicate back and forth with the flight team.

The CPU that was chosen for the Lunar Vanguard rover was the RAD750. Manufactured by BAE Systems, an international defense, aerospace and security company, the RAD750 has proven to be very reliable excelling in performance, cost, availability, and flight heritage. The RAD750 is a powerful radiation-hardened general-purpose microprocessor that is considered one of the most powerful of its kind/ It is said to be 10 times better than other radiation-hardened space processors while being able to withstand extreme temperatures and radiation.This chip's architecture also supports the industry leading performance of >400 MIPS operating at 200 MHz.

The evaluated TRL of this processor is a TRL 7. This is due to NASA's Mars 2020 Perseverance Rover which has evidently proven the reliability of the RAD750 processor in its ongoing mission since its landing on Mars on February 18, 2021.

Storage Devices

The storage devices are responsible for storing and handling all data that comes in and out of the Lunar Vanguard rover. This primarily includes the scientific data gathered from the rover's instruments and commands that the rover receives from the flight team throughout the mission. However, the rover must be able to process and analyze the raw data it receives from the instruments. It is important to utilize a variety of storage devices to expand the rover's storage options when a situation calls for it. This will allow the rover to handle its data more efficiently and effectively. The team decided to equip the rover with 2 gigabytes of flash memory, 256 megabytes of dynamic random access memory, and 256 kilobytes of electrically erasable programmable read-only memory.

The flash memory will serve as a long-term, high-capacity storage device with fast transfer speeds. Since flash memory is non-volatile, it retains stored data even when the power is off. Its durability and simple build will prove reliable over the course of the mission.

The DRAM will allow the rover's processor to run efficiently by providing quick access to essential data in order to keep the rover running at high-performance levels. DRAM is faster than many other types of memory and its random access capabilities allow the processor to access any part of the memory directly. The reason why the team prioritized DRAM instead of regular RAM is because DRAM will allow the rover's computer to process data much more quickly compared to using a slower type of RAM. The purpose of using EEPROM is primarily to store data that does not need to be modified. It will be used to store small amounts of data within the rover. This kind of memory is ideal because it will allow the computer to quickly access information without having to constantly write and rewrite data. Read-only memory is particularly useful for storing the rover's firmware. Additionally, EEPROM is a type of nonvolatile memory meaning that it also retains stored data without power just like flash memory. EEPROM will be beneficial to the rover's performance throughout the mission because it offers more flexibility than EPROM or regular ROM with its enhanced capabilities.

The evaluated TRL of these storage devices are all TRL 6 based on Nasa's ongoing Mars 2020 mission carried out by the Perseverance rover, successfully demonstrating their credibility.

Antennas

The antenna is responsible for sending and receiving all communication between the rover and the flight team throughout the mission. It transmits and receives data to and from the moon using Earth's orbiters. The antenna is an essential part of telecommunications for the rover because it is its only means of communication with the flight team. Without it, it cannot receive commands back on Earth from to complete its tasks nor can it send back its findings, which would cause the mission to lose all its meaning. The team decided to use two antennas for the rover because it provides more operational flexibility and potential backup options in case the mission goes awry. The two antennas that will be used for the Lunar Vanguard rover IS an UHF omnidirectional antenna and an X-band medium-gain (directional) antenna.

The UHF omnidirectional antenna is able to utilize Earth's orbiters as a more efficient means of communication because the rover and the orbiter's antenna are within close range of each other. Using orbiters to relay messages is more efficient because they are much closer to the rover than the DSN antennas on Earth. The antenna's omnidirectional capabilities provide the rover with a wider, more flexible range of communication that is not dependent on a specific alignment. Additionally, it provides a balanced antenna gain across all frequencies, enabling them to receive signals from any direction.

The X-band medium-gain antenna performs well in sending data directly back to Earth utilizing the DSN rather than through an obiter. What sets the medium-gain antenna apart from the UHF antenna is that the medium-gain antenna is able to transmit data to Earth significantly faster. Its relatively high gain allows it to focus its beam, allowing higher data rates on the long transmission back to Earth. Moreover, the antenna's steerable capabilities allow it to point its radio beam in a specific direction. Having a steerable antenna means that the entire rover does not need to change position to communicate with the team back on Earth wherever it is on the moon. This way, the rover can save energy and keep things simple by moving only the antenna.

A score of TLR 6 was chosen for both the antennas. This is backed by the successful demonstration of the Perseverance rover which utilizes antennas with very similar designs and specifications.

Transceiver/Transmitter

The transceiver is responsible for facilitating communication between the Lunar Vanguard rover and mission control centers on Earth, enabling the transmission of scientific data, telemetry, and commands. Transceivers allow personnel to monitor and control the rover, gather its findings, and execute complex movements. They help the rover process incoming and outgoing data that goes through the antenna. It will be equipped with two transceivers to pair with the two different antennas. The rover's transceivers will help ensure the success of the mission by providing a means of reliable communication and data exchange to and from the moon. The transceivers that the team chose for the Lunar Vanguard rover are the L3 Harris C/TT-510 Electra-Lite UHF transceiver and the Comtech XSAT-7080 X-Band transceiver.

The L3Harris C/TT-510 Electra-Lite UHF transceiver has flexibility in its design which provides an ease-of-use experience beneficial for the mission. This is the reduced mass version of a similar design to another transceiver, which is why it is ideal for the Lunar Vanguard mission with stringent mass and energy constraints. The evaluation of this transceiver is a TRL 6 because of its reliability in the mission of Mars through the Perseverance rover on Mars.

The Endurosat X-Band Transmitter provides effectiveness as well with its high-performance capabilities while utilizing a compact design. Moreover, the design of the transmitter provides a high TOI that allows multi-carrier applications without the concerns normally associated with low-power environments. This will prove to be beneficial for the Lunar Vanguard mission especially as the rover traverses a low power environment such as the PSRs. The evaluation of this transceiver is a TRL 6 given its validated testing in a relevant environment.

Considering all the evaluated TRLs of each subassembly of the subsystem, the TRL of the subsystem itself is a TRL 6.

Table 17. CDH Subsystem Overview.

CDH Subassemblies	Mass	Volume	Max Power Draw
CPU	0.550kg	0.1m x 0.16m	17W
Flash Memory	0.04kg	0.02m x 0.02m x 0.001m	1W
DRAM	0.07kg	0.03m x 0.01m x 0.001m	2W
EEPROM	0.02kg	0.01m x 0.01m x 0.001m	0.3W
UHF Antenna	1kg	0.15m x 0.15m x 0.01m	3W
X-Band Antenna	5kg	1m x 1m x 0.2m	20W
UHF Transceiver	3kg	0.161m x 0.104m x 0.203m	65W
X-Band Transmitter	0.27kg	0.096m x 0.090m x 0.023m	18W

2.1.3.3. CDH Subsystem Recovery and Redundancy Plans

Within the subsystem there are two CPUs. During regular operational hours the computer runs normally using the primary processor. The other is normally asleep and will awaken when the primary processor runs into problems. In the case that one of the CPUs loses its functionality or becomes incapacitated, the rover has the spare CPU within the system that can be awakened if this situation should occur.

Similarly, the Lunar Vanguard rover is equipped with two sets of antennas and their compatible transceiver. In the case where an antenna or a transceiver becomes incapacitated from either set, the other set will serve as a back-up to maintain communication. The system will then switch from utilizing both sets of communication to switching completely to the set that is still functional. As the storage system in the subsystem will be partitioned, there is less risk of the loss of data should a storage device become damaged or corrupted. This way, the subsystem will still be able to store and handle data.

The telemetry components of the CDH subsystem have multiple steps for recovery. If there are internal issues within the system that cause a loss of communication, the system will first wait for the component to come back online. If communications are still not back online, the system will then reboot itself to resolve the underlying issues. In some cases, either the antennas or the transceivers will not function properly. This may be due to the alignment issues or issues in calibrating the frequency. In an attempt to resolve these issues, the system will first attempt to recalibrate the system itself autonomously. If it proves to be unsuccessful, the system will then reboot the system to clear the temporary data and reset the software. If the UHF communication system encounters issues from either the transceiver or antenna, the X-Band antenna and transmitter are capable of communicating through the orbiter as a replacement. If there are issues with the orbiter, the X-Band system has long-distance capabilities to transmit information directly to Earth.

2.1.3.4. CDH Subsystem Manufacturing and Procurement Plans

CPU
PRIMARY SUPPLIER: BAE Systems
SECONDARY SUPPLIER: Artisan Technology Group
LEAD TIME: 4 Months

The team chose BAE Systems as the primary supplier for the CPU. As the manufacturer of the RAD750, which is the CPU the rover will be utilizing, BAE Systems has also provided the same CPU for the Perseverance rover for NASA’s 2020 Mars mission. They have worked with NASA on many projects, including satellites, instruments, and other space exploration projects.

If BAE Systems is not available to provide the CPU, the RAD750 CPU will be acquired through the Artisan Technology Group. This company is known to work with BAE Systems and carries their products including the RAD750 available for purchase.
A lead time of 3 months is to be expected from both BAE Systems and Artisan Technology Group since they have been reliably manufacturing and supplying the RAD750 for many years already. Since there are no adjustments to be made, the product can just be used as is. It is expected to take some time to get into contact with these suppliers for them to check the availability of their stock first, and for them to be shipped and delivered. Once the CPU is delivered the product will just need to be configured to the rover's system and put through tests to find any potential adjustments that need to be made.

Antenna
PRIMARY SUPPLIER: JPL
SECONDARY SUPPLIER: Airbus
LEAD TIME: 6 Months

JPL was selected to be the primary supplier for the rover's antennas. The reason for this is because JPL has been manufacturing and supplying many materials for NASA for years. This is especially important with space exploration technology such as rovers. JPL has partnered with NASA in developing and testing rovers for many past space-exploration missions.

If JPL is unable to supply the antennas, the team's second option is Airbus. Airbus built the Mars 2020 High Gain Antenna System for JPL which included an X-band steerable antenna for transmission and reception that provide high data-rates of communication from the Perseverance rover on Mars directly back to Earth. The company has also worked with JPL in the past with the notable Curiosity rover.

JPL and Airbus will need a lead time of 6 months to supply the antennas. The reason for this is that it will take some time to detail all the specifications needed for the rover's antenna as some modifications will need to be made to fit its needs. It will also be needed to check JPL's or Airbus' stock to see if there exists the right materials to create the desired antennas. After, it will take additional time for the product to be shipped and delivered, with ample time left over in the case of any unforeseen delays on the way. It will also take some time to adjust the antennas during its testing phase to make sure if the antennas are working properly.

Transceiver
PRIMARY SUPPLIER: L3 Harris Technologies
SECONDARY SUPPLIER: In-House

LEAD TIME: 3 Months

The primary supplier for the rover’s transceivers will be L3Harris Technologies. L3 Harris technology has been onboard numerous NASA programs including multiple space shuttles, the ISS and previous Mars missions. The company has also supported NASA’s Mars exploration for two decades including the Spirit, Opportunity, Curiosity and Perseverance vehicles which speaks volumes about their reliability as a supplier for the Lunar Vanguard mission.

In the event L3Harris Technologies cannot support the transceiver for the Lunar Vanguard mission, the team will fall back to in-house resources such as Goddard Space Flight Center. They have multiple options from previous missions and projects over the years.

A lead time of 3 months is expected as the product should be able to be used as is with only minor adjustments that may need to be made. Factoring additional time accounting for shipping and delivery, it will take some time for the product to reach the rover. Other than that, testing and calibration should go smoothly given previous data and experience with the product from last missions.

Transmitter
PRIMARY SUPPLIER: EnduroSat
SECONDARY SUPPLIER: In-House
LEAD TIME: 3 Months

The primary supplier for the rover’s transceivers will be EnduroSat, an aerospace manufacturing company that designs, builds, and operates CubeSats and Nanosatellites for commercial and scientific missions. They are also developing inter-satellite linking and data applications as well. Notably, Endurosat is, and will be working with NASA alongside other institutions in California on spacecraft technology projects. This proves the company’s reliability as a primary supplier for the Lunar Vanguard mission.

If EnduroSat is not able to supply the transmitter for the mission, the team will resort to in-house resources such as the Goddard Space Flight Center in order to procure the product. Considering that many rover missions in the past have utilized transmitters to communicate with the flight team, there should not be any issues for adjustments to be made.

A lead time of 3 months is the expected time for the product to be procured. It will take time for the team to get into contact with EnduroSat to check their stock availability so that they can ship and deliver the transmitter. It is expected that there will be a need to make time to make any adjustment during testing.

Flash Memory
PRIMARY SUPPLIER: Cobham Advanced Electronic Solutions
SECONDARY SUPPLIER: In-House
LEAD TIME: 6 months

Cobham Advanced Electronic Solutions will be the primary supplier for the rover's 2 gigabytes of flash memory. Cobham successfully assisted the ESA's Solar Orbiter Mission with several components, including flash memory.

A lead time of 6 months is expected. A low number of adjustments and testing is expected as Cobham's has a long and credible history among space missions with varying technology.

DRAM
PRIMARY SUPPLIER: Micron Technology
SECONDARY SUPPLIER: In-House
LEAD TIME: 8 months

The primary supplier for the rover's 256 megabytes of DRAM is Micron Technology. Micron Technology is a global leader in memory and storage technology for various applications and has great options for handling conditions in space.
As Micron Technology does not have an extensive history with space missions, a lead time of 8 months is expected in order to optimize and test the component for the application.

EEPROM
PRIMARY SUPPLIER: Microchip Technology
SECONDARY SUPPLIER: In-House
LEAD TIME: 6 months

Our team has selected Microchip Technology to supply the rover with 256 kilobytes of EEPROM. Microchip Technology has played a significant role in several NASA Mars missions, such as Spirit, Opportunity, Curiosity and Perseverance, as well as the Jet Propulsion Laboratory's mission to develop a High-Performance Spaceflight Computing processor.

A lead time of 6 months is expected from Microchip Technology, as they are reliable and have been successfully involved in several NASA missions. Only testing is needed and minimal adjustments are expected.

2.1.3.5. CDH Subsystem Verification Plans

Table 18. CDH Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
CDH 1.0	The system shall determine the compositional state & distribution of volatiles in polar lunar sites.	Demonstration	The team will evaluate the mission's capabilities though direct observation in order to maintain this requirement	This will be done by monitoring the mission as a whole and suppressing any unexpected obstacles that it may face throughout its lifetime
CDH 2.0	The system shall determine the source(s) of the volatile deposits in lunar polar regions.	Demonstration	The team will evaluate the mission's capabilities though direct observation in order to maintain this requirement	This will be done by monitoring the mission as a whole and suppressing any unexpected obstacles that it may face throughout its lifetime
CDH 1.1	The system shall have a subsystem that is responsible for collecting, processing, storing, and sending scientific and system data efficiently.	Demonstration	This requirement will be maintained through frequent observation of the rover's performance	This demonstration will be made by constantly monitoring and analyzing data and system health transmissions to be sure no issues are occuring
CDH 1.1.1	The subsystem shall contain a CPU that will facilitate all actions of the rover while monitoring its health.	Inspection	Direct inspection of the CPU and its capabilities will be most effective to evaluate readiness	Volume, mass, and technical capabilities should be evaluated by inspection in order to confirm it is capable of all tasks

CDH 1.1.1.1	The system shall log and manage environmental and system health data including temperatures, power generation, and structural condition.	Test	Testing the management/logging of system data will most effectively evaluate its readiness	We can do this by simulating rover conditions and health and ensuring that the system writes and stores logs/data properly and securely
CDH 1.1.2	The subsystem shall contain storage devices that allow the rover to store all kinds of data it receives.	Inspection	Direct inspection of the storage devices and its capabilities will be most effective to evaluate readiness	Volume, mass, and technical capabilities should be evaluated by inspection in order to confirm it is capable of storing all possible types and volumes of data
CDH 1.1.2.1	There shall be multiple kinds of storage devices so that memory is processed and stored in the most efficient way.	Inspection	Direct inspection of the types of storage devices and each of their specifications will be most effective to evaluate readiness.	The technical capabilities of the storage devices should be evaluated by inspection to confirm it has flexible capabilities of storing and transferring data
CDH 1.1.3	The subsystem shall contain at least one transceiver that processes radio signals for the rover to receive and transmit.	Inspection	Direct inspection of the transceiver(s) and its capabilities will be most effective to evaluate readiness	Volume, mass, and technical capabilities of the transceiver(s) should be evaluated to confirm they are capable of processing radio signals for reception and transmission and compatible with antenna(s)
CDH 1.1.3.1	The transceiver(s)/transmitter(s) shall be compatible with the frequencies of the antenna(s).	Inspection	Direct inspection of the transceiver(s)/transmitter(s) will be most effective in evaluating its compatibility with the antenna(s).	The technical capabilities of the transceiver(s)/transmitter(s) should be evaluated to confirm that their frequencies are compatible with those of the antenna(s)

CDH 1.1.4	The subsystem shall contain at least one antenna that allows the rover to send and receive radio signals between the rover and the flight team.	Inspection	Direct inspection of the antenna(s) and its capabilities will be most effective to evaluate readiness	Volume, mass, and technical capabilities of the antennas(s) should be evaluated in order to confirm they are capable of sending and receiving radio signals and compatible with transceivers
CDH 1.1.5	The subsystem shall support software updates and patches.	Test	Testing the system's ability to receive, process, and install software updates is the best way to ensure it will be capable during the mission	Sending mock software updates and patches to the rover and ensuring they are properly managed and implemented will evaluate if the rover is capable of meeting this requirement
CDH 1.1.6	The electronic components of the subsystem shall be radiation-hardened to resist radiation exposure of 100 krads and extreme temperatures of -55°C to 125°C	Test	Testing the components' resistance to extreme temperatures is the most effective way to ensure this requirement is met	This can be done by exposing the electronic components under extreme temperatures from -55°C to 125°C and monitoring performance

2.1.4. Thermal Control Subsystem Overview

The thermal subsystem is responsible for regulating temperatures throughout the rover to maintain operations on the lunar surface. The rover's systems will require components to function in the harsh sun and the below freezing PSR. Taking into account both the worst case scenario in cold and hot environments the thermal control system (TCS) will need various components, passive and active to endure the environment.

Table 19. Thermal Subsystem Overview

Thermal Components	Mass	Volume/Density	Max Power Draw
Q-RAD Radiator	4 kg	.055m^3	0W
ACT LHP & VCHP	12kg	.901m^3	75W
MINCO ThermoFoil Heaters	50g	.0095m^3	50W
APTEK 2711 Coating	Negligible	1L	0W
Dunmore 200HN MLI	Negligible	1.42g/cc	0 W
Total	16.05 kg	0.97m^3	125 W

Thermal Sub-Assemblies

The way these components will be knitted together will be crucial for the Lunar Vanguard Rover's survival in the mission. Some major ways components will be utilized are methods like using the special coated radiator panels to remove excess heat from the warm box that will house the vital electronics. Complementary to the radiator the looped heat pipe system will be a game changer for the mission as it can be used to remove heat from the components in the warm box to the dual radiators we have.

Also to provide a barrier for the heat and the precious warm box multi layered insulation will be utilized in specific layers to optimize the heat in and out of the system. During the frigid events on the expedition heaters will come in handy as they will be the primary effort to heat the rover in case we are insufficient in colder areas of the Amundsen PSR.

Housed inside the rover subsystems like CDH, power, and payload will need specific operating temperatures that will allow them to efficiently operate throughout the mission. The important task of maintaining a certain temperature is crucial for the TCS. But for the mechanical subsystem the motorized drivetrain is the only component that will need thermal protection. With an integrated temperature sensor it will self regulate the temperature but the average operating temperature for the drivetrain will be at 323K. Next for electrical power systems, it ranges from a plentiful of components for example the batteries, avionics unit, PDU, and the solar cells. In particular the solar cells can run a little hot compared to the other components in power, but the average operating temperature of all components will be at 360K.

For the main communications throughout the rover the CDH branch of the subsystems has the most amount of components that will fit in the warmbox. From the CPU to the transceiver the temperature plays an important part in keeping the PCB of various parts intact. Usually made of fiberglass and a type of epoxy many of these boards and or components come with integrated heat sinks to dissipate unwanted heat. But the average operating temperature of the CDH subsystem will be around 335K. Taking into consideration all operating temperatures of the components housed inside the rover the team came to a conclusion that thermal regulation shall be at 300K.

Heat Flow Maps

When analyzing the rovers' heat taken in and heat dispersed, the team assembled the severest temperature environment at the moon's south pole to be at an excruciating 400K. On the other hand the most freezing case for the south pole will assumed to be at a sub-zero 40K. The TCS’s goal to ensure the warmbox of the rover shall maintain system temperatures around 300K, this is all while assuming a singular surface panel area of the rover is 1.25 m^2.

In stages where the Lunar Vanguard rover is exposed to the harsh rays of the sun the team took into consideration the methods of heat transfer that are possible while on the lunar surface. The primary methods you will see involve radiation and conduction, unfortunately convection isn’t common in space application since that requires a fluid medium to pass heat through like a liquid or gas. The main stepping blocks for coming to the conclusion on heat in and out are determined by the following equations; radiation: $\varepsilon\boldsymbol{\sigma}FA(T_1^{\ 4} - T_2^{\ 4})$, conduction:$kA(T_1 - T_2)/L$. As seen, radiation is not a linear process where conduction is, and this is an important detail that is vital when taking into consideration the heat transfer calculations.

Some givens in the case are, ε is the emissivity of the material used and its ability to emit heat, next $\boldsymbol{\sigma}$ is the boltzmann constant which is in basic helpful in relating temperature to energy in the units W/m^2k^4. Lastly for radiation F is the view factor from the surface that is being observed to the source of energy coming in. For example if the sun is straight above the object being observed the view factor will be at F=1, and in another case a view factor may be moving and therefore the view factor will not be a perfect F=1, and it can be calculated using trigonometry to find the view factor of a situation. In the conduction method the k value is ability for the material to conduct heat energy.

Heat Transfer Calculations

The team's calculations for the most extreme case, the Lunar Vanguard rover's TCS, was able to fend off excess heat efficiently. Although the system is able to withstand the hellish temperatures it will need around 12 Watts of cooling to stabilize the internal system to a net 0. This can be done through various components apart of the system, the most reliable will be using the passive heat switches to dissipate the excess heat out of the system. In a case where the heat switches may malfunction or are unusable the radiators will be able to use the looped heat pipe connection to dissipate the heat.

As for the extreme cold case the rover will need more heat to ensure the internals of the system are at operating temperatures. This scenario was inevitable due to the research of some PSR's never seeing sunlight; having our rover freeze would spoil the Luna Vanguard mission. But to counteract the situation the team will use the variable conductance heat pipe to bring in more heat through convection using a reservoir that contains a non-condensable gas. That can expand and contract as the pressure inside the pipe changes with various temperatures(ACT 2024), the VCHP will be able to provide 60W of heat to the internal system and this will leave a surplus of around 2 Watts which shouldn't impact the rovers health in any particular way.

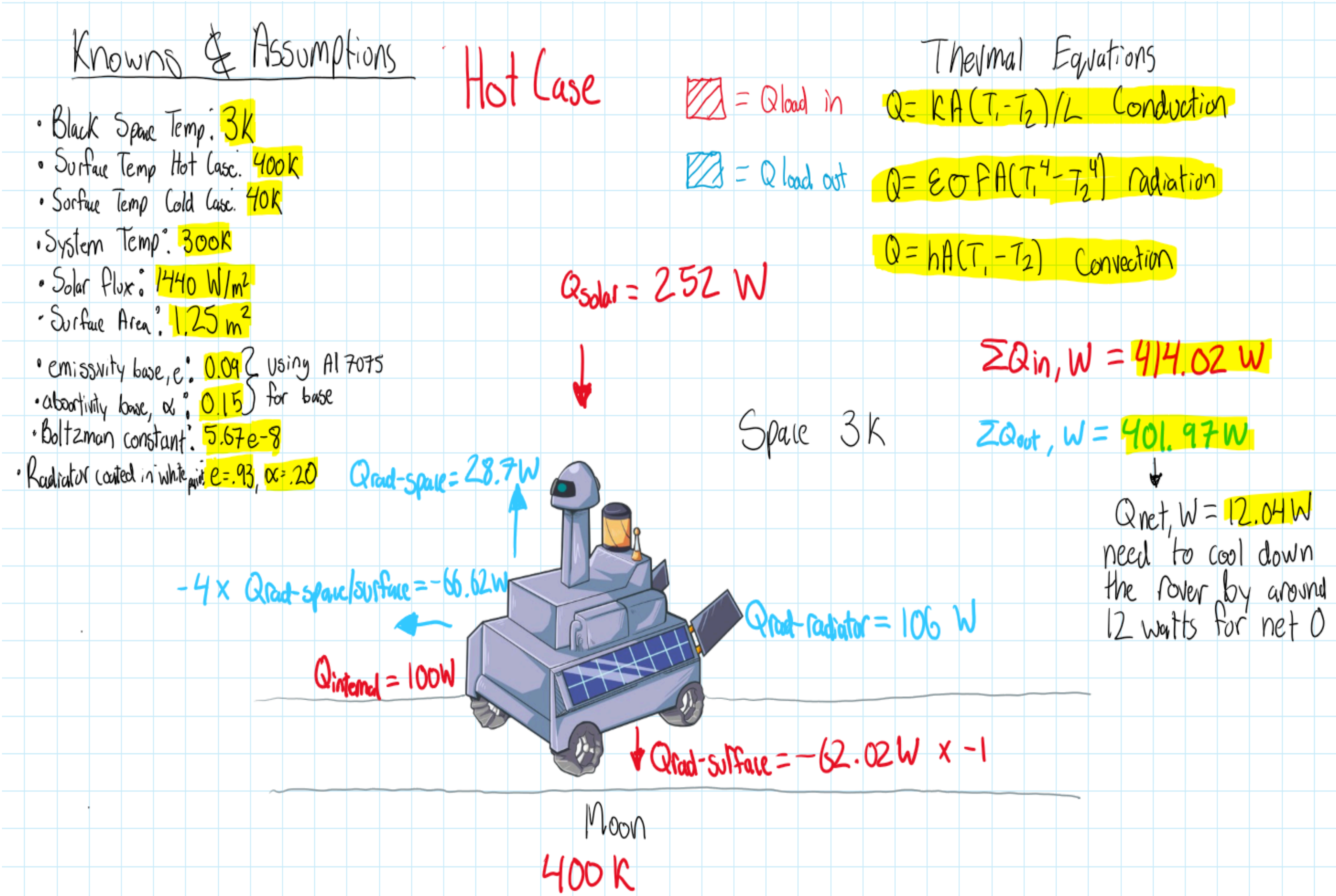


Figure #14: Thermal Control System: Hot Case

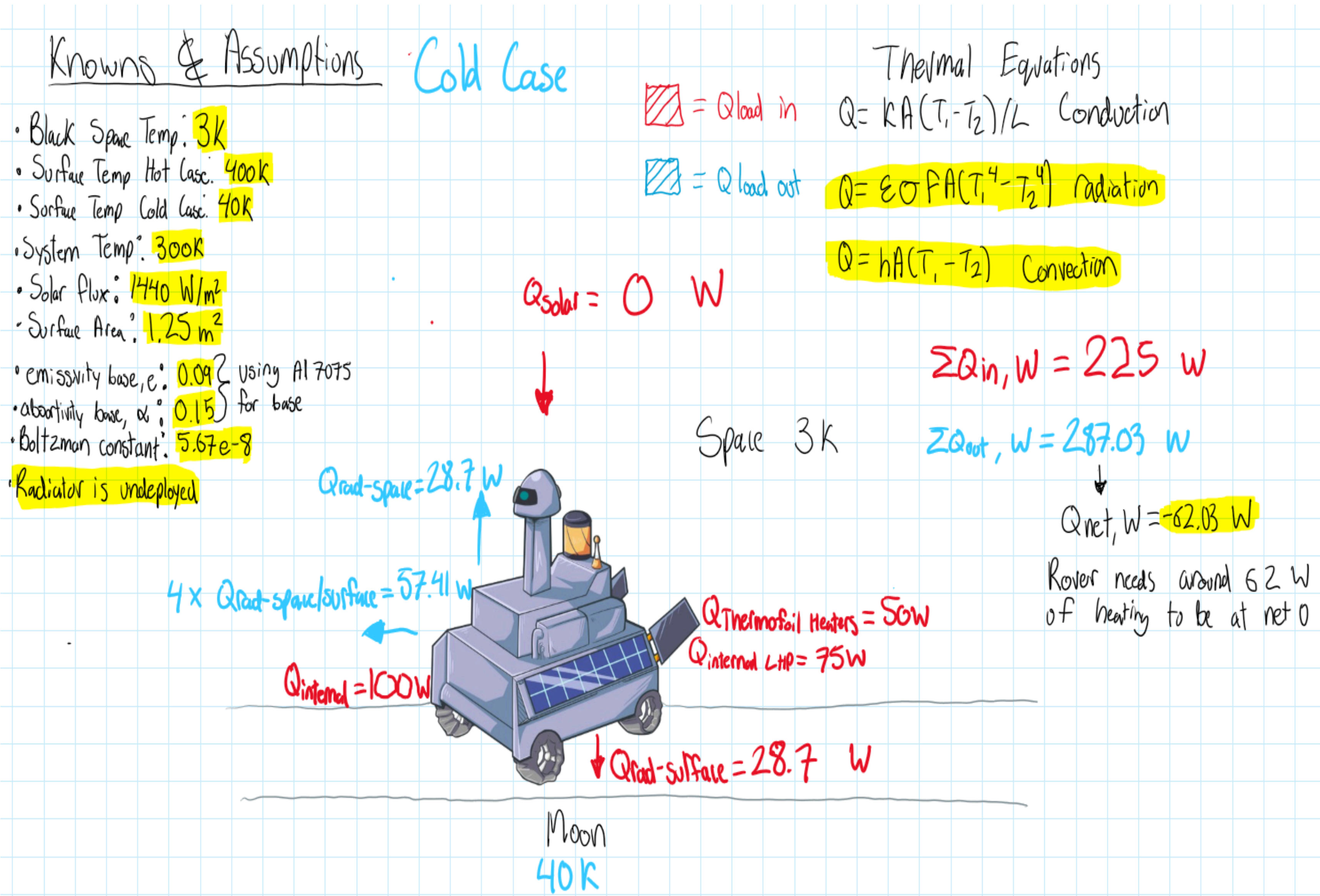


Figure #15: Thermal Control System: Cold Case

2.1.4.1. Thermal Control Subsystem Requirements

Table 20. Thermal Subsystem Requirements

WBS Level	Requirement ID	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
Level 1	TCS 0.1	The System will be able to traverse through the lunar surface.	Derived from the top-level mission requirements	MR 1 MR 2	TCS 1.2	Demonstration	All	Not Met
Level 1	TCS 0.2	The System will be able to survive the lunar surface for 90 days.	Derived from the top-level mission requirements	MR 1 MR 2 MR 7	TCS 1.2	Demonstration	All	Not Met
Level 2	TCS 1.2	The spacecraft shall contain a thermal control system that maintains necessary operating temperatures for all other subsystems.	Thermal Control System will be the glue holding the mission together on the lunar surface	TCS 0.1 TCS 0.2	TCS 1.1.1 TCS 1.1.2 TCS 1.1.3	Demonstration	TCS	Met
Level 3	TCS 1.1.1	The subsystems shall have a thermal system that will heat the system when needed to maintain operating temperatures.	The heating subassembly that makes apart of the thermal control system	TCS 1.2	TCS 1.1.1.1	Test	TCS, CDH	Met

Level 3	TCS 1.1.2	The subsystem shall have a thermal system that will insulate the system for better resistance to external heat flow.	Insulating subassembly that makes apart of the thermal control system	TCS 1.2	TCS 1.1.1.1	Test	TCS, CDH	Met
Level 3	TCS 1.1.3	The subsystem shall have a thermal system that will cool the system when needed to maintain operating temperatures from 40K - 400K	Cooling subassembly that makes apart of the thermal control system	TCS 1.2	TCS 1.1.1.1	Test	TCS, CDH	Met
Level 4	TCS 1.1.1.1	The thermal control system shall contain a warm box, VCHP & LHP, radiator panels, MLI blanket, special thermal coatings, heat switches, thermal control valves, and component heaters.	Parts that form the thermal control system	TCS 1.1.1 TCS 1.1.2 TCS 1.1.3	TCS 1.1.1.1.1 TCS 1.1.1.1.2 TCS 1.1.1.1.3 TCS 1.1.1.1.4	Inspection	TCS	Met
Level 5	TCS 1.1.1.1.1	The subassemblies shall have the vital components of te system housed and wrapped in an MLI blanket insulated by a warm box that will be connected to exterior radiator panels.	Keeping the internal components at operating temperatures	TCS 1.1.2 TCS 1.1.1.1		Inspection	TCS	Met

Level 5	TCS 1.1.1.1.2	The exterior radiator shall be coated in special paint and connected to a LHP. regulated by a passive TCV to help reduce thermal conductance during lunar day & night.	Radiator subassembly with looped heat pipes, and passive thermal control valves	TCS 1.1.3 TCS 1.1.1.1		Test	TCS	Met
Level 5	TCS 1.1.1.1.3	The LHP subassembly with the TCV will be accompanied by a VCHP that will passively control the heat transfer to either remove heat from the warm box or add heat depending on the environment.	Looped heat pipe & Variable Conductance Heat Pipe that optimize the rover's warm box	TCS 1.1.1 TCS 1.1.3 TCS 1.1.1.1		Analysis	TCS	Met
Level 5	TCS 1.1.1.1.4	During the days thermal switches shall make contact to the radiator panels to allow thermal conductivity between the warmbox and the radiator. When Lunar night hits the switches shall retract.	Thermal switches for improving the thermal conductivity of the radiator panels.	TCS 1.1.1 TCS 1.1.3 TCS 1.1.1.1		Demonstration	TCS	Not Met

2.1.4.2. Thermal Control Sub-Assembly Overview

Insulation

In the vacuum of space with no significant atmosphere on the moon, radiation heat transfer is the most ideal for mitigating heat loss in a system. Multi-layered insulation (MLI) handles heat leaks in the system as it's usually fabricated in multiple layers with non-conductive spacers between to reduce ESD. The multiple layers help decrease the absorptivity which reduces radiation heat transfer between layers. It can also be contorted to fit over many sorts of shapes, mounting or application to the rover can include certain adhesives or velcro.

For the Lunar Vanguard mission, the Dumore Kapton 200HN MLI was the most viable option with low absorbance (0.14) and low emissivity (.05) at temperatures ranging from 23K to 550K. This MLI material is widely used. The TRL 7 was chosen due to multiple heritage missions such as the 2012 Curiosity Mars and 1997 Cassini-Huygens mission successfully demonstrating how important the durability of MLI blankets are for space missions.

The team is expecting to implement multiple layers for the insulation component, the stages from outside to the inside will include the following types of layers; reflective, separating, and an inner cover. For the front of the line reflective layers the team has chosen to go with the Kapton single aluminized that has a low absorption and emissivity, on top of that the outer reflective layer has to be stitched carefully in order to allow enough venting through the entire blanket. The amount of layers for the reflectors will be around 25 layers since long term LEO spacecrafts use around 15-25 layers(NASA).

Radiator

The radiator will be crucial for dissipating excess heat caused by the internal components, or solar loads. Efficient radiators have high emissivity and low solar absorptivity. Deployable radiators are a great passive component for missions that have tight constraints when it comes to volume.

For the Lunar Vanguard mission, the radiator chosen was the RedWire Deployable Q-Rad. The small compactness of the design can allow for multiple Q-Rad's to be mounted on the side of the rover. Accompanied by the APTEK 2711 coating to the radiator panel will provide an emittance of 0.93 and a max absorption of 0.20. The TRL5 for the Q-Rad is chosen according to RedWire Space's current datasheet for the radiator. While the APTEK 2711 coating's TRL6 was chosen due to the 2012 Curiosity rover's Mars Science Laboratory that used this special coating, the coating had also undergone and passed NASA's outgassing per ASTM-E 595 at Goddard Space Flight Center.

The radiators will be hooked up to the LHP system in order to disperse or move heat around the rover. The placement of the radiators is key to getting in contact with the energy in and also outputting the heat out. Since the radiator is deployable the pivoting of the radiator's directions shall depend on the internal system temperature and what time of day it is on the lunar surface. According to those details the rover will be in a more optimal position to efficiently use the radiator panels.

LHP & VCHP

Looped heat pipes (LHP) in general operate by bringing a fluid in the pipes to a boiling level when the heat pipe is forced to heat at operating temperatures. In the Lunar Vanguard mission the fluid's vapor shall move to the opposite direction of the heat pipe where the heat will be rejected from the Q-Rad radiators.

Likewise, a variable conductance heat pipe (VCHP) uses non-condensable gasses to adjust the amount of heat the pipe can pass while operating at a fixed temperature. The VCHP will be controlled by a thermal control valve (TCV), which can passively control pressure build-up from the fluid at higher temperatures. With the valve control, the increase in pressure from heat loads will compress the non-condensable gas into a reservoir in the heat pipes allowing for more condensibility. This means the system can push more heat to the radiators via the heat pipe system.

Similar to the heating load on the system, a decrease in temperatures will allow the TCV to read a decrease in pressure thus allowing the non-condensable gas to fill more volume of the heat pipe and also reducing the condenser volume. The fluid that will be used in the LHP will be ammonia which is ideal for the below freezing situations in the PSR's, and compared to propylene it does wonders in inclines and gravity (ACT). In addition to the LHP's fluid the VCHP will accommodate the rover with helium as its non condensable gas(NCG). Helium in particular is also used during lift off of high powered rockets to keep fuel cool during the early stages(ACS).

For the Lunar Vanguard mission, the rover will be supporting a warm box containing the precious components for operation and the vital TCS. The option that the team chose was the LHP, VCHP, and thermal switch combination from Advanced Cooling Technologies (ACT), since they are the developers behind the thermal system for NASA's VIPER mission. The main LHP and TCV will be connected to the exterior Q-Rad radiators, where it will be able to transfer high amounts of heat during the lunar day. With the high thermal conductivity and its efficiency in hellish temperatures, the ACT system will also thrive on lunar nights by reducing its thermal conductance via the TCV and VCHP. A TRL5 was decided on the system from ACT since it hasn't been trialed in space, but there have been similar fluid loops used in smaller Cubesat missions.

Heaters

Small electric heaters will be placed on critical components just in case a heating system receives an anomaly. The primary goal of these heaters is to maintain the temperature of these components slightly above their minimum operating temperature throughout the mission. Similar to the heaters implemented, thermally conductive switches will be placed on the top side of the rover for the ability to conduct heat through the exterior of the chassis to the warm box if needed. But during lunar night the switches shall retract to prevent heat from escaping the warmbox.

For the Lunar Vanguard mission, the team selected MINCO Polyimide FEP Thermofoil Heaters due to their durability in fluctuating temperatures, and tight resistance tolerance which allows for more power when needed. A TRL5 was given to the MINCO heaters since they have contributed to more than 60 space programs. Also, their heaters have many certifications including NASA GSFC S-311-P-079 and NASA-RP-1061. Heater power will be zero during normal operations, only to be used in unordinary circumstances where wasting the heat is not enough, the MINCO heaters will make up the heat loss when necessary. The important TCS is needed to be reliable therefore the team is presenting the overall subsystem with a TRL5 for this mission.

2.1.4.3. Thermal Control Subsystem Recovery and Redundancy Plans

The thermal subsystem includes heat switches, which in the case of heating loop failure, are able to passively regulate temperature. They switch between thermal conductors and thermal insulators depending on whether the rover is currently overheating or underheating. Additionally, there are strip heaters that can act as a replacement for the main heating loop. There is no redundant heating loop because of mass/bulk constraints. Also since the part is very costly to manufacture.

The thermal subsystem has a recovery mode for the case where a component is beyond its operating temperatures. The rover shall halt or slow the operation of the component, expend additional energy to heat the component, and can also request a reboot of the component in critical cases.

2.1.4.4. Thermal Control Subsystem Manufacturing and Procurement Plans

MLI Blanket

Primary Supplier: Dunmore

Secondary Supplier: In-House (GSFC)

Lead Time: 6 months

Due to Dunmore's long history of designing and installing multi-layered insulation on spacecraft, Lunar Vanguard considers them to be the most promising manufacturer for MLI Blankets. Some of Dunmore's past collaborations with NASA include (1) the Cassini-Huygens mission, which was sent to Saturn to study its largest moon Titan, and (2) the Mars Curiosity rover (Dunmore 2024). Since they are familiar with NASA protocols and procedures the Lunar Vanguard team chose them as a strong primary for the insulating component.

Since Dunmore has worked with NASA on MLI blankets and various insulatory components previously, the lead time shouldn't be an issue. A lead time of 6 months has been given for developing Lunar Vanguard's MLI Blankets, as the blanket will need multiple layers to insulate the interior of the rover. The company may also have to include testing done on similar conditions to where the Lunar Vanguard mission is planning on trekking to so that will definitely take up a chunk of time. Lastly, fabricating this component will need to be detailed as it is customized for the harsh lunar conditions.

On the odd occasion that Dunmore can't support the Lunar Vanguard mission, the team will fall back to in-house resources such as Goddard Space Flight Center. They have multiple options on types of MLI for different occasions, and their approach in MLI beats Dunmore in absorptivity but may take more time to develop and test.

Thermal Insulating Paint

Primary Supplier: APTEK

Secondary Supplier: AZ Technology

Lead Time: 6 months

APTEK was chosen as the primary supplier for the Lunar Vanguard mission as NASA has previously made use of APTEK's paint in the Mars Science Laboratory. Primarily applying it to the chassis and the radiators, APTEK has also worked in the past with Boeing on their satellite systems. Various paints have gone through outgassing trials (ASTM-E 595) through NASA, and have JPL field approved formulation (APTEK 2024).

Because of APTEK's many affiliations and connections with multiple aerospace giants, the Lunar Vanguard team decided to make the company the primary supplier for the insulating paint that will be on the chassis and radiator of the rover. Also a lead time for 6 months has been expected for the APTEK 2711 paint for the Lunar Vanguard mission. This lead time has been chosen because of the known outgassing trials that have been done previously with APTEK's paint through NASA. However it may need a couple tweaks as the primary use will be on the radiators.

If APTEK isn't available for production of thermal insulating paint for the LVR then the conversations for producing a similar coating will be with AZ Technology. Similar to APTEK AZ Tech. has been partnering with NASA in the past for missions like the 2020 Curiosity rover, and is the only company officially licensed by NASA to paint the agency's famous meatball logo on the ISS (AZ Tech 2024).

Thermofoil Heaters

Primary Supplier: MINCO

Secondary Supplier: Omega

Lead Time: 6 months

The primary supplier for the active internal heating system is MINCO. They've been selected because of their decades long history with NASA and the European Space Agency. MINCO has been included in the ESA's QPL (Qualified Part List), which means they have been involved in many space programs including Meteosat Third Generation (MTG) and Juice (Jupiter Icy Moons Explorer). The task of keeping a spacecraft alive for the duration of a mission is very crucial for the lifetime of the program and future confidence for missions (MINCO 2020).

Given the circumstances on the moon, MINCO is expected to have a lead time of 6 months for manufacturing heaters. This lead time has been given to ensure the proper function of the heaters when needed for the Lunar Vanguard mission, as the cold case scenario will likely utilize the heaters for the most part. During this period the company will test and analyze the watt density charts for the heaters, depending on their operational temperature we may need to use our variable conductance heat pipe to provide heat to the system in the dire cold.

If MINCO cannot fulfill the team’s needs, Omega will be considered. Heaters from Omega have less tolerance to temperature fluctuations and use more power, however, which is why MINCO was prioritized as the primary supplier.

LHP & VCHP

Primary Supplier: A.C.T.

Secondary Supplier: JPL

1 year 6 months

Originally, NASA contracted ACT to design and implement both a looped heat pipe and variable conductance heat pipe for the recently canceled VIPER mission. Although VIPER was canceled, the Lunar Vanguard team still intends using thermal experts from ACT to survive the harsh lunar polar environment (Open Systems 2021).

Having experience with NASA’s VIPER partnership with ACT will greatly benefit the expected lead time. The team is confident that the manufacturing and various testing of these components will take around a year and half. This lead time has been for the heat pipes since these components will be very vital in surviving lunar day and night. The company will test certain liquids that will be the most optimal for convection heat transfer when necessary on lunar night. In addition the company will also work with fellow collaborators on the mission to ensure compatibility with the Q-rad radiators to the looped heat pipe. This process will definitely be lengthy and will need meticulous creativity to all be knitted together hence the year and a half lead time.

If ACT isn’t up to manufacturing the heat pipe components, the team will propose a solution with in-house resources like JPL. Since they have experience with designing and researching heat pipes, lead times should not be adversely affected.

2.1.4.5. Thermal Control Subsystem Verification Plans

Table 21. Thermal Control Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
TCS 0.1	The System will be able to traverse through the lunar surface.	Demonstration	Demonstration of surviving the harsh conditions of the lunar surface and observing and recording the functionality of the rovers' operations during the mission will be a key factor for this method.	ensuring this verification method will be done through observing the actual mission itself and keeping up with any issues or risks that may pop up in the missions 90 day plan. Ultimately trying to avert those inevitable problems that can come up during a mission.
TCS 0.2	The System will be able to survive the lunar surface for 90 days.	Demonstration	Through observation of the mission from home base, the team will conclude whether the mission is capable of further moving on. While ensuring the chances of future updates and plans that will need to be done to the mission.	Through observing the active and passive components in action on the mission the team will recognize where to adjust from live data given through various temperature sensors inside the warm box and throughout the rover.
TCS 1.2	The spacecraft shall contain a thermal control system that maintains necessary operating temperatures for all other subsystems.	Demonstration	Necessary operating temperatures will be determined through the active mission data. The thermal system will be the glue of the rover ensuring it doesn't melt or freeze during the mission.	Observation of temperature fluctuations will be monitored during specific stages of the rovers life, from drilling in the PSR, to traversing the terrain to its next excavation site.
TCS 1.1.1	The subsystems shall have a thermal system that will heat the system when needed to maintain operating temperatures.	Test	Testing is the most optimal method to ensure the viability of the component in the real scenario of the moon. Where as other methods wouldn't be as promising and confidence-inducing as a mock test.,	With a controlled environment, particularly a vacuum chamber that would have conditions similar to the moon's surface or even extreme, the team will test the limits of the heating system and the capabilities that are required for the coldest cases for the moon.

TCS 1.1.2	The subsystem shall have a thermal system that will insulate the system for better resistance to external heat flow.	Test	Similar to the heating requirement of the system the insulation is as vital for the mission. No other methods will come close to giving the team a clear answer as a test would.	Insulation tests can be administered through a controlled environment where again a vacuum chamber is necessary, since the lunar surface doesn't have a medium like Earth to pass heat through it will be necessary to test for extremes and what will be optimal for the MLI, this method could also give more insightful information for how many layers are required for future daunting missions.
TCS 1.1.3	The subsystem will have a thermal system that should cool the system when needed to maintain operating temperatures from 50K - 370K	Test	Testing the entire system when fully assembled is important in ensuring the safety of the rover while on the lunar surface, thus a test is necessary.	An entire system check will be ideal to understand how the rover will deal with the environment. This will likely be done on a smaller scale compared to the Lunar Vanguard mission. But would consist of a mock rover with similar components at a lower end to observe and ensure the rover can dissipate and provide heat when necessary to the warm box.
TCS 1.1.1.1	The thermal control system will contain a warm box, VCHP & LHP, radiator panels, MLI blanket, special thermal coatings, heat switches, thermal control valves, and component heaters.	Inspection	Direct inspection of the rovers systems will ensure the readiness of the components and as they're fitted inside our compact rover.	Reviewing engineering drawings, dimensions, and material that is applied to the exterior and the interior of the rover is crucial in ensuring the mission will be a success with few variables or mistakes.
TCS 1.1.1.1.1	The subassemblies will have the vital components of the system housed and wrapped in an MLI	Inspection	Inspection of the connection and pipes that are connected to the radiator panels is important in providing the team with information that all components are operating in the correct order and will	To ensure this the team can have various sensors that will be checked or give feedback through CDH making sure the components are useable throughout the mission, and if not this should help the team decide to fall back on other necessary

	blanket insulated by a warm box that will be connected to exterior radiator panels.		work when needed.	components that recover from risk.
TCS 1.1.1.1.2	The exterior radiator will be coated in special paint and connected to a LHP. regulated by a passive TCV to help reduce thermal conductance during lunar day & night.	Test	Looped heat pipe testing will be the most beneficial method to report the amount of heat that can be transferred in certain scenarios that are extreme from the lunar temperatures.	Looped heat pipe testing can be done through a similar mock test on a smaller scale with a prototype, this can help to ensure the team is handling anomalies within the environment with accuracy. Most likely to be done in a lab with a vacuum chamber and controlled environment to test the capabilities of the LHP.
TCS 1.1.1.1.3	The LHP subassembly with the TCV will be accompanied by a VCHP that will passively control the heat transfer to either remove heat from the warm box or add heat depending on the environment.	Analysis	Using an analysis method with models of the heat acting upon the rover and by also using the various parts including the LHP, VCHP, and radiator, the team can conclude how passive the rover can stay until using its precious active systems.	Analysis can be done through various programs, the goal will be to analyze where the rover is gaining heat and this is where the team can predict and give solutions to certain extremes. These scenarios will be simulated through programs such as MATLAB, Thermal Desktop, etc.
TCS 1.1.1.1.4	During the days thermal switches will make contact to the radiator panels to allow thermal conductivity between the warmbox and the radiator. When Lunar night hits the switches shall retract.	Demonstration	Through demonstration, the thermal switch efficiency will be observed and taken note of where it can come to use when traversing the lunar surface. Through observation of how the switches contact the rover, and how efficiently the heat is transferred in or out of the system the team can provide invaluable information for future lunar missions.	Some areas along the way to the excavation sites in the Amudsen PSR will need heat in or out, and this passive method of heat transfer will be the most efficient option, with the close second being the radiator.

2.1.5. Payload Subsystem Overview

Table 22: Itemized Payload and Sample Collection Subassembly

Payload Subassemblies	Mass	Volume/ Density	Max Power Draw	Cost
TRIDENT Drill (Resized)	7.067 kg	37,042.92cm^3	200W	$5,808,000
Spectrometry Suite Pyrolytic Cell Gas Chromatography x2 TLS x2 Scrubbers Getters	30.0 kg	47,250cm^3	66W	$9,626,359
6-DoF RO1 Robotic Arm (Modified for space)	13 kg	20,000cm^3	30W	$1M
SQRLi (Front)	1.7 kg	11,109cm^3	10W	$440,979
SQRLi (Back)	1.7 kg	11,109cm^3	10W	$440,979
Total	53.467 kg	126,510.92 cm^3	316 W	$17,316,317

To ensure the payload system is capable of drilling, extracting, and analyzing regolith in the south lunar pole environment to a depth of 1 meter, the payload will be equipped with a TRIDENT drill (designed and tested for NASA's VIPER lunar volatile mission by Honeybee Robotics). These samples will be delivered to Lunar Vanguard rover's spectrometry suite by a 6-DoF RO1 Robotic Arm (designed and modified for space-grade use by Standard Bots). The sample will first be loaded into a pyrolysis cell where its volatiles will be sublimated and the solid regolith and particulate matter disposed of. The gasses will then travel through spectrometry capillaries equipped with scrubbers and getters to ensure the proper gasses are delivered to the gas chromatography system. Gas chromatography will be used to further parse these gasses down to the C, H, O, and N isotopes that the Lunar Vanguard mission is primarily interested in. Finally, the Tunable Laser Spectrometer (TLS) unit will measure the concentration of water ice and stable isotopes in each sample and pass the information on to the rover's software system for data recording and transfer.

As stated in previous sections, operating in a lunar environment requires a drilling system that is capable of withstanding extremely cold temperatures (20-100K), kickback/recoil within low gravity, abrasions from rough lunar regolith, and a lack of atmosphere to pull away heat generated by internal systems and friction.

Research and trade studies have been conducted to ensure both selected payload instruments are capable of operating in this environment to a satisfactory TRL (see appendix). Instruments also must facilitate data collection in one of the two, main overarching science goals of the Lunar Vanguard mission: (1) collecting information about the concentration of water volatiles in the Amundsen PSR region, or (2) analyzing and calculating the stable isotopic ratios of D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, or $^{15}N/^{14}N$ for comparison to the ratios in other parts of the solar system to better ascertain lunar water volatile origin.

TRIDENT Drill

The TRIDENT drill is a 20.6 cm x 33.3 cm x 168 cm rotary-percussive drill (and augur) that was specifically designed for extracting lunar regolith to around a depth of 1 meter (Zacny et al. 2021). In order to adhere to mission constraints, the Lunar Rover TRIDENT drill will be resized to 19.98 cm x 12.36 cm x 150 cm. Rotary-percussive drills are ideal for soil sampling in hard soil since the percussive device is able to break through any hard rocks within the soil and the rotary mechanism allows the retrieval of samples from deeper in the soil (CA Drillers, 2024). These drills are also known for producing minimal noise and vibrations (CA Drillers 2024), which makes them a prime candidate for remaining in place while drilling in lunar gravity.

Originally, the TRIDENT drill was designed by Honeybee Robotics for use in NASA’s VIPER mission to retrieve volatiles from the lunar south pole regolith (Hoover 2023). To allow the drill to operate within the low temperatures of the lunar south pole, the drill was designed with a 40 W internal heating system that is capable of keeping the drill at a consistent and optimal temperature (Zacny 2021). The potential for overheating is dealt with by limiting drill usage to 10 cm bits of soil at a time (Zacny 2021). This limitation allows data to be taken in 10 cm chunks, however, as the drill also has sensors that monitor the temperature and strength of the rock it’s drilling through (Zacny 2021). Both measurements on these 10 cm bits can be recorded to get a better sense of the physical chemicals of the south lunar pole regolith. For example, perhaps a regolith with high concentrations of water ice contains high layers of solid (hard) ice (low temperature) on the surface, but, as depth increases, gives way to lighter, higher temperature regolith.

As of August 12th, 2024, the TRIDENT drill has been integrated onto the VIPER payload, but its launch has been postponed until further notice (NASA 2024). It has been tested in NASA Glenn Research Center's vacuum chambers (Zacny 2021), as well as Houghton Crater in Canada as an analog site (Glass et al. 2024). All tests have come back favorable, meaning that the TRIDENT drill has a TRL of 6: It was built for a similar environment and mission as the Lunar Vanguard mission (so no deduction of TRL is necessary), has been thoroughly tested to ensure it functions properly in said environment and has completed all testing prior to launch. However, as VIPER launches in late 2024, the results of testing it *in situ* on the moon are unknown. Furthermore, Lunar Vanguard will be resizing the TRIDENT drill, meaning that the TRL will drop back to TRL 4 (since all tests conducted in relevant environments were done on the drill in its original scale, not on the drill in its modified scale. In order to account for the low TRL, Lunar Vanguard will be conducting extensive testing on the TRIDENT drill in analog environments throughout the development process. Through successful testing, the TRIDENT drill can be brought back up to TRL 6.

6-DoF RO1 Robotic Arm

The RO1 is a 50cm x 20cm x 20cm robotic arm initially built for industrial conveyors and repetitive processes (Standard Bots 2024). It uses machine learning to autonomously maneuver around obstacles and make last-second adjustments to its trajectory (Standard Bots 2024). Both of these properties make the RO1 an optimal robotic arm for the Lunar Vanguard rover since they allow for autonomous decision making and efficient performance during the highly repetitive process of sampling 1m of regolith. The RO1 has been thoroughly tested in a terrestrial environment, but has not yet been implemented for a lunar environment (Standard Bots 2024). Therefore, it would have a TRL of 5 and would need to undergo further testing to bump the TRL up prior to deployment.

As mentioned above, the only function of the robotic arm will be to take the samples collected by the TRIDENT drill and deliver them to the spectrometer suite. Six degrees of freedom will be sufficient to fulfill this task. The RO1 robot arm is capable of carrying up to 18kg, which is far more than the intended payload of a single 1 meter sample (Standard Bots 2024). Modifications to the robotic arm would focus on preparing the arm to function in the colder, lighter gravity, and high-regolith environment. Extensive testing would need to be conducted in analogous environments to ensure the arm will function properly.

Pyrolysis Cell

The pyrolysis cell receives the solid 1 meter regolith sample from the RO1 robot arm, sublimates the volatiles within the sample by superheating it to gas, and then transfers the gasses to the capillary system of the spectrometry suite. This chamber superheats the regolith sample to about 400-600°C and disposes of all solid remains (Mahaffy et al. 2012). Although not an instrument itself, telemetry data will be collected on the pyrolysis cell to ensure it's functioning properly due to the importance of its role in the pyrolysis-gas chromatography-mass spectrometry method (Mahaffy et al. 2012). Telemetry collected will include the temperature of the pyrolysis chamber, the weight of substance within the chamber (to ensure the solid regolith is disposed of after volatiles are superheated), power usage (to ensure the pyrolysis is not drawing power at improper times), and the time it takes to reach the intended temperature (if it takes the pyrolysis cell longer than normal to reach its optimal temperature, there may be something wrong with the device).

Since Lunar Vanguard will be using a similar pyrolysis cell to the one used in Curiosity's SAM, the unit will have a TRL of 5: It has been tested and proved operational in analogous environments, but has not been deployed and used in the intended lunar environment. Similar to the previous instruments, this low TRL will have to be increased through environmental testing to ensure the pyrolysis cell can heat to the proper temperatures in the frigid, south lunar pole environment.

Tubing, Scrubbers and Getters

Lunar Vanguard Rover's spectrometry suite filters out unwanted gasses and particulates through the use of capillary tubing, scrubbers, and getters. Capillary tubing is smaller than its packed column alternative (Shimadzu 2024). Because of this, subsequent instrument readings tend to have higher and more precise peaks, leading to easier isotopic characterization: It's easier to see which elements the sample contains since the peaks are sharper and more distinct (Shimadzu 2024). Capillary tubing does not filter out the gasses and particulates per say, but they do allow instruments to more easily read the presence of all elements that are there (Shimadzu 2024).

Scrubbers, on the other hand, ensure that the gas stream within the spectrometry suite remains free of inconsequential gasses or harmful particulate matter (Nathanson 2024). Packed tower scrubbers can be used to remove sulfur-based elements from the gas stream and impingement wet scrubbers can remove solid particles–such as lose flecks of regolith that leak into the system from the pyrolysis cell–to ensure the Chromatography and TLS instruments are not adversely influenced by the outside environment (Nathanson 2024). Electrostatic precipitation can further be utilized to ensure no outside solid matter infiltrates the gas stream (Nathanson 2024). In Electrostatic precipitation, all solid particles that enter the capillary tubing are given an electrical charge and then removed through the use of an electrical field (Nathanson 2024). All these scrubbing methods working together should ensure the Lunar Vanguard rover's spectrometry suite produces data with high integrity and low noise.

To ensure isotopes of C, H, O, and N are enriched and easier to read by the TLS, the Lunar Vanguard rover's spectrometry suite will also utilize metallic getters (VAC AERO 2017). Getters are mechanisms that grab onto certain elements using adsorption, absorption, and chemical bindings to ensure that elements currently being researched reach the spectrometry instruments (VAC AERO 2017). By implementing getters, Lunar Vanguard's spectrometry suite ensures not only that noise (unwanted elements or particulates) will be minimized, but that information (the stable isotopes that the payload intends to measure) will be maximized.

Capillary tubes, getters, and scrubbers are all standard practise in spectrometry and have been implemented on multiple space-grade missions. Curiosity's SAM used all three, as did Volatile Analysis by Pyrolysis of Regolith (VAPoR). However, neither of these systems actually deployed the capillaries, getters, or scrubbers to the lunar surface. Therefore, the highest TRL these components can reach is TRL 5. Once again, tests will need to be done to increase their TRL.

Gas Chromatography

The purpose of gas chromatography in the pyrolysis-gas chromatography-mass spectrometry method is to separate gasses prior to entering the mass spectrometry device (in this case, the TLS) to enhance the latter's reading of the isotopes contained within the sample (Mahaffy et al. 2012). The Lunar Vanguard rover's gas chromatography device will be equipped with six columns to ensure the C, H, O, and N isotopes are properly separated prior to arriving at the Tunable Laser Spectrometer.

Similar to most gas chromatography systems, Helium will be used as the carrier gas to ensure optimal separation and stability (Mahaffy et al. 2012).

Similar to previous examples, gas chromatography has been used on Curiosity's SAM mission. This means that the unit has been tested and operated on Mars. However, it has not been proven on the moon and would therefore have a TRL of 5.

Tunable Laser Spectrometer (TLS)

Retrieving data on water ice and stable isotope presence in Amundsen Crater's PSR requires the use of a spectrometer to identify the type and amount of isotopes in each sample to calculate the proper ratios. In the1980s, JPL developed the Tunable Laser Spectrometer as a more compact way to take spectrometry measurements in situ on other planetary bodies (Webster 2022). These spectrometers are made more compact by bouncing the sample off of mirrors to create the distance required to assess the identity of the sample. Despite their small sizes, TLS is able to detect the level of parts per billion to parts per million (Webster 2022), ensuring that the science performed is able to ascertain water and stable isotope concentration at an acceptable rate of precision.

TLS has a proven history of taking accurate in situ measurements of stable isotopes on planetary bodies. Curiosity's SAM, for example, was equipped with a TLS that assisted in taking measurements of atmospheric and geological elements on Mars (Webster 2014). This system used Curiosity's ChemCam to vapourize rocks to release gas, which was then used by the TLS to identify rock composition (NASA 2024). ISRU also used a TLS to assess volatiles, as well as potential contamination by the ISRU unit (Kleinhenz et al. 2021). The performance of TLS on these missions was so successful that TLS is being worked into future missions for Venus, Saturn, and Uranus (Webster et al. 2014). Since the TLS has been used before by past missions, but it has not been implemented in a south lunar pole environment, its TRL should be bumped down from 7 to 6.

The Lunar Vanguard rover will have three TLS–primary, secondary, and tertiary–and will utilize all three during normal operations. After collecting a sample, the rover will identify the sample, heat the substance up to sublimate the volatiles into gas, and then direct the gasses to the primary, secondary, and tertiary TLS for analysis. The TLS results will be recorded and ratios will be calculated by the software system. If one of the TLS breaks, the other two will act as backup.

SQRLi

In order to navigate in the PSR of Amundsen A, the Lunar Vanguard rover must have a way to navigate in the dark. LiDAR allows for navigation outside of the optical spectrum, using laser pulses to ascertain distance between objects. SQRLi is a version of LiDAR built explicitly around rover navigation (TechPort NASA). It allows for a longer line of sight (36m) and a larger field of view (40x40) than some LiDAR and has been optimized for space environments (TechPort NASA). According to NASA TechPort, SQRLi has a TRL of 6 (TechPort NASA).

Since the lowest TRL is 4 (due to modifications on the TRIDENT drill), the TRL for the payload will be 4 as well. As mentioned in previous sections, simulations and tests in an environment similar to that of the PSR must be undertaken to raise the payload's TRL. Since *in situ* stable isotopic analysis has not been common in recent years, the risk associated with the payload's low TRL will be mitigated through testing as far as possible and then accepted as a consequence of proven technology on a newer frontier.

2.1.5.1. Science Instrumentation Requirements

Table 23. Requirements Pertaining to Physical Properties of South Lunar Pole

WBS Level	Requirement ID	Requirement	Notes
Level 1	PAY 1	The payload system will drill into the lunar regolith and retrieve a 1-meter-deep sample.	Derived from MR 1 and MR 2
Level 1	PAY 2	The payload system will be capable of operating between 20-100K.	Derived from MR 1 and MR 2
Level 1	PAY 3	The payload system will work with CDH to record and transmit data back to Earth.	Derived from MR 1 and MR 2
Level 2	PAY 1.1	The payload system drill will sense and record the temperature and weight of the sample regolith.	Derived from MR 1; PAY 1
Level 2	PAY 1.2	The drill will heat the sample regolith to sublimate volatiles into gasses for the	Derived from MR 1 & 2; PAY 1

		spectrometer.	
Level 3	PAY 1.1.1	The payload system drill will sense and record the temperature (in Kelvin) and weight (in grams) of the sample regolith to 4 precision points minimum.	Derived from PAY 1.1

Table 24. Requirements Pertaining to the South Lunar Pole Sample Assessment

WBS Level	Requirement ID	Requirement	Notes
Level 1	PAY 4	The spectrometer should have a proven history of operating in situ on other planets.	Derived from MR 1 and MR 2
Level 1	PAY 5	The spectrometer should be able to sense multiple stable isotopes from sublimated gas to the parts per billion or parts per trillion.	Derived from MR 1
Level 1	PAY 6	The spectrometer should interface with CDH system to record and transmit isotope abundance data to Earth	Derived from MR 1 & 2
Level 2	PAY 5.1	The spectrometer should be able to sense and record peaks between 1.4 - 1.9 μm (for water).	Derived from PAY 5
Level 2	PAY 5.2	The spectrometer should be able to sense and record peaks between 2.6 - 2.7 μm (for Deuterium/Protium).	Derived from PAY 5
Level 2	PAY 5.3	The spectrometer should be able to sense and record peaks between 2.7 - 6.3 μm (for 18O/16O).	Derived from PAY 5
Level 2	PAY 5.4	The spectrometer should be able to sense and record peaks between 4.32 - 4.38 μm (for 13C/12C).	Derived from PAY 5
Level 2	PAY 5.5	The spectrometer should be able to sense and record peaks between 2.3-2.4 μm (for 15N/14N).	Derived from PAY 5

2.1.5.2. Payload Subsystem Recovery and Redundancy Plans

Due to top-level size, weight, and budget constraints, it would not be feasible to add another TRIDENT drill for redundancy purposes. Mitigating the risk of drill failure will require the use of software (to monitor, diagnose, and fix possible issues) as well as the inclusion and installment system of key drill parts (as opposed to adding another drill entirely.)

Since the TLS is relatively smaller and cheaper, redundancy is ensured by the presence of three total TLS. During normal operations, all three will be used and their current state will be monitored. Upon failure of one, the sampling system can be slowed to ensure that measurements for water ice and all stable isotopes can be accomplished before digging and logging the next sample. Performance will become sub-optimal for every TLS device lost, but the redundancy will ensure that data can still be collected.

In case of failure, TRIDENT is equipped with automated software that is able to resolve common drill failure states (Glass et al. 2024). The software will also monitor each of the TLS sensors to ensure all three are still in operation. In the off-chance that one fails, the system will alter its sampling speed to accommodate, as mentioned in the previous paragraph.

2.1.5.3. Payload Subsystem Manufacturing and Procurement Plans

TRIDENT Drill

PRIMARY SUPPLIER: Honeybee Robotics (Altadena California)

SECONDARY SUPPLIER: In-House

LEAD TIME: 1 year

Honeybee Robotics applied for and was granted the opportunity to work on the TRIDENT for the NASA VIPER project (Dougherty 2020), therefore, they should be considered for primary supplier for the TRIDENT drill. They are a Blue Origin-owned subsidiary that specializes in the development of robotics for motion control and exploration purposes (Honeybee Robotics 2024). In addition, they have worked on projects with NASA in the past, meaning that they will be familiar with NASA’s design review process and expectations (Honeybee Robotics 2024).

On the off-chance that Honeybee Robotics is unavailable to manufacture and supply the TRIDENT drill, the existing design can be taken and manufactured in house or at a contracting facility such as JPL.

If Honeybee Robotics is able to supply the part, a lead time of 1 year is expected. The drill has already been designed and previously manufactured. However, the drill will need to be altered and redesigned slightly to ensure proper function in the new rover. In addition, parts must be shipped and the product must be tested to ensure they are up to Lunar Vanguard's standards.

Spectrometry Suite

PRIMARY SUPPLIER: Nanoplus

SECONDARY SUPPLIER: Commercial off the shelf with modifications

LEAD TIME: 1 year 4 months

Since NASA previously collaborated with Nanoplus to design, implement, and manufacture Curiosity rover's SAM spectrometer suite (Nanoplus 2024), Nanoplus is the top choice for the development of the Lunar Vanguard spectrometer suite (TLS, pyrolytic oven, and GC-MS). Nanoplus specializes in laser and LED-based sensors that detect gasses and are familiar with the TLS and GC-MS method that Lunar Vanguard is utilizing to obtain measurements of volatiles and stable isotopes (Nanoplus 2024).

If Nanoplus is unable to fulfill this request, Lunar Vanguard will modify a commercial off the shelf (CoTS) mass spectrometry system developed by Kennedy Space Center. This will increase lead times by a few months at the very least, but is a strategy utilized by VIPER's MSoLo, since the gas chromatography to mass spectrometry strategy is common practice in industry (Ayala et al. 2019). Only a few modifications would be required.

6-DoF RO1 Robot Arm

PRIMARY SUPPLIER Standard Bots

SECONDARY SUPPLIER: JPL

LEAD TIME: 2 year 7 months

Stan

Owing to their original development of the RO1 autonomous Robotic Arm, Standard Bots is being considered for the development of Lunar Vanguard’s sampling arm. This is a bit of an odd choice as Standard Bots typically develops robotic arms for assembly lines and industry. However, Lunar Vanguard considers Robotic Bots' prior experience on space-grade robotic parts sufficient expertise for the design and manufacture of this part.

JPL is being considered if Standard Bots is unable to fulfill the request since the Adaptive Caching Assembly system developed for Perseverance shares similarities with the sample collection method design for the Lunar Vanguard (namely the 5-degrees of freedom robotic arm) (Silverman 2020).

Since the Sampling Arm will require more modifications than other instruments, this instrument has been given a lead time of almost 2 years. Both Standard Bots and JPL have previous designs for robotic arms that can be modified to fit into the Lunar Vanguard’s sampling system, but these modifications will add extra time and testing that need to be accounted for.

SQRLi

PRIMARY SUPPLIER: Optotune

SECONDARY SUPPLIER: In House (NASA Goddard)

LEAD TIME: 7 months

NASA originally awarded the design and implementation of SQRLi to Optotune (Washington 2023), so Lunar Vanguard intends to renew this partnership. Optotune specializes in the development of optical devices and sensors and has prior experience in partnering with the space industry (Optotune 2023).

If Optotune is unavailable, the design for SQRLi can be modified and manufactured in house since NASA Goddard has a long history with Lidar (NASA Spinoff 2005).

Since the SQRLi has already been designed for a similar purpose, less modification will be required. The estimate of 7 months accounts for manufacture, testing, and integration.

2.1.5.4. Payload Subsystem Verification Plans

Table 25: Payload Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAY 1	The payload system will drill into the lunar regolith and retrieve a 1-meter-deep sample.	Demonstration	Demonstrating the system's ability to successfully drill and retrieve a 1-meter-deep sample under mission conditions validates its readiness	A full-scale test of the TRIDENT drill will be conducted in a simulator that mimics lunar regolith and environmental conditions. The drills performance will be monitored to see if it can consistently achieve the 1-meter-depth. Data on the sample's retrieval will be recorded.
PAY 2	The payload system will be capable of operating between 20-100K.	Demonstration	Ensuring the payload system operates efficiently within the specified temperature range is crucial for mission success.	Thermal testing in a controlled environment that simulates lunar temperatures of 20-100K will be conducted in order to evaluate the system's operational stability and data accuracy under these conditions.
PAY 3	The payload system will work with CDH to record and transmit data back to Earth.	Demonstration & Analysis	Demonstrating the integration between payload and CDH ensures that data is being accurately recorded and transmitted.	A simulation test will be conducted where data collected from the payload is processed by the CDH system and transmitted to Earth. The data will be verified by comparing it with the original data collected by the payload system and seeing if any data was altered during the transmission from CDH.
PAY 1.1	The payload system	Demonstration	Continuous monitoring	Sensors embedded in the

	drill will sense and record the temperature and weight of the sample regolith.	& Inspection	and data recording during the sample retrieval cycle is critical to ensure accurate temperature and weight measurements.	drill will be tested to record the temperature and weight of regolith samples during the drill test. Data accuracy will be verified by comparing recorded data with data from simulation testing.
PAY 1.2	The drill will heat the sample regolith to sublimate volatiles into gasses for the spectrometer.	Demonstration	Ensuring the drill can effectively heat regolith to release volatile is essential for spectrometer analysis.	A demonstration will be conducted where the drill heats a regolith simulant. The effectiveness of sublimation will be measured by analyzing the released gasses with a spectrometer.
PAY 1.1.1	The payload system drill will sense and record the temperature (in Kelvin) and weight (in grams) of the sample regolith to 4 precision points minimum.	Demonstration & Calibration	High precision in recording temperature and weight is necessary for accurate scientific analysis	Precision testing of the drill's sensors will be conducted, focusing on their ability to record within the required accuracy. The system will be tested several times under varying conditions to ensure that it provides consistent readings.

Table 26: Verification Pertaining to the South Lunar Pole Sample Assessment

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAY 4	The spectrometer should have a proven history of operating in situ on other planets.	Inspection & Review	Proven history in similar environments minimizes risk of failure during the mission	Review of the spectrometer's performances and operational data in the past on other planetary missions confirms its reliability.
PAY 5	The spectrometer should be able to sense multiple stable isotopes from sublimated gas to the parts per billion	Demonstration & Calibration	Ensuring the spectrometer can detect isotope at required levels is critical for mission success.	A calibration test using gas mixtures with known isotope concentrations will be used to validate the spectrometers' ability to detect and measure

	or parts per trillion.			isotopes at parts per billion/trillion.
PAY 6	The spectrometer should interface with CDH system to record and transmit isotope abundance data to Earth	Demonstration & Analysis	Guaranteeing the spectrometer can effectively communicate with CDH is essential for data transmission.	The same test from PAY 3 will be used to validate the spectrometer data
PAY 5.1	The spectrometer should be able to sense and record peaks between 1.4 - 1.9 μm (for water).	Demonstration & Calibration	Making sure the spectrometer can detect water at the required wavelength is essential for mission success	The spectrometer will be tested using a gas sample with known water content to ensure that it can sense and record peaks between 1.4 - 1.9 μm
PAY 5.2	The spectrometer should be able to sense and record peaks between 2.6 - 2.7 μm (for Deuterium/Protium).	Demonstration & Calibration	Accurate detection of Deuterium/Protium is required for isotope analysis.	The spectrometer will be tested with gas samples containing Deuterium/Protium. The spectrometer will be calibrated to ensure accurate peak detection between 2.6 - 2.7 μm.
PAY 5.3	The spectrometer should be able to sense and record peaks between 2.7 - 6.3 μm (for 18O/16O).	Demonstration & Calibration	Accurate detection of 18O/16O is needed for understanding the lunar volatiles.	The spectrometer will be calibrated and tested with known oxygen isotope ratios. The spectrometer will be calibrated to ensure accurate peak detection between 2.7 - 6.3 μm.
PAY 5.4	The spectrometer should be able to sense and record peaks between 4.32 - 4.38 μm (for 13C/12C).	Demonstration & Calibration	Accurate detection of 13C/12C is needed for understanding the lunar volatiles.	The spectrometer will be calibrated and tested with known carbon isotope ratios. The spectrometer will be calibrated to ensure accurate peak detection between 4.32 - 4.38 μm.
PAY 5.5	The spectrometer should be able to sense and record peaks between 2.3-2.4 μm (for	Demonstration & Calibration	Accurate detection of 15N/14N is needed for understanding the lunar volatiles.	The spectrometer will be calibrated and tested with known nitrogen isotope ratios. The spectrometer will be calibrated to ensure

	15N/14N).			accurate peak detection between 2.3-2.4 μm.

2.2. Interface Control

In order to organize the interfaces between systems, an N^2 (N-squared) chart was created. It does not display the types of interfaces between systems but is meant only for displaying the relations between each system's interface with other systems. This chart includes every subsystem of the Lunar Vanguard rover, with CD&H broken up into "Data Handling" and "Communications" systems, and "Navigation" added as a system. In total, the N^2 chart is left with 6 systems: "Payload," "Data Handling," "Comm (communications)," "Mechanical," "Thermal," and "Power."

The Payload system includes the Rover's two scientific instruments: TRIDENT, and the Lunar Rover Spectrometry Suite (sampling arm, pyrolytic cell, gas chromatograph, and TLS). It interfaces with Data Handling in order to provide and organize the collection & storage of scientific data obtained from the volatile samples.

The data handling system the rover's onboard computer and data storage devices and interfaces with every other system. The inputs to the data handling system are every single component's status, along with obtained scientific data from the payload subsystem. Certain types of information that comes through the system such as information of the volatile samples, are sent to the communications system to then be sent back to Earth. The navigation paths are sent to the mechanical system, and the thermal status of each component is sent to the thermal system.

The Communications system includes radio transmitters and antennas for sending information back to the Orbiter, for analysis on the ground. It receives science data and telemetry packets from the data handling system and will return manually transmitted commands, and other incoming data back to the system.

The Mechanical system includes the mobility components for the rover. Its main interface is with Data Handling, to report its status and obtain navigation paths.

The Thermal system includes radiators and heaters for raising or lowering the temperature of Rover components. In order to do this, it receives all of the components' thermal status and then interfaces with every component in order to keep temperature within operating conditions.

The Power system includes solar panels, power storage, and power distribution. It interfaces with every component to supply it with electricity.

Table 27. N^2 Diagram

Payload	Science Data Payload Status				
Science Collection Command	**Data Handling**	Telemetry & Component Status Science Data	Navigation Paths	Component Thermal Status	
	Manual Commands Incoming Data Comm Status	**Comm**			
Payload deployment	Mechanical Status Navigation		**Mechanical**		
TCS	TCS Thermal Status	TCS	TCS	**Thermal**	TCS
Power	Power Power Status	Power	Power	Power	**Power**

In order to show interfaces between individual components, and the type of interfaces, a systems-level functional block diagram was created. Although many subsystems have decided on specific components, the generic names of some components are used in case of supply shortages, budget constraints, or other unforeseen issues with obtaining components. Additionally, components that only interface within their own subsystem are not displayed on this diagram. The types of interfaces included in this diagram are: Thermals, through the use of heat pipes. Data Interfaces, using a TBD communication protocol. Power, using a DC power circuit. Science Observables, which are physics events or traits measured using science instruments. Finally, RF signals are shown interfacing with the rover’s antennas from an external source

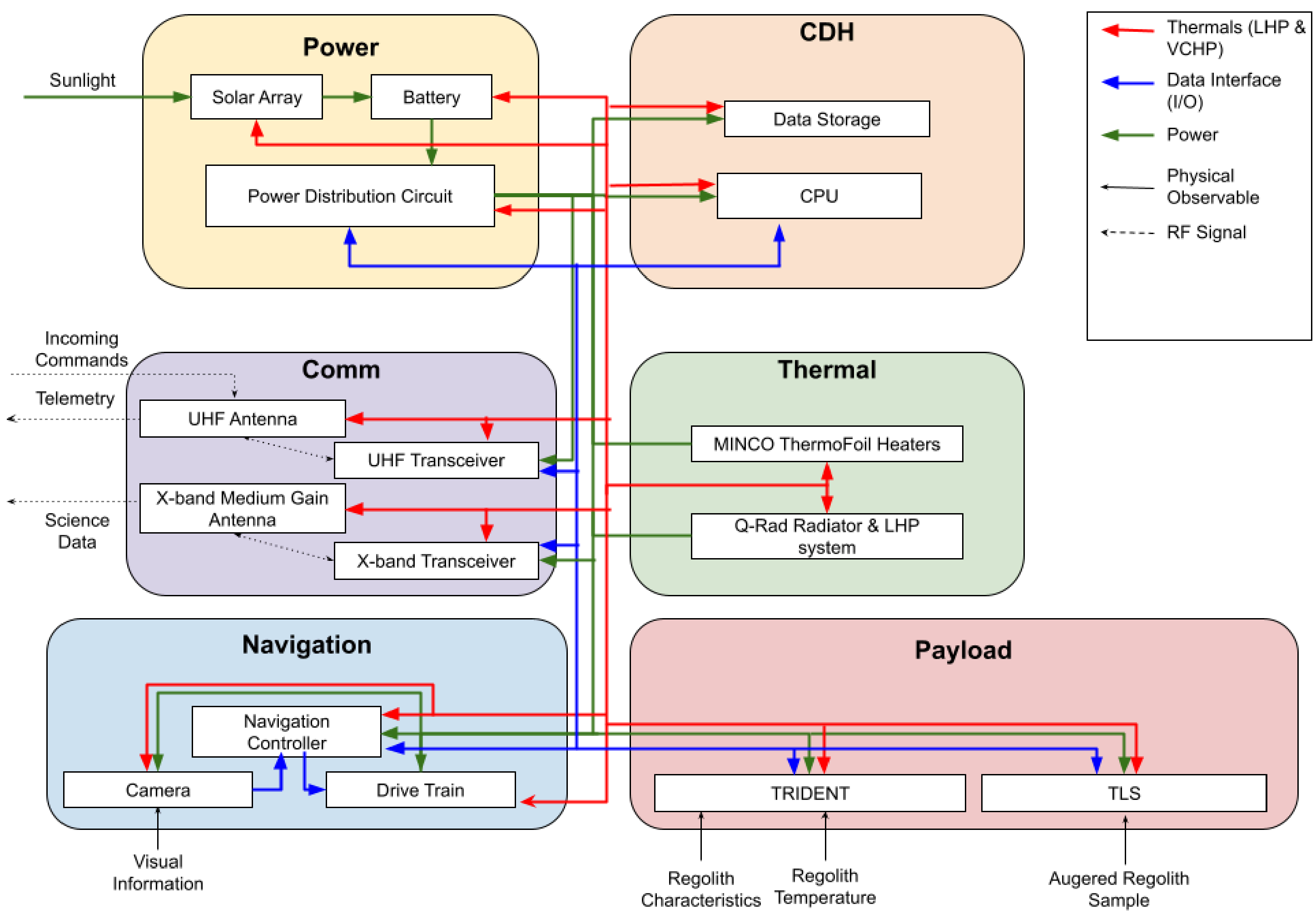

Power
Sunlight
Solar Array
Battery
Power Distribution Circuit
CDH
Data Storage
CPU
Thermals (LHP & VCHP)
Data Interface (I/O)
Power
Physical Observable
RF Signal
Incoming Commands
Telemetry
Comm
UHF Antenna
UHF Transceiver
X-band Medium Gain Antenna
Science Data
X-band Transceiver
Thermal
MINCO ThermoFoil Heaters
Q-Rad Radiator & LHP system
Navigation
Navigation Controller
Camera
Drive Train
Visual Information
Payload
TRIDENT
TLS
Regolith Characteristics
Regolith Temperature
Augered Regolith Sample

Figure #16 Systems Functional Block Diagram

3. Science Mission Plan

3.1. Science Objectives

Scientists believe volatiles on the moon derive from one of three main processes: Endogenous processes, exogenous processes, and solar wind (Mahaffy 2012). Endogenous processes include geological phenomena such as volcanism that are endemic to the moon itself (Mahaffy 2012). In contrast, exogenous processes stem from a source outside the moon. Comet impact, for example, is a strong candidate to explain water ice presence on the south side of the moon (Mahaffy 2012). Processes associated with intense solar wind (like photodissociation) have also been known to result in water ice (Mahaffy 2012). In order to understand the compositional distribution (Artemis Science objective 2a) and origin (Artemis Science objective 2b) of these lunar volatiles, Lunar Vanguard has developed six mission objectives:

> Mission Objective 1: Determine the water ice abundance of Amundsen A PSR within the top 1 meter of regolith to at least +/- 5% accuracy.
>
> Mission Objective 2.1: Determine the temperature of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.2: Determine D/H stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.3: Determine $^{18}O/^{16}O$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.4: Determine $^{13}C/^{12}C$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.
>
> Mission Objective 2.5: Determine $^{15}N/^{14}N$ stable isotopic ratio of Amundsen A PSR, within the top 1 meter of regolith.

Mission Objective 1 concerns the physicochemical properties of water ice on the south lunar pole. The TRIDENT drill will be utilized for sample collection and the spectrometry suite for an analysis of water abundance measured in percentage water ice per sample volume (eg. 10%, 25%, 50%). This information can then be compared to remote-gathered data on hydrogen presence (LAMP or LEND data, for example) to discern how these remote measurements correspond to *in situ* data collection. For example, does a higher measurement in LAMP/LEND also correspond to a higher measurement *in situ*? Or are there occasions when *in situ* data reports a higher level of water than is reflected in its LAMP/LEND counterpart?

Mission 2.1 expands upon this physicochemical analysis by providing temperature information about the temperature of each 10 centimeter chunk. This granularity allows the analysis to discover patterns about water ice abundance and temperature. In this case, the question is whether a lower temperature corresponds to a higher abundance of water ice concentration. Knowing the relationship between water ice presence and temperature (if there is any) can improve scientific and predictive models of the south lunar pole. To facilitate this mission, temperature (in Kelvin) will be recorded by the TRIDENT drill during each 10cm chunk sample extraction.

Missions 2.2-2.5 are focused on understanding the origin of volatiles within the PSR and, because of this, are heavily focused on stable isotope analysis. Stable isotopes are ratios of isotopic concentration that scientists use to identify everything from cosmic origin to atmospheric escape to biological presence (Webster 2012). C, H, N, O, and S-based isotopes are particularly insightful ratios for planetary science (Webster 2012) and, because of this, account for all isotopic ratios collected by the Lunar Vanguard rover: D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$. These ratios are calculating through the use of the TRIDENT drill (which collects a sample of regolith to 1 meter beneath the lunar surface), the sample collection suite (which transfers the regolith sample to a pyrolysis cell to sublimate volatiles within the sample; this gas is then pushed through a system of tubes–including scrubbers and getters–that transfer gas to a chromatography chamber to ensure the proper gasses are directed to the TLS), and, finally, to the TLS (which calculates all isotopes and their concentration in the sample. These isotopic concentrations are used to calculate the respective isotopic ratios of interest (for example, Deuterium and Protium concentrations can be used to calculate the D/H ratio). These ratios will then be used by Lunar Vanguard Astrophysicists to determine the origin of the Amundsen A PSR volatiles. For example, if a sample has a higher concentration of ^{12}C than ^{13}C, Astrophysicists may argue that the sample has Earth as its origin (since ^{12}C tends to outweigh ^{13}C on Earth), whereas if the reverse is true, the volatile sample may derive from a comet (Webster 2012).

3.2. Experimental Logic, Approach, and Method of Investigation

Since Lunar Vanguard is a lower-budget discovery mission and only two scientific instruments may be integrated into the payload, the mission's sampling method will utilize Systematic Random Sampling to extract regolith samples from Amundsen PSR (as opposed to using a device such as VIPER's Neutron Spectrometry System (NSS) to probe the lunar surface for hydrogen presence and drilling only in areas with high likelihood of water ice volatiles). Although less advanced than the NSS, Systematic Random Sampling also ensures randomness is introduced into Lunar Vanguard's *in situ* sample collection process so that bias is not inadvertently introduced by only sampling regolith with a high likelihood of containing water ice (The Complete…Sampling 2023). Otherwise, the sample collected by Lunar Vanguard would not be representative of the intended population of study–the edge of the Amundsen A PSR overall (The Complete…Sampling 2023).

To utilize Systematic Random Sampling, Lunar Vanguard will be splitting the edge of the Amundsen A PSR into a transverse grid of lines, each of the diamonds between these lines measuring 10 meters by 10 meters. This size is entirely arbitrary and selected to allow for quicker rover navigation (and easier calculations of how many grids should be sampled by Systematic Random Sampling). Similar to a field study, Systematic Random Sampling will be employed to sample each k-th grid, ensuring randomness while allowing the entire area to be researched; maximizing environmental coverage while minimizing the introduction of bias (Williams 2019). Using Cochran's formula for Sample Size (infinite at first), rounding the length of the Amundsen A PSR edge up from 9.26km to 10km (or 10,000m), calculating the number of total 10mx10m grids within this distance to be 1,000, assuming a confidence interval of 95% (and therefore a Z-value of 1.96), a precision level of 0.05, and a population variability of 0.5 for maximum randomness, an initial sample size of 385 is received:

$$n_0 = \frac{Z^2 \times p \times (1 - p)}{e^2}$$

$$n_0 = \frac{1.96^2 \times 0.5 \times (1 - 0.5)}{0.05^2}$$

$$n_0 = \frac{3.8416 \times 0.25}{0.0025}$$

$$n_0 = 384.16$$

$$n \approx 385$$

Since the population size is finite, Cochran's correction formula can be used to properly resize this to 278 samples:

$$n = \frac{385}{1 + \frac{385 - 1}{1000}}$$

$$n = \frac{385}{1 + \frac{384}{1000}}$$

$$n = \frac{385}{\frac{1384}{1000}}$$

$$n = 278.05$$

$$n \approx 278$$

Given that the Lunar Rover will be collecting samples from 278 grids and there are 1,000 total grids, we can calculate the systematic interval to be 4:

$$k = \frac{N}{n}$$

$$k = \frac{1000}{278}$$

$$k = 3.59712230216$$

$$k \approx 4$$

To ensure that the Lunar Vanguard rover is not introducing bias by starting from the first grid, a random number (between 0 and 4) will be provided and this will be the first grid the rover will start with. The rover will then sample every 4th grid afterwards until it reaches the edge of the Amundsen A PSR. It will not return to Earth and will remain on the moon after reaching end-of-life.

Upon reaching a grid it will sample, the Lunar Vanguard rover will perform the following steps:

1) TRIDENT will be used to extract a 1m deep sample of regolith in 1 cm chunks. This process will take 30 minutes to ensure that granular temperature and porosity data is taken for each 1 cm chunk and to prevent the drill from overheating.

2) RO1 6-DoF robotic arm will take the sample extracted by TRIDENT and load it into the heating chamber for sample analysis. To reduce power usage and ensure the proper movement of samples, this process will take 10 minutes.

3) Pyrolysis cell will heat the samples to 400-600°C to ensure all volatiles are properly sublimated (Mahaffy 2012). Gas will be repelled or pushed on through the spectrometry suite tubes using scrubbers and getters to ensure the gasses of interest enter the system while particulates and unwanted gasses are removed from the system alongside the remaining regolith sample (Mahaffy 2012). This process will take a maximum of 30 minutes (Mahaffy 2012).

4) Gasses will then enter the gas chromatography system where they are further assessed and sorted to ensure that only gasses pertaining to our isotopic ratios of interest (D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, $^{15}N/^{14}N$) push forward into the TLS. This process will take around an hour (Mahaffy 2012).

5) All gasses that pass through the gas chromatography system will be analyzed by the TLS. This process will take a further hour (Mahaffy 2012). The results will be logged onto the rover's local data storage and sent back to the main data storage using the rover's CDH system (Mahaffy 2012).

Overall, this entire process will take 3 hours and 10 minutes. The rover will then skip over the next three grids and sample the fourth. The analysis method utilized by Lunar Vanguard rover's spectrometry suite is known as Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) and is a common method utilized by chemists to attain stable isotopic ratios (Kusch 2012). This system provides a higher spectrometry range than either the gas chromatography or TLS unit can provide alone and will assist Lunar Vanguard Rover in achieving its precision and accuracy goals despite the difficulties inherent in sample analysis *in situ* (Kusch 2012).

After the data is transferred back to the team on Earth, a proper analysis can take place. Scientists will calculate the abundance of water ice, as well as the D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$ ratios. Simple multiple linear regression models can be used to assess potential relationships between water ice abundance (the dependent variable) and sample temperature, porosity, and isotopic ratios of the sample. Comparisons can be made between remote data and water ice abundance in certain areas. Finally, the stable isotopic ratios can be used to determine the origin of water volatiles using dual isotope plots and simple statistical models.

All data will be made public at regular intervals to facilitate scientific discovery and provide transparency to Lunar Vanguard's operations and budgetary use.

3.3. Payload Success Criteria

Pyrolytic Oven:

- **Success Criteria**: The Pyrolytic Oven must successfully heat each sample to the specified temperature to convert the collected volatiles into gaseous form for further analysis. Success is defined as the complete pyrolysis of at least 95% of the collected samples without contamination or loss of volatile gasses.
- **Failure Modes**: Potential failures include incomplete pyrolysis due to insufficient heating, contamination of samples due to leakage, or failure to maintain the required temperature, leading to inaccurate chemical composition analysis.

SAM GC-MS (Primary):

- **Success Criteria**: The primary SAM GC-MS must accurately separate and identify the chemical composition of volatile gasses derived from the lunar regolith. Success is defined as the successful identification of at least 95% of the expected volatile compounds with a precision of ±5%.
- **Failure Modes**: Failure could occur if the GC-MS is unable to separate the gasses properly, if the mass spectrometer fails to detect certain compounds, or if there is contamination in the gas chromatograph that skews the results.

SAM GC-MS (Secondary):

- **Success Criteria**: The secondary SAM GC-MS must function as a backup to the primary unit, ensuring continuous analysis in the event of a primary unit failure. Success is defined as the secondary unit being able to replicate the results of the primary unit with a precision within ±5%.

- **Failure Modes**: The secondary unit could fail to engage when needed, or produce inconsistent results compared to the primary unit, leading to uncertainties in the chemical analysis.

Tunable Laser Spectrometer (TLS) (Primary):

- **Success Criteria**: The primary TLS must accurately measure the isotopic ratios of water vapor, carbon dioxide, and other volatiles in the extracted gas samples. Success is defined as obtaining isotopic ratios with a precision of ±5% for all targeted isotopes across all samples.
- **Failure Modes**: Potential failures include calibration drift, inability to detect certain isotopes, or interference from lunar dust or other environmental factors that reduce measurement accuracy.

Tunable Laser Spectrometer (TLS) (Secondary):

- **Success Criteria**: The secondary TLS should serve as a reliable backup, capable of taking over analysis if the primary unit fails. Success is defined as the secondary TLS providing isotopic ratios within ±5% of the primary TLS measurements.
- **Failure Modes**: The secondary TLS might fail to engage or produce inconsistent data compared to the primary TLS, leading to potential data gaps or inaccuracies.

Sampling Arm:

- **Success Criteria**: The Sampling Arm must successfully collect and transfer regolith samples from the drill to the Pyrolytic Oven without contamination or spillage. Success is defined as the precise and contamination-free transfer of at least 95% of the samples.
- **Failure Modes**: Possible failures include mechanical malfunction, such as joint failure or loss of grip, which could result in dropped samples, contamination, or inability to transfer samples to the analysis instruments.

SQRLi (Front):

- **Success Criteria**: The SQRLi (Front) camera system must provide clear, high-resolution images for navigation and scientific observation. Success is defined as maintaining at least 90% image clarity and resolution under all lighting conditions encountered in the PSR.
- **Failure Modes**: Potential failures include loss of image clarity due to dust or lens obstructions, camera sensor failures, or inability to adjust to extreme lighting conditions, which could hinder navigation or scientific analysis.

SQRLi (Back):

- **Success Criteria**: The SQRLi (Back) camera must provide consistent, clear images for navigation and reverse movements. Success is defined as maintaining at least 90% image clarity and resolution under all lighting conditions encountered in the PSR.
- **Failure Modes**: Failures might include sensor malfunctions, lens obstructions, or an inability to capture images under low light, which could affect the rover's ability to safely maneuver in reverse.

3.4. Testing and Calibration Measurements

Pyrolytic Oven:

- **Testing Plan**: Upon arrival at the lunar surface, the Pyrolytic Oven will undergo a series of test runs using small, non-essential sample materials to verify that it heats to the correct temperature and achieves complete pyrolysis.
- **Calibration**: The oven's temperature sensors will be calibrated using onboard reference materials with known thermal properties to ensure accurate temperature readings and control.
- **Control Variables**: Temperature and heating duration will be carefully controlled to ensure consistent and complete pyrolysis across all samples.

SAM GC-MS (Primary):

- **Testing Plan**: The SAM GC-MS will perform initial analysis on calibration gas samples to confirm that the gas chromatograph and mass spectrometer are functioning correctly and that no contamination is present.
- **Calibration**: Calibration will involve running known reference gases through the GC-MS to ensure that the instrument correctly identifies and quantifies each compound.
- **Control Variables**: The flow rate of the gas, temperature, and pressure within the GC-MS will be controlled to ensure consistent performance.

SAM GC-MS (Secondary):

- **Testing Plan**: The secondary SAM GC-MS will be tested in parallel with the primary unit to ensure it can provide consistent results. It will analyze the same calibration gas samples used for the primary unit.

- **Calibration**: Calibration procedures will mirror those of the primary unit, ensuring that both instruments are aligned and capable of producing consistent results.
- **Control Variables**: As with the primary unit, flow rate, temperature, and pressure will be tightly controlled.

Tunable Laser Spectrometer (TLS) (Primary):

- **Testing Plan**: The primary TLS will be tested using onboard calibration gases to verify its ability to accurately measure isotopic ratios before it begins analyzing lunar samples.
- **Calibration**: Calibration involves adjusting the laser tuning and detector sensitivity based on known isotopic ratios from the calibration gases.
- **Control Variables**: Laser power, temperature of the gas sample, and environmental conditions inside the spectrometer chamber will be controlled to ensure accurate measurements.

Tunable Laser Spectrometer (TLS) (Secondary):

- **Testing Plan**: The secondary TLS will undergo the same testing as the primary TLS, including analysis of calibration gasses to verify consistent performance.
- **Calibration**: The secondary TLS will be calibrated using the same methods and reference gasses as the primary TLS to ensure both are aligned.
- **Control Variables**: Identical to the primary TLS, including laser power and chamber conditions.

Sampling Arm:

- **Testing Plan**: The Sampling Arm will perform a series of test movements and sample transfers using mock samples to ensure it can accurately position and transfer materials without contamination.
- **Calibration**: Calibration will involve adjusting the arm's movement algorithms to ensure precise control and positioning, using onboard fiducial markers or reference points.
- **Control Variables**: Positioning accuracy, grip strength, and movement speed will be controlled to ensure reliable operation.

SQRLi (Front):

- **Testing Plan**: The front SQRLi camera will capture test images under various lighting conditions to ensure it can provide clear images for navigation.

- **Calibration**: The camera will be calibrated for focus, exposure, and sensor alignment using onboard targets and test patterns.
- **Control Variables**: Lighting conditions, focus settings, and exposure times will be controlled to optimize image quality.

SQRLi (Back):

- **Testing Plan**: The back SQRLi camera will undergo similar testing to the front camera, capturing images to ensure clarity and resolution in all expected lighting conditions.
- **Calibration**: Calibration will involve adjustments for focus, exposure, and alignment, similar to the front camera, using onboard reference targets.
- **Control Variables**: Control over lighting conditions, focus, and exposure will be critical to ensure the camera provides consistent, high-quality images.

3.5. Precision and Accuracy of Instrumentation

To ensure the integrity of Lunar Vanguard's data, instruments have been painstakingly selected based on their range of accuracy and ease of calibration.

TRIDENT Drill

Lunar Vanguard rover uses a modified TRIDENT Drill for sample collection, temperature data (of each 10cm chunk of the 1m regolith samples), and regolith density/porosity data (also taken with a 10cm granularity). TRIDENT uses a Class A Resistance Temperature Detector (RTD), housed in its drill bit, to assess sample temperature (Zacny et al. 2021). Class A RTDs are able to detect temperature with an error range of ±0.55°C at around -20K (Thermometrics Corp 2023), which is a sufficiently low margin of error for the Lunar Vanguard Rover's needs.

Density and porosity of samples is calculated by the TRIDENT Drill using drill power and percussion rate (Zacny et al. 2021). The more power used and the higher the percussion rate, the denser the regolith sample (Zaxny et al. 2021). Both drill power and percussion rate are included in TRIDENT's base telemetry metrics and have high levels of accuracy because of this. However, it should be noted that the TRIDENT drill's density and porosity calculations are not direct measurements of the lunar regolith, itself, but are secondary calculations derived from primary observations of power and percussion rate. Although the drill power and percussion rate accuracy ratings could not be explicitly discovered, these telemetry sensors typically maintain an accuracy of 99%

or higher to ensure the proper functioning of space-grade instruments (Texas Instruments Incorporated 2023). Accuracy of these instruments also fluctuates depending on the intensity of power usage (Texas Instruments Incorporated 2023). Therefore, tests to ensure a low margin of error on these vital telemetric measurements will take place in the early stages of Lunar Vanguard rover's manufacture and all necessary modifications will be made to ensure both high precision and accuracy.

SCRUBBERS & GETTERS

Lunar Vanguard rover's sample collection system makes use of packed tower scrubbers to remove sulfur dioxide from regolith samples and impingement wet scrubbers to ensure regolith particles do not leak into the main spectrometry suite and cause instrument errors (SLY Staff 2019). Metallic getters will also be used to ensure isotopes of C, H, O, and N make their way to the TLS (Espe 2017). Implementing both scrubbers and getters will bolster the accuracy of Lunar Vanguard's stable isotopic measurements, as well as minimize the likelihood of the lunar environment–namely coarse and EMF-influential lunar regolith particles–negatively impacting data analysis and integrity.

SPECTROMETRY SUITE (GAS CHROMATOGRAPHY + TLS)

Finally, the Lunar Vanguard spectrometry suite (the gas chromatography to filter substances and TLS to measure the presence of individual isotopic presence) is capable of detecting isotopic ratios with negligible error margin. D/H ratios can be measured down to 10 parts per billion, $^{18}O/^{16}O$ to 5 parts per billion, $^{13}C/^{12}C$ to 5 parts per billion, and $^{15}N/^{14}N$ to 5 parts per billion (Mahaffy 2012). All of these fit within the accuracy ranges specified in the early stages of the Science Traceability Matrix (parts per billion specified). Furthermore, the spectrometry suite has a dynamic range of around 10^9 and a sensitivity lower than 10^{-2} counts per second/parts per second ensuring maximum accuracy (Mahaffy 2012). Helium will be used as the carrier gas in the gas chromatography system, which will increase the speed and efficiency of the subsequent TLS measurement.

3.6. Expected Data & Analysis

The determination of isotopic ratios for Carbon, Oxygen, Nitrogen, Hydrogen, and Sulfur is crucial for comprehending the characteristics of celestial bodies within our solar system. Consequently, one of the primary scientific objectives of the Lunar Vanguard mission is to extract stable oxygen isotopes, specifically targeting the detection of O^{16} and O^{18} peaks. This endeavor aims to enhance our understanding of the enigmatic nature of permanently shadowed regions (PSRs) on the moon. To achieve this, the mission team has chosen pyrolysis–gas chromatography–mass spectrometry as the analytical method and equipped the rover with two Tunable Laser Spectrometers (TLS), designating one as the primary instrument and the other as a backup for the sake of redundancy.

Since the preferred technique for locating isotopic ratios on the Amundsen Ridge is mass spectrometry, research was conducted to identify sample data from previous missions in order to compare and contrast the predicted results for the Lunar Vanguard mission. One of the missions that was used as example data was the successful Mars Curiosity Rover that has been conducted for over 10 years. One of the detections of the Tunable Laser Spectrometer included $^{18}O/^{16}O$ and D/H isotopic ratios in water. These measurements, along with numerous others, marked the discovery of paired isotopes in water on a planet other than Earth (Webster, 2023). Lunar Vanguard is able to forecast that these isotope ratios could very well be present in the one-meter samples that will be collected on the Amundsen Ridge crater of the PSR based on the data that Curiosity has found on Mars.

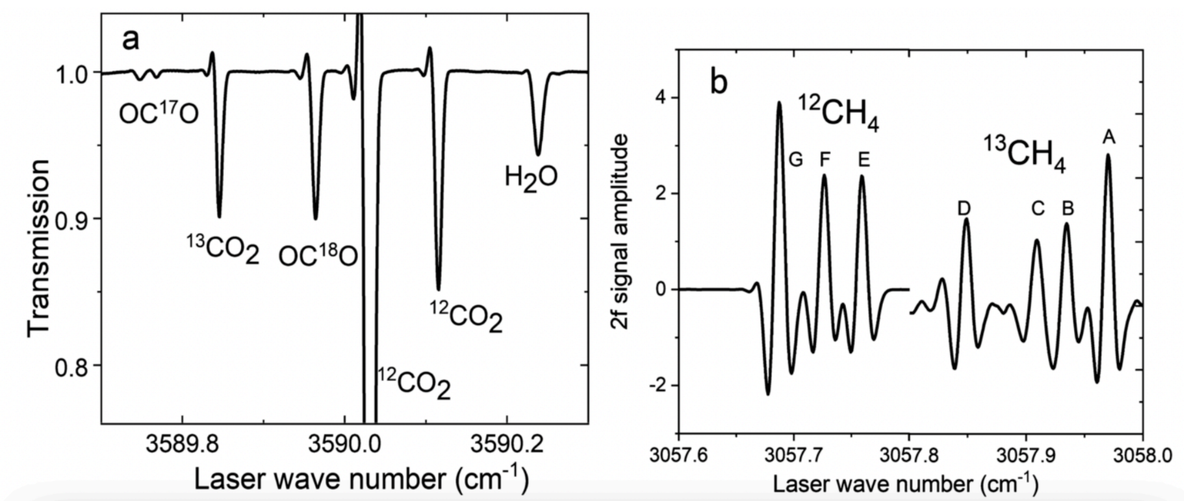


Figure #17: Actual recorded spectra from TLS (Webster, 2023)

The Discovery Program's mission to Ceres, the only dwarf planet in the inner solar system located within the asteroid belt between Mars and Jupiter, served as another crucial precedent for Lunar Vanguard. Data collected by the Ceres lander unveiled a previously unknown world, characterized by oceans containing ammonia and water molecules interacting with silicate rocks (Webster, 2023). For this mission, the Tunable Laser Spectrometer was employed to measure the D/H ratios in both species, the $^{15}N/^{14}N$ isotope ratio of ammonia, and the H_2O/NH_3 ice ratios. In a similar vein, Lunar Vanguard aims to extract regolith samples of water ice and stable isotopes of $^{15}N/^{14}N$ and D/H from the Amundsen Ridge on the moon. By utilizing the data from the Ceres mission, Lunar Vanguard can predict a high likelihood of discovering water on the moon if its results align with those observed on Ceres.

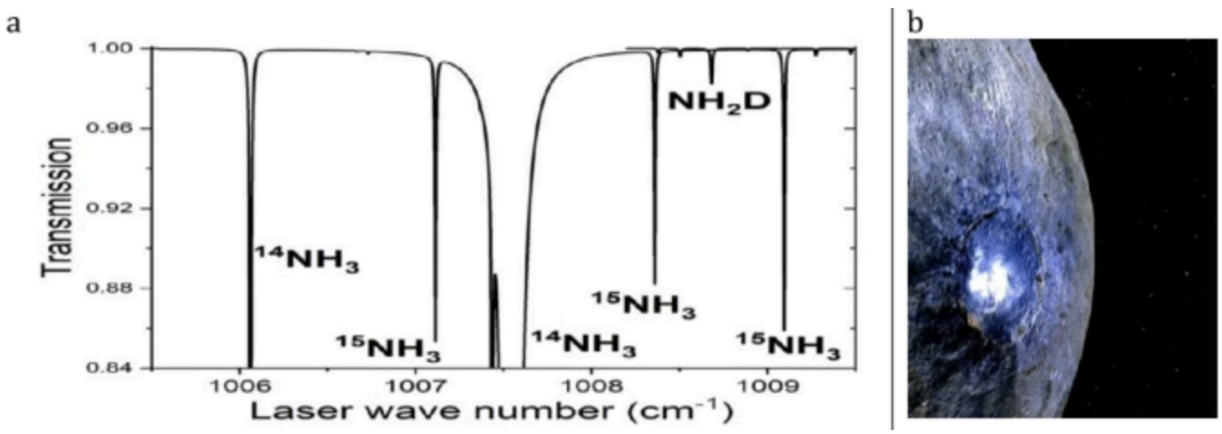


Figure #18: Determination of $^{15}N/^{14}N$ and D/H by TLS (Webster, 2023)

The Lunar Vanguard science team also drew on data from the Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging (DAVINCI) mission. DAVINCI, set to launch in 2029, involves a descent probe into Venus' atmosphere, accompanied by an orbiter that collects data during a flyby (Webster, 2023). Although it has not yet launched, DAVINCI has provided valuable insights into the expected outcomes for Lunar Vanguard's (TLS) data. The Venus Tunable Laser Spectrometer (VTLS) payload, along with the Venus Mass Spectrometer (VMS), will record vertical mixing ratio profiles of gasses such as H_2O, CO, CO_2, OCS, SO_2, and H_2S. VTLS will specifically focus on high-precision isotope ratio measurements of D/H and $^{18}O/^{16}O$ in water (Webster, 2023). Given that many of the goals of both missions are extremely similar, DAVINCI's technology serves as a good example of what to look for when Lunar Vanguard launches.

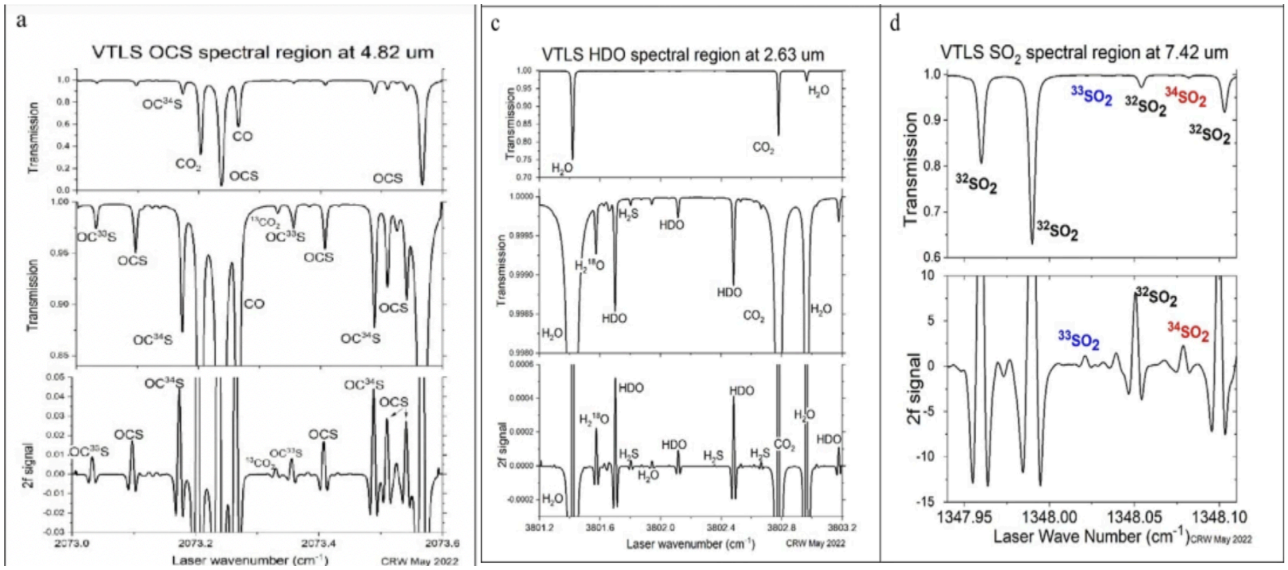


Figure #19: VTLS Scanned Regions (Webster, 2023)

Protons and electrons are known to impart a negative charge to lunar regoliths, potentially complicating Lunar Vanguard's spectrometry analysis by introducing calibration challenges and reducing precision and accuracy (Choi, 2023). To mitigate these issues, the Lunar Vanguard science team implemented a scrubber system for the sampling process. This system removes specific elements from the gas stream, thereby reducing potential errors and ensuring that any unwanted gasses or elements are eliminated from the charged regolith samples (Choi, 2023). And as for ensuring the accuracy and precision of the instruments, a standard procedure involves testing and calibrating them before the lunar mission. This process provides a baseline understanding of any potential deviations in the instruments' measurements.

The Lunar Vanguard mission, building on the insights from the Discovery Program's lander on Ceres and the upcoming DAVINCI mission to Venus, is designed to deepen the understanding of the moon’s surface and its potential water content. Utilizing advanced spectrometry techniques like the Tunable Laser Spectrometer, along with a scrubber system to reduce errors, the mission aims to collect precise data on the regolith's composition. Drawing on lessons from past missions, particularly in handling charged lunar regolith, Lunar Vanguard is poised to significantly enhance the knowledge of lunar resources. Careful calibration and testing of instruments, informed by previous mission data, will ensure accurate results, paving the way for future lunar exploration and expanding space science.

4. Mission Risk Management

4.1. Safety and Hazard Overview

Analyzing risks is crucial to ensuring a smooth launch for the mission, and successful completion of science objectives within the budget allocated to the mission. Risks are events or possible oversights that may force a reduction in scope or result in mission failure. Of course, some risks are impossible to avoid, and there will always be some level of uncertainty. This is why risk analysis requires identifying high-likelihood and high-consequence risks. These risks are worth spending more resources to mitigate.

The first level of risk analysis performed by the team is the risk table and the risk matrix. This is simply a non-comprehensive list of many faults that could occur to the rover. Along with risks for each subsystem of the rover, there are risks concerning development schedules, workplace hazards, and planetary protection risks. This is a living document maintained by the team and updated before every deliverable with new assessments.

The next level of risk analysis is the FMEA (Failure Mode and Effect Analysis) chart. This describes many possible failure modes that may occur during the rover's operation, and methods of reducing the severity of the failure modes. When a single component fails or a deviation from normal operations occurs, the rover enters a failure mode. This could be a loss of communications, a navigation error, or many other operational failures with different systems. An important difference from the other risks and the FMEA chart is that the FMEA chart describes entire failure modes, and how the mission should proceed in the event of the failure modes. It doesn't provide design decisions or mitigations that reduce the severity or occurrence of risks, it simply describes 'what to do' in the event of failures. Of course, the risks that cause the failure modes of the FMEA chart are also listed in the risk matrix.

There's a few types of risks the mission may encounter. The most common type is component and system faults, as described on the risk matrix. These can include components overheating, malfunctioning, or getting damaged. Another common type of risk is workplace hazards, which can include supply delays, machining/manufacturing hazards, and any unexpected logistical issues. Additionally, the mission also considers planetary protection risks. In the context of the mission, contamination of the lunar environment with terrestrial microbes and organics is the primary concern.

4.1.1. Risk Analysis

Effective risk analysis is crucial for the success of the mission. This makes outlining the approach used to manage these risks crucial including risk identification, assessment, and mitigation strategies. The primary source of risks stem from physical environmental hazards (MCR 1.5), which are considered “conditions” that can give rise to various risks. These hazards are meticulously identified and cataloged to form the basis of the risk management process. Each identified risk is classified according to the subsystem it impacts which ensures a structured and organized approach to risk management and analysis.

Risks are managed using a risk matrix, a tool that facilitates the systematic evaluation and prioritization of risks. The risk matrix assesses each risk based on two key factors: likelihood and consequence. For each risk, likelihood and consequence ratings are assigned and they provide a quantitative measure of the potential impact of each risk. As the design phase progresses, the severity of each risk is monitored and updated. In the current review process, the trends have changed to decreasing and unchanged with the findings of mitigations. Risks are assigned one of the following approaches: accept - the risk is acknowledged but no immediate action is taken, typically because the risk is deemed acceptable or unavoidable. Research - further investigation is needed to understand the risk better before deciding on a course of action. Mitigate - active steps are taken to reduce the likelihood or consequence of the risk. Watch - the risk is monitored closely without immediate action, often because the risk is not currently significant but may become so.

Risks assigned to *mitigate* or *research* are escalated to the relevant subteams. These subteams are responsible for developing and implementing strategies to mitigate the risks. Some risks come with preliminary mitigation plans included in their risk statements, providing a starting point for further planning and action. Depending on the research or mitigation measures decided by the subteam, the trend of the risk could also change. By systematically identifying, assessing, and addressing these risks, the team ensures that potential issues are managed proactively, thereby safeguarding the mission’s success.

NASA's Risk Informed Decision Making (RIDM) and Common Research Model (CRM) methodologies both contributed to the team's mitigation strategy. RIDM ensures that decisions between alternatives are made with a clear understanding of the associated risks, helping to prevent late design changes that often drive risk, cost overruns, schedule delays, and even project cancellations. Most opportunities for cost savings in a project arise during the definition, planning, and early design phases. The CRM professionals are employed to monitor and track progress effectively.

Table 28. Risk Summary Table

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Communications	1	3	↓ **- Decreasing (improving)**	M	Given the vibrations or surface impacts or lack of power, there is a possibility of losing power. This adversely impacts antennae, which can result in the loss of communications. For vibration a dampening system can be used and an additional power supply can be added.	The rover will use two communications systems, which can (with less effectiveness) act as redundancies.
2	Communications	2	4	→ **- unchanged**	A	Space weather has the possibility of interrupting signals, which can result in partial loss of communications. Most space weather happens out of the scope of human power leading this to be an acceptable risk.	Active
3	Electrical	2	3	↓ **- Decreasing (improving)**	M	Given the lunar night period, there is a possibility of component damage overnight, which can result in loss of power systems function for the rest of the mission.	Updated heat retention, batteries, and hibernation modes

4	Thermal	1	4	↓ - **Decreasing (improving)**	A	Due to problems in landing phase or impact from regolith, there is a possibility of losing power, which can result in heaters malfunctioning, which can result in not supporting the required temperatures for the sensitive instruments and other payloads.	Likelihood lowered due to the fact that the power system is unlikely to fail except for unlikely failure modes. Backup heater was added to mitigate risk.
5	Thermal	2	2	↓ - **Decreasing (improving)**	M	Given the lack of power, there is a possibility of not having enough power to heater, which can result in not maintaining required temperatures for the sensitive instruments and other payloads.	The rover shall enter a low power mode, prioritizing safety functions like heating. The rover will also have an additional battery to help mitigate the risk.
6	Mechanical	2	2	↓ - **Decreasing (improving)**	M	Given that the rover is traversing an unstable Lunar Regolith, there is a possibility of the Rover's wheels losing traction or getting stuck, which can result in the rover being unable to navigate to targets.	Rover is now using aluminum wheels w/ grousers which are more resilient to Lunar Regolith properties.
7	Mechanical	3	3	→ - **unchanged**	A	Given that there will be rocks being bumped around the rover, there is a possibility of large particles getting stuck within the	This risk is mitigated through robust chassis and casings for components.

						Rover's mechanical system, which can result in components being unable to be deployed or move.	
8	Mechanical	1	1	→ **- unchanged**	A	Given that the Moon has no protective atmosphere, there is a possibility of high-energy particles impacting the rover, which can result in material decay over time. Because this process takes place over a very large timescale, this risk is accepted.	Active
9	Electrical	1	3	↓ **- Decreasing (improving)**	M	Given that the rover will be experiencing mechanical vibrations or impacts, there is a possibility of the solar panels being electrically disconnected from the power grid, resulting in the rover being unable to charge.	Vibration testing of components should reduce the chance of impact-related failures. The risk is also mitigated through a backup power supply or dampening/protective systems
10	Electrical	1	3	↓ **- Decreasing (improving)**	M	Given that the rover will be experiencing mechanical vibrations or impacts, there is a possibility of the battery being electrically disconnected from the power grid, resulting in the	Vibration testing of components should reduce the chance of impact-related failures. This risk is also minimized through a backup power supply and dampening/protective systems.

						rover being unable to charge.	
11	Electrical	1	3	↓ - **Decreasing (improving)**	M	Given that there is no thermally conductive atmosphere on the moon, there is a possibility of the onboard computer overheating, reducing it's performance.	Thermal system of the rover is designed so that overheating of components is very unlikely
12	Budget	1	2	→ - **unchanged**	M	Given that the current supply chain problems, there is a possibility of lack of supply, which can affect the prices with the demand and supply relations and may result in affecting the total mission cost.	This risk can be mitigated by ordering materials ahead of schedule.
13	Budget	3	2	→ - **unchanged**	A	Due to any technical problems, there is a possibility of new materials, which results in an increase in the total budget.	Active
14	Schedule	3	3	→ - **unchanged**	A	Given that to any technical problems, there is a possibility of falling behind on schedule leading to missing deadlines. This risk is accepted due to unknown technical problems.	This risk is mitigated through organizational practices.
15	Schedule	3	4	→ - **unchanged**	A	Due to schedule conflicts from technical problems, there is a possibility of not meeting the	Active

						launch window, which can result in extending the mission timeline that may cost more.	
16	Personnel	3	2	→ - **unchanged**	M	Given that the physical hazards, there is a possibility of injuries, which can cause shortage in staff and create deterioration in the health of the personnel.	This risk is mitigatd by enforcing safety rules in the physical work environment.
17	Personnel	2	2	→ - **unchanged**	M	Due to overworking during the mission, the personnel might have mental health related burnout that can lead to health issues for the personnel.	This risk is mitigated through organizational charts and tracking personnel work.
18	Navigation	3	2	↓ - **Decreasing (improving)**	M	Given the rough surface of the Moon, the rover might get stuck on a rock that results in the rover to not be able to move.	Locomotion Bogie suspension reduces the chance of getting stuck on rough, unweathered surfaces.
19	Navigation	1	4	↓ - **Decreasing (improving)**	M	Due to the moon's harsh terrain, the rover has the potential to fall into ditches or craters which could result in the rover getting stuck, ending the mission.	Navigation plan is routed around obstacles and areas of concern.

20	Science	1	3	→ **- unchanged**	W	Due to the abrasive elemental characteristic of the regolith on the landing site, the drill may get clogged while trying to collect samples. This could cause significant delays, increased maintenance costs, and potential damage to the drill.	Active
21	Science	2	3	↓ **- Decreasing (improving)**	M	Due to harsh operational environments, the thermometer on the drill could break resulting in inaccurate temperature readings, potential damage to the drill, and delays in the project timeline.	The drill thermometer is fully enclosed within the drill mechanicals.
22	Science	2	3	↓ **- Decreasing (improving)**	M	Due to the extreme cold on the Amundsen crater, the arm deploying the drill may malfunction and thus stop the rover from collecting samples. This could result in the loss of critical scientific data, mission delays, and/or increased mission costs.	The risk is mitigated by simulating the Amundsen crater's environment to test the rover.

23	Science	3	3	→ - **unchanged**	M	Due to the unique climate on the crater, the thermometer could potentially fail to calibrate, resulting in inaccurate temperature readings.	This risk is mitigated by implementing a more robust thermometer design.
24	Science	2	4	→ - **unchanged**	M	Due to potential technical issues with the rover from the rough properties of the crater, there is a risk of the sampling drill getting jammed during the mission.	Reinforced sampling drill.
25	Science	1	2	↓ - **Decreasing (improving)**	M	Due to the debris being kicked up during the rovers' mission, there is a possibility of the spectrometer being covered up.	Spectrometer is mostly enclosed and protected within the rover's chassis.
26	Science	2	4	↓ - **Decreasing (improving)**	M	Given that the regolith has firmer parts to it, the drill could run into one of those harder parts, resulting in damage to the drill.	Active
27	Science	2	3	↓ - **Decreasing (improving)**	M	Given that the environment, properties, etc. on the Amundsen Ridge are in some ways hazardous, this could cause the spectrometer to fail to calibrate.	A redundant TLS has been added to the rover.

28	Planetary Protection	1	3	→ **- unchanged**	A	Given that the rover's components have a chance to carry microorganisms from being fabricated on Earth, there is a possibility of biocontamination of the Lunar surface from the rover, resulting in unexpected consequences to the Moon's environment.	Active
29	Planetary Protection	1	5	→ **- unchanged**	A	Given the possibility of landing phase failure, there is a possibility of spacecraft breakdown, resulting in debris contamination of the Lunar surface	Active

LIKELIHOOD					
5					
4					
3		18, 13, 16	7, 14, 20, 23	15	
2		2, 5, 6, 17	3, 21, 22, 27	24, 26	
1	8	12, 25	1, 9, 10, 11, 28	4, 19	29
	1	2	3	4	5
	CONSEQUENCES				

Figure #20. Risk Matrix

Mitigation for the risks that had the highest likelihood and consequences are followed as:

5. “Given the lack of power, there is a possibility of not having enough power to heater, which can result in not maintaining required temperatures for the sensitive instruments and other payloads.”
    - The rover shall enter a low power mode, prioritizing safety functions like heating
    - The rover will also have an added additional power source

6. “Given that the rover is traversing an unstable Lunar Regolith, there is a possibility of the Rover’s wheels losing traction or getting stuck, which can result in the rover being unable to navigate to targets.”
    - This risk will be mitigated using wheels that are resilient to Lunar Regolith’s properties
    - The rover’s wheels will use aluminum wheels with grousers

9. “Given that the rover will be experiencing mechanical vibrations or impacts, there is a possibility of the solar panels being electrically disconnected from the power grid, resulting in the rover being unable to charge.”
    - This risk can be mitigated through a backup power supply or dampening/protective systems
    - Vibration testing of components should rescue the chance of impact-related failures

10. “Given that the rover will be experiencing mechanical vibrations or impacts, there is a possibility of the battery being electrically disconnected from the power grid, resulting in the rover being unable to charge.”
    - This risk can be mitigated through a backup power supply or dampening/protective system
    - Vibration testing of components should reduce the chance of impact-related failures

11. “Given that there is no thermally conductive atmosphere on the moon, there is a possibility of the onboard computer overboarding, reducing it’s performance.”
    - This risk is mitigated through the rover’s thermal systems
    - The thermal system of the rover is designed so that overheating of components is very unlikely

18. “Given the rough surface of the Moon, the rover might get stuck on a rock that results in the rover not being able to move.”

- The locomotion Bogie suspension rescues the chance of getting stuc on rough, unweathered surfaces

19. “Due to the moon’s harsh terrain, the rover has the potential to fall into ditches or craters which could result in the rover getting stuck, ending the mission.”

- The risk was researched to find ways for the rover to maneuver to get back on
- The navigation plan is routed around obstacles and areas of concern

25. “Due to debris being kicked up during the rover’s mission, there is a possibility of the spectrometer being covered up.”

- This risk can be mitigated by adding protection (i.e. covers/shields) around the spectrometer
- The spectrometer is mostly enclosed within the rover’s chassis

4.1.2. Failure Mode and Effect Analysis (FMEA)

The team tracks potential faults through the use of an FMEA (Failure Mode and Effect Analysis) Chart. This chart is for regular operations of the rover, meaning that any mitigation methods aforementioned risk analysis have already been taken by the time of the fault. The FMEA chart describes failures and recovery actions that could be taken after mission launch, that can be done without physical access to the rover or any components.

The ‘functions’ listed on the chart describe operations of the rover, processes which are able to get interrupted by certain faults. The ‘failure mode’ describes these faults, and commonly include individual components that can fail in multiple ways, or specific ways in which these components’ operations can be interfered with. The ‘cause’ describes the deviation from operations or physical hazard causing the component fault. Also listed in the chart are ‘prevention’ methods, which are the already-implemented methods to reduce the chance of the risks occurring, and ‘actions’ which can be taken in the event of the failure mode to return to regular operations or descriptions of how the mission objectives may be reduced in scope.

Additionally, each failure mode is granted a RPN (Risk Priority Number), based on assigned values of severity, occurrence chance, and ability to be detected. A high RPN suggests a risk is important to monitor for, and may imply a need for additional mitigation measures.

Table 29. FMEA Table

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Communication between rover and orbiter	Rover UHF Radio Failure	Reduced TLM Transmission capabilities	3	Power disconnect to radio, or over/underheating	1	Component Health Checks	4	12	Use X-band for TLM data
	Rover UHF Antenna Failure		3	over/underheating, or physical impact with antenna	1	Component Health Checks	4	12	
	Rover X-Band Radio Failure	Reduced science & navigation data transmission capabilities	7	Power disconnect to radio, or over/underheating	1	Component Health Checks	4	28	Use UHF for science & navigation data. Descope expected science data reception
	Rover X-Band Antenna Failure		7	over/underheating, or physical impact with antenna	1	Component Health Checks	4	28	
	Noise/Interference from space weather	Reduced transmit effectiveness.	2	Naturally occurs.	10	Attempt to schedule important data transmission around space weather predictions	1	20	Descope expected science data reception
	Orbiter Failure	Communications between Earth and Rover completely severed	9	Outside of mission scope.	1	Outside of mission scope.	1	9	Attempt to establish data link directly with ground

Internal Communication between rover components and Onboard Computer (OBC)	CPU Bus Failure	Individual component connection lost	4	Physical disconnection from bus, packet loss, software error	3	Software checks, resetting components after deviation from nominal operations	1	12	Attempt to reboot / re-establish connection
	CPU Failure	Most systems rendered inoperable temporarily	6	Physical impact, electrical discharge, power or thermal system failure	1	Component Health Checks	5	30	Wait for automatic reboot; else switch to redundant CPU
	Physical Cable Fault	Individual component connection lost	8	Physical impact, sharp particulates inside chassis.	1	Avoid physical environmental hazards	2	16	modify nominal operations to not require affected component
Solar Power Energy Generation	PV Panel Obstruction	Reduced Generation capability	2	Lunar Regolith will stick to panels. Larger debris is unlikely but possible from other physical environmental hazards	8	Component Health Checks	1	16	Continue as planned, but watch for buildup. If necessary, attempt to jostle debris with mechanical arm
	PV Panel Damage	Reduced Generation capability	4	Physical impact, Thermal system failure	2	Component Health Checks	2	16	Assess damage, possibly descope mission objectives if power production is low.
	Physical Disconnection	Reduced ability to charge batteries	8	Physical impact	1	Component Health Checks	1	8	Descope mission objectives & plan for shortened lifetime

Power Distribution to Rover Components	Physical Cable Fault	Individual component receives reduced power	6	Physical impact which damages a cable, or over/underheating	1	Component Health Checks	1	6	Attempt to reroute power to affected component, or modify nominal operations to not require affected component
	Power Distribution Circuit Failure	All rover components receive reduced power	10	Physical impact which damages the power distribution board, or over/underheating	1	Component Health Checks	1	10	Descope mission objectives & plan for shortened lifetime
	Single Battery Failure	Reduced total battery capacity	3	Physical Impact which damages a battery, or over/underheating	2	Component Health Checks	1	6	Utilize possible power saving methods, and watch for additional battery failures.
	Battery Connection Fault	Reduced battery usage	8	Physical Impact, Thermal system failure	1	Component Health Checks	1	8	Attempt to regain battery connection. Descope mission objectives & plan for shortened lifetime.
Lunar sample aquisition through drilling of Lunar surface	Drill failure	Inability to drill into Lunar surface	9	Power disconnect from drill, or over/underheating	1	Component Health Checks	1	9	Descope science objectives. Modify sampling depth
	Drill head debris clog	Reduced drill operation	2	Loose material, or deviations from normal drilling activity can clog the drill.	3	Assess sampling points for optimal drilling conditions	6	36	Attempt to unclog drill. Proceed as normal, monitor the fault.
	Drill chipped / shattered	Reduced drill operation	1	Lack of drill heating or lack of sufficient power	3	Steady temperature regulation and power flow to drill	8	24	Proceed as normal, monitor the fault.

	Drill deployment fault	Drill would need to be re-checked and re-deployed	3	Mechanical deployment failure	5	Checks before drill deployment	2	30	Attempt to re-deploy drill, or descope science objectives to not require drill.
Lunar sample analysis	Arm Failure	Reduced ability to transfer surface samples into TLS chamber	7	Mechanical deployment failure, Power or thermal system failure	3	Mechanical Arm Collision checking, Health checks	1	21	Descope science objectives do not require a mechanical arm.
	TLS Heater Failure	Inability to heat samples to required temperature	7	Power or Thermal system failure	2	Component Health Checks	2	28	Descope science objectives to not require heated samples
	TLS Chamber Failure	Inability to hold gases for spectrometry analysis	7	Physical impact, issue in previous sample analysis	2	Component Health Checks	2	28	Descope science objectives to not require use of TLS
	Drill Analysis Failure	Inability to read surface information from drill	4	Sensors damaged by debris, power or thermal system failure	1	Component Health Checks	2	8	Descope science objectives to not require drill
Movement of rover across Lunar Surface	SQRLi Failure	Rover will be unable to use SQRLi for positioning	7	Power or Thermal system failure	1	Component Health Checks	1	7	Attempt to reboot SQRLi, descope navigation plans

	Wheel damaged	A single wheel will have reduced movement capabilities	2	Physical impact, navigation fault	3	Physical awareness	5	30	Assess damage, possibly descope navigation plans.
	Wheel stuck	Rover will have reduced movement capabilities	3	Navigation fault	3	Physical awareness	1	9	Attempt to dislodge wheel using mechanical arm
	Drive Train Failure	Rover will have reduced movement capabilities	8	Power or Thermal system failure, Physical impact, navigation fault	1	Component Health Checks	2	16	Attempt to restart drive train. Descope navigation plans.
	Obstruction in Drive Train	Rover will have reduced movement capabilities	5	Large debris from lunar surface gets into drive train system	1	Component Health Checks	3	15	Attempt to remove obstruction with mechanical arm. Possibly descope navigation plans
	Inability to proceed	Rover may have to detour around obstruction	2	Navigation error puts the rover in a position that there is an obstruction blocking the path.	3	Physical awareness	1	6	Create navigation plan around obstruction

4.1.3. Personnel Hazards and Mitigations

In addition to risks that directly affect the rover, there are also plenty of risks that affect various personnel working on the mission. The Lunar Vanguard team places the highest priority on human safety. The team understands that personnel injuries lead to increased costs, jeopardizes mission timelines, and diminishes trust within the team, with NASA, and with the public.

The Workplace Safety & Health document for NASA describes how the Lunar Vanguard team will safely conduct operations. This handbook describes how all employees shall handle various hazards & emergency conditions in the workspace. In addition to this, manufacturing operations will follow Occupational Safety and Health Administration (OSHA) guidelines. These describe methods of safely operating machinery required for manufacturing/assembly of the rover.

Table 30. Personnel Hazards

Category:	Hazards:	Mitigations:
Machining and Manufacturing	Mechanical Injuries: Cuts and bruises from machinery	Personal Protective Equipment: Goggles, gloves, ear protection, closed toe shoes
	Flying Debris: Eye injuries from metal shavings or other debris	Machine Guards: Use guards on all moving parts of machinery
	Noise Exposure: Hearing damage from loud machinery	Ear protection
	Chemical Exposure: Issues from solvents or coolants	Training: Comprehensive training when using dangerous equipment
	Fire and explosion: Flammable materials and sparks	Fire Safety Protocols: Fire extinguishers, no open flames, and proper storage of flammable materials
Integration	Electrical Hazards: Shock or burns from exposed wires and components	Lock/Tag Out Procedures: Ensuring all electrical systems are de-energized

	Lifting Injuries: Back injuries from incorrect lifting heavy components	Ergonomic Training: Learning proper lifting techniques
	Falls: Accidents from tall platforms	Fall Protection: Use of harnesses, guardrails, and secure equipment
Testing	Radiation Exposure: Exposure to hazardous radiation	Radiation Safety Training: Proper use of shielding
	Thermal Hazards: Burns for hot surfaces or materials	Thermal Safety: Insulating materials, thermal gloves, proper signage
	Cryogenic Hazards: Frostbite or burns from extremely cold materials	Cryogenic Safety: Face shields, proper gloves, protective clothing
Research Facility and Lab Safety	Laser Damage: Eye or skin damage from laser equipment	Laser Safety Training: Training and safety goggles
	Slip Hazard: Spilled liquids or obstructed walkways	Cleaning: Regular cleaning to prevent spilled liquids
	Ergonomic Strain: Strain from prolonged lab work	Ergonomic Assessments: Adjustable workstations and regular breaks to reduce strain
General Safety / Office	Emergency Situation: Fires, earthquakes, or other unexpected events	Emergency Preparedness: Regular drills, clear evacuation routes, and accessible first aid kits
	Fatigue: Accidents due to long working hours or insufficient rest	Work Hour Management: Limiting overtime, ensuring rest brakes, encouraging a healthy work-life balance
	Electrical accidents: electrical shock or electrocution.	Electrical safety: Disable power to unused appliances, avoid use of worn/frayed cables, exposed wiring.

5. Activity Plan

5.1. Project Management Approach

From the given budget constraints, the personnel to complete this mission is determined to be 36. The organizational chart for the Lunar Vanguard mission is indicated in Figure #.

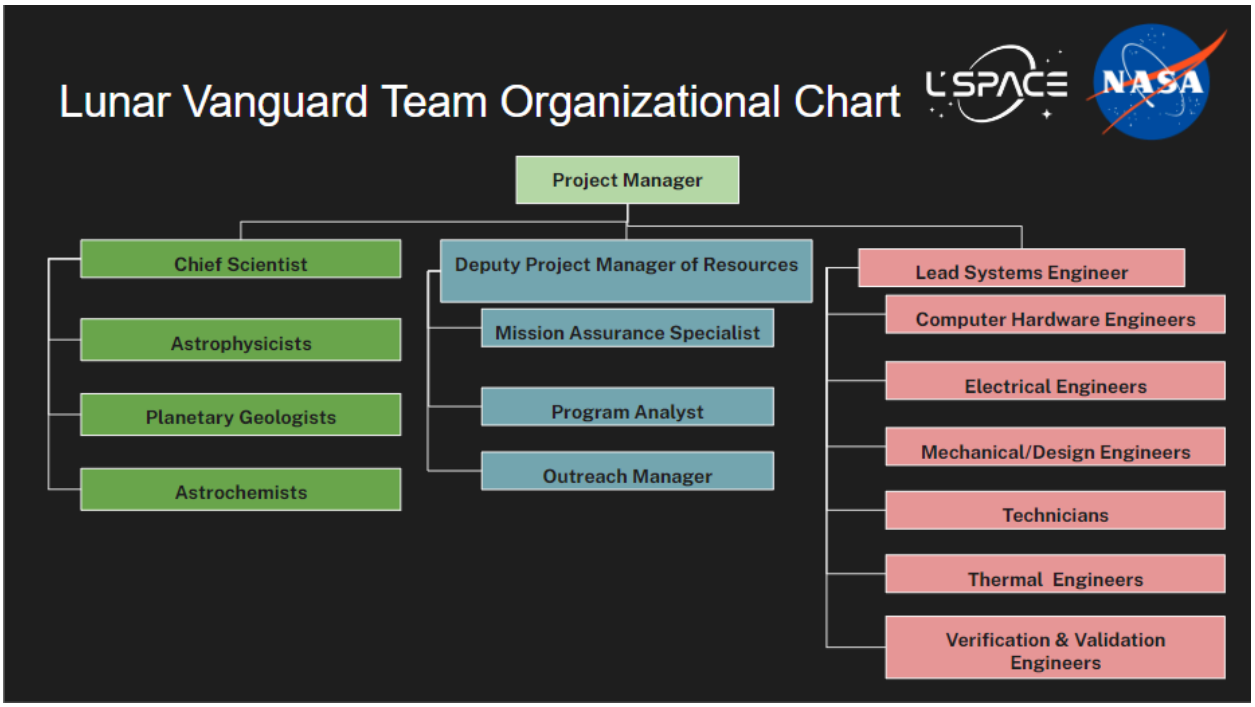


Figure 21. Lunar Vanguard Mission Organizational Chart

Each subteam separated into subteams. The maximum personnel number for each subteam has been determined as follows in Table 29.

Table 31. Personnel Distribution

	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:	5	5	5	5	7	7
Engineering Personnel:	7	8	12	12	12	7
Technicians:	8	11	11	11	5	2
Administration Personnel:	3	3	3	3	3	3

Management Personnel:	4	4	5	5	4	4

All personnel are expected to demonstrate responsibility and respect in the workplace, possess the requisite knowledge, and be open to learning and innovating. They should also embody a researcher's spirit and if necessary should seek clarification or cancel procedures.

The mission will be managed by four managers. The Project Manager holds the highest authority, with team leads reporting directly to the PM. The other managers include the Chief Scientist, Deputy Project Manager of Resources, and Lead Engineer. Each manager will ensure that all necessary steps are taken to meet the customer deadline successfully. Subteams will operate autonomously within their respective teams. Subteams will integrate systems during the meetings.

Each subteam will be informed of its budget percentage and margin prior to commencing the mission. A team of 7 scientists will work to achieve the science objectives. This team is composed of two astrophysicists, two astrochemists. and three planetary geologists at most. From FY 1 to the end of FY 4, scientist personnel will be 5 and will increase to 7 in FY 5 and 6. During the FY of 1 to 4, there will be two astrochemists, two planetary geologists, and one astrophysicist.

Each scientist is expected to have proficiency in their field and contribute to meeting the science objectives. Scientists will have the communication and teamwork skills as well as creative thinking, problem solving, and adaptability to uncertainty. The Chief Scientist, the leader of the science team, will liaise with other managers to manage the schedule and budget effectively.

Astrophysicists are responsible for taking the stable isotopic data that is being collected and have them analyzed by the planetary geologists and assess the possible origin of lunar volatiles. They also assist the planetary geologists in identifying possible errors and write a paper that summarizes their findings. As the astrophysicists are working more in analyzing the data, there will be one astrophysicist during the first four fiscal years of the mission. The astrochemists' role is to ensure that the spectrometry suite is calibrated and functioning properly. They also assist the planetary geologists in compiling and analyzing data from the rover. Planetary geologists have the role of assessing TLS data to identify stable isotopes and their concentrations in samples. They discern if the data contains anomalies or possible errors.

The engineering subteam is composed of technicians and engineers dedicated to delivering innovative solutions for the rover. This team will include three mechanical/design engineers, three thermal engineers, two computer hardware engineers, two electrical engineers, two verification/validation engineers, and eleven technicians. During FY 1 and FY 6, there will be two mechanical/design engineers, two thermal engineers, one computer hardware engineer, one electrical engineer, and one verification/validation engineer. In FY 2, there will be two mechanical/design engineers, two thermal engineers, two computer hardware engineers, one electrical engineer, and one verification/validation engineer.

In total, the engineering subteam will consist of 23 personnel led by the Lead Engineer, who will ensure effective communication with the other subteams. The Lead Engineer is also responsible for the continuation and delegation of the engineering subteam to fully stay in the schedule of the customer. Mechanical engineers are tasked with researching and designing the necessary drivetrain and components of the rover to apply the findings and tests into the lunar surface. They utilize sketches and CAD softwares such as NX Siemens to draw out the 3D models of the rover design. Thermal engineers are responsible for the sustainability of the rover systems on harsh lunar environments within working temperatures. As there will be ranging temperatures on the lunar surface, thermal engineers analyze thermal modules and determine the necessary modules. They also conduct vacuum chamber testing to simulate the lunar surface. CDH engineers design and estimate requirements to complete driver analog systems and digital systems. They ensure the signal has been communicated through LRO. Electrical engineers are responsible for generating and storing and distributing electrical power to various components around the rover. Verification and validation engineers identify which method verification is applicable for each component or subsystem.

In the first FY technician number will be 8 and in the following three years it will increase to 11. After the launch, the number of technicians will decrease to 5 and in the final phase of the mission, there will be 2 technicians. Technicians are responsible for manufacturing and testing the rover for the mission.

The administration team will include three personnel responsible for outreach, mission assurance specialist, and program analyst. They will oversee the mission's adherence to the stipulated time schedule and budget, identify potential risks, and organize events to raise awareness of the mission. Program analysts will be responsible for creating the budget and schedule of the mission while working with management. Mission assurance specialist is responsible for creating the possible risks regarding the mission. Mission assurance specialist creates the risk matrix and FMEA table and monitors the safety. Outreach manager is responsible for increasing the awareness of the public at different levels.

5.2. Mission Schedule

5.2.1. Schedule Basis of Estimate

The team has started its baseline schedule from the customer constraint, and Mission Task document, and created an outline according to that. The team has utilized NASA Project Life Cycle to establish the necessary tasks to be done.

From the start of the mission concept development, analog missions were researched to get baseline values for budget estimates and overall project timeline. One particular mission that was used is the VIPER mission, due to its similar mission class and scope to the Lunar Vanguard mission. As a result of this, the team made inherent assumptions that developing a mission similar to VIPER would result in similar timelines and budgets, even though the scope of both missions vary slightly. Additionally, the VIPER mission was developed earlier than the Lunar Vanguard mission, and as a result, gained exposure to various technologies/components and relevant lunar data.

Furthermore, a number of assumptions were made in order to achieve maximum efficiency for both scheduling and budgeting. For example, The Lunar Vanguard budgets are divided based on fiscal year rather than the calendar year. This is so that the mission’s budget intervals align with governmental funding and budgeting. Additionally, NASA’s strategic plan is used to estimate the resources available to future missions. Also from the NASA Project Management handbook, the team expects the instrument development schedule to grow by around 33% (NASA 2014).

5.2.2. Mission Schedule

Mission Schedule

TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	Dayoff/Holidays	2024 S	O	N	D
Phase C		0%	2/17/25	9/30/27	596	66	360				
Critical Design Review (CDR)	All	Not complete	11/12/24	12/12/24	20						
Fabricate the product	Engineering	Not complete	9/5/25	5/12/27	417						
Complete System Intregration Review (SIR)	All	Not complete	5/26/27	7/19/27							
Phase-C Margin			7/19/27	9/30/27	[illegible]						
◆ KDP-D		Not complete	9/29/27	9/30/27	2						
Phase D		0%	3/6/28	9/30/28	145	16	64				
Test Readiness Reviews (TRRs)	All	Not complete	3/23/28	6/30/28	20						
Operational Readiness Review (ORR)	All	Not complete	7/3/28	8/18/28	20						
Launch	All	Not complete	9/1/28	9/1/28	1						
Schedule Margin			9/6/28	9/27/28	16						
◆ PLAR (Post launch assessment review)	All	Not complete	9/28/28	9/29/28	2						
Phase E		0%	10/2/28	12/31/29	309	46	147				
Conduct the intended prime mission	All	Not complete	10/31/28	11/21/28	15						
Process and analyze mission data	Science/Engineering	Not complete	11/22/28	1/23/29	44						
Critical Event Readiness Review (CERR)	Science/Engineering	Not complete	1/24/29	2/28/29	20						
Develop final mission report	All	Not complete	3/31/29	8/8/29	90						
Decommissioning Review (DR)	All	Not complete	8/9/29	10/19/29	50						
Schedule Margin			10/20/29	12/27/29	45						
◆ KDP-F / End of the mission		Not complete	12/28/29	12/31/29	2						
Phase F		0%	1/1/30	3/31/30	61	7	29				
Disposal Readiness Review (DRR)	All	Not complete	1/28/30	3/25/30	60						
Final mission Phase F reviews	All	Not complete	2/26/30	3/18/30	15						
Schedule Margin			3/19/30	3/27/30	7						
◆ Final Archival of Data		Not complete	3/28/30	3/29/30	2						

Figure 22. High Level Overview of the Mission Schedule with significant milestones

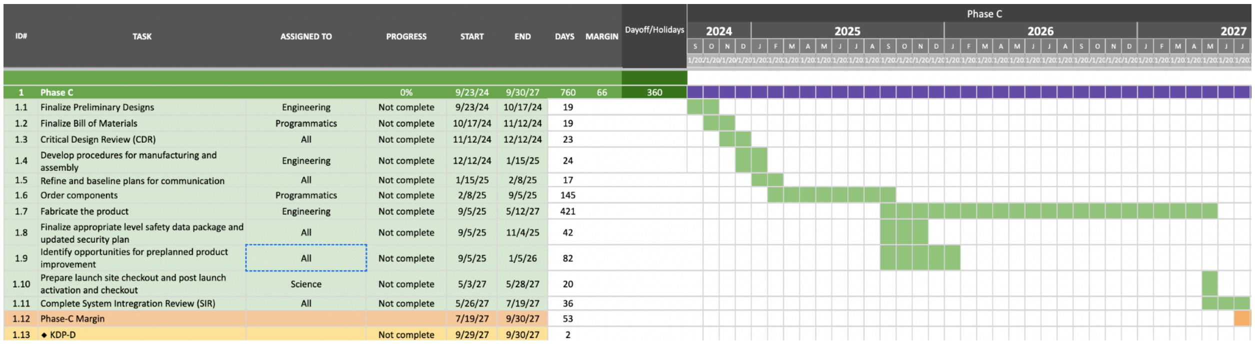
<u>Significant Milestones</u>

Phase C: CDR review, SIR, Phase-C Margin, KDP-D

Phase D: TRRs, ORR, Launch, PLAR

Phase E: Conduct the intended prime mission, Process and analyze mission data, CERR, Develop final mission report, DR, KDP-F

Phase F: DRR, Final mission Phase F review, Final Archival of Data



ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	Dayoff/Holidays
1	Phase C		0%	9/23/24	9/30/27	760	66	360
1.1	Finalize Preliminary Designs	Engineering	Not complete	9/23/24	10/17/24	19		
1.2	Finalize Bill of Materials	Programmatics	Not complete	10/17/24	11/12/24	19		
1.3	Critical Design Review (CDR)	All	Not complete	11/12/24	12/12/24	23		
1.4	Develop procedures for manufacturing and assembly	Engineering	Not complete	12/12/24	1/15/25	24		
1.5	Refine and baseline plans for communication	All	Not complete	1/15/25	2/8/25	17		
1.6	Order components	Programmatics	Not complete	2/8/25	9/5/25	145		
1.7	Fabricate the product	Engineering	Not complete	9/5/25	5/12/27	421		
1.8	Finalize appropriate level safety data package and updated security plan	All	Not complete	9/5/25	11/4/25	42		
1.9	Identify opportunities for preplanned product improvement	All	Not complete	9/5/25	1/5/26	82		
1.10	Prepare launch site checkout and post launch activation and checkout	Science	Not complete	5/3/27	5/28/27	20		
1.11	Complete System Intregration Review (SIR)	All	Not complete	5/26/27	7/19/27	36		
1.12	Phase-C Margin			7/19/27	9/30/27	53		
1.13	◆ KDP-D		Not complete	9/29/27	9/30/27	2		

Figure 23. Phase C Schedule

Phase C

The mission in Phase C is scheduled to span from September 23, 2024, to September 30, 2027. During this phase, the team will carefully assess each role and position needed according to the established sequence. The engineering team will finalize the preliminary designs, after which the programmatics team will complete the bill of materials. Upon completing these tasks, the entire team will initiate the Critical Design Review. Subsequently, the engineering team will develop procedures for manufacturing and assembly, followed by a collaborative effort across the team to refine baseline communication plans. Once these steps are completed, the programmatics team will order the necessary components, enabling the engineering team to begin product fabrication upon their arrival. Following fabrication, the team will finalize the security plan and review the safety data packages. The team will then identify opportunities for planned product enhancements. Finally, the science team will begin planning for post-launch activation, checkout, and launch site preparation. Finally, the team will focus on completing the System Integration Review (SIR), a critical task for this phase. Phase C includes a margin of exactly 66 days to accommodate any delays, resolve potential issues, or address unexpected challenges.

Additionally, the tactical scheduling of Phase C focused on a few key assumptions and references to maximize efficiency. For instance, the NASA Program/Project Life Cycle handbook guided the timing of the CDR, ensuring it occurs before starting hardware fabrication or software coding.

2	Phase D		0%	10/1/27	9/29/28	250	16	64
2.1	Update the risks, and change in baseline	All	Not complete	10/1/27	11/1/27	21		
2.2	Assemble Components/Systems	Engineering	Not complete	11/1/27	1/6/28	45		
2.3	Test Components/Systems	Engineering/science	Not complete	1/7/28	3/22/28	52		
2.4	Integrate/Assemble components according to the integration plan	Engineering	Not complete	3/23/28	4/11/28	14		
2.5	Perform verification and validation on assemblies according to the V&V Plan and procedures	Engineering	Not complete	3/23/28	4/11/28	14		
2.6	Test Readiness Reviews (TRRs)	All	Not complete	3/23/28	6/30/28	70		
2.7	Operational Readiness Review (ORR)	All	Not complete	7/3/28	8/18/28	34		
2.8	Prepare launch, operations, and ground support sites including trainings as needed: KDP-E	Programmatics	Not complete	8/15/28	8/31/28	13		
2.9	Launch	All	Not complete	9/1/28	9/1/28			
2.9	PLAR (Post launch assessment review)	All	Not complete	9/1/28	9/28/28	1		
2.10	Schedule Margin			9/6/28	9/27/28	16		
2.11	◆ KDP-E		Not complete	9/28/28	9/29/28	2		

Figure 24. Phase D Schedule

Phase D

For this mission, Phase D is scheduled to span from October 1, 2027, to September 29, 2028. During this phase, the team will meticulously update any risks or changes in the baseline plan. Upon arrival of the components ordered during Phase C, the engineering team will commence the assembly of the necessary systems. Following the assembly, both the science and engineering teams will collaborate in the rigorous testing of the components and systems. The integration plan will then be rigorously adhered to by the engineering team to assemble the components and conduct comprehensive verification and validation (V&V) processes on the assemblies. Upon the completion of integration and V&V, the entire team will collaboratively engage in the Test Readiness Review (TRR) and Operational Readiness Review (ORR) to ensure full preparedness for launch. Concurrently, the programmatics team will prepare the launch, operations, and ground support sites, incorporating any necessary additional training. Finally, launch will be set for September 1, 2028.

The scheduling strategies for Phase D involved using references and assumptions to estimate the duration of each phase component. For instance, the TRR and PLAR dates were extended to provide the team with additional time, reflecting the professional setting of the project.

3	Phase E		0%	10/2/28	12/31/29	311	46	147
3.1	Conduct launch vehicle performance assesment	Engineering	Not complete	10/2/28	10/30/28	20		
3.2	Conduct the intended prime mission	All	Not complete	10/31/28	11/21/28	15		
3.3	Process and analyze mission data	Science/Engineering	Not complete	11/22/28	1/23/29	41		
3.4	Critical Event Readiness Review (CERR)	Science/Engineering	Not complete	1/24/29	2/28/29	25		
3.5	Capture lessons learned	All	Not complete	2/22/29	3/14/29	15		
3.6	Develop final mission report	All	Not complete	3/31/29	8/8/29	90		
3.7	Decommissioning Review (DR)	All	Not complete	8/9/29	10/19/29	50		
3.8	Schedule Margin			10/20/29	12/27/29	46		
3.9	◆ KDP-F / End of the mission		Not complete	12/28/29	12/31/29	2		

Figure 25. Phase E Schedule

Phase E

Phase E is scheduled to span from October 2, 2028, to December 31, 2029. At the outset of this phase, the engineering team will undertake a series of assessments to evaluate the performance of the launch vehicle, ensuring its optimal functionality. Following these evaluations, the science and engineering teams will collaborate closely to process and analyze both existing and newly acquired data. Throughout this period, they will also conduct periodic assessments of the Critical Event Readiness Review (CERR) to maintain rigorous oversight and ensure continual preparedness for critical mission events. As the mission progresses, all subteams will work cohesively to execute the primary mission objectives. Towards the conclusion of Phase E, the entire team will document any lessons learned, using these insights to develop a comprehensive final mission report. Subsequently, a decommissioning review (DR) will be prepared based on this report. The scheduled margin for this phase extends from October 20, 2029, to December 27, 2029, with the Key Decision Point-F (KDP-F), marking the end of the mission, projected between December 28, 2029, and December 31, 2029.

The scheduling strategies for Phase E built upon the approaches used in Phases C and D, incorporating references, assumptions, and considerations of a professional work environment. Minor adjustments were made to the time allocated for each task, ensuring sufficient time for efficient completion.

4	Phase F		0%	1/1/30	3/31/30	61	7	29
4.1	Dispose of the system and supporting process	All	Not complete	1/1/30	1/8/30	5		
4.2	Document lessons learned	All	Not complete	1/9/30	1/15/30	5		
4.3	Baseline mission final report	All	Not complete	1/16/30	1/27/30	7		
4.2	Disposal Readiness Review (DRR)	All	Not complete	1/28/30	3/25/30	40		
4.5	Final mission Phase F reviews	All	Not complete	2/26/30	3/18/30	15		
4.7	Schedule Margin			3/19/30	3/27/30	7		
4.8	◆ Final Archival of Data		Not complete	3/28/30	3/29/30	2		

Figure 26. Phase F Schedule

Phase F

The final phase of this mission, spanning from January 1, 2030, to March 31, 2030, will involve comprehensive collaboration among the entire team to consolidate the mission's findings. During the closeout period, the team will responsibly dispose of all systems and supporting processes utilized throughout the mission. Detailed documentation of lessons learned will be compiled to capture significant events and insights, contributing to the creation of the final baseline mission report. The team will conduct a Disposal Readiness Review (DRR), followed by final mission reviews. The scheduled margin for Phase F is from March 19, 2030, to March 27, 2030. Post-closeout, a thorough review of the final archive of all mission data will be conducted to ensure completeness and accuracy.

Like in Phases C, D, and E, the scheduling of Phase F was carefully structured using references, assumptions, professional considerations, and extended deadlines. These factors enabled Lunar Vanguard to establish a robust and reliable schedule for the mission.

5.3. Budget

5.3.1. Budget Basis of Estimate

Lunar Vanguard established a consistent set of guidelines, presumptions, and motivators to enable precise estimation and budget development for this mission. The budget and estimates for the expedition were able to be as precise and trustworthy as feasible because of these shared understandings.

A number of assumptions were made regarding the amount of people on the expedition. Given the multitude of categories involved, including science, engineering, technicians, administration, and project management, this assumption was particularly significant. The total for the year and the cumulative total at the end varied depending on how many employees are in each category. Currently, Lunar Vanguard is carrying out this operation with 43 personnel, which is about typical. The overall staff total after accounting for all six years will be roughly $26,242,168, according to the budget template provided by Lunar Vanguards.

The remuneration of each individual employee was another supposition. As previously said, scientists, engineers, technicians, administrators, and project managers are among the individuals working on this project. Since these are only estimates based on preliminary calculations for each income, all of the results for each category are regarded as flat. Over the duration of the anticipated six years of this mission, inflation rates, federal and administrative percentages, and ERE for staff were all taken into consideration and contributed to the flat values for each personnel compensation. Over the course of the six years, the inflation rates varied, but the percentages for the F&A and ERE categories remained constant.

One other item that needed to be considered when making estimates and creating the budget was travel expenses. Details on the number of travelers, the itinerary's days, hotel costs, ticket costs, transportation, and meals were all included in the spreadsheet. Since every traveler will get some form of stipend to help with mission-related expenses, per diem also needs to be considered. These expenditures are calculated using the maximum price range. All travel expenses and each of the subcategories remained the same throughout the predicted 6 years of this mission while the total came out to be approximately $539,863

5.3.2. Total Mission Cost

The mission is projected to cost around $174 million and can be seen from Table 32. From the given budget cap of $175 million, the team utilized MCCET tools and necessary elements to satisfy the customer request. Each budget has been detailed in the next sections of the document.

Table 32. Total Mission Cost

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	$ 400,000	$ 410,400	$ 420,800	$ 431,200	$ 618,240	$ 632,800	$ 2,913,440
Engineering Personnel	$ 560,000	$ 656,640	$ 1,009,920	$ 1,034,880	$ 1,059,840	$ 632,800	$ 4,954,080
Technicians	$ 480,000	$ 677,160	$ 694,320	$ 711,480	$ 331,200	$ 135,600	$ 3,029,760
Administration Personnel	$ 180,000	$ 184,680	$ 189,360	$ 194,040	$ 198,720	$ 203,400	$ 1,150,200
Project Management	$ 480,000	$ 492,480	$ 631,200	$ 646,800	$ 529,920	$ 542,400	$ 3,322,800
Total Salaries	$ 2,100,000	$ 2,421,360	$ 2,945,600	$ 3,018,400	$ 2,737,920	$ 2,147,000	**$ 15,370,280**
Total ERE	$ 586,110	$ 675,802	$ 822,117	$ 842,435	$ 764,153	$ 599,228	**$ 4,289,845**
Personnel Margin	$ 210,000	$ 242,136	$ 294,560	$ 301,840	$ 273,792	$ 214,700	**$ 1,537,028**
TOTAL PERSONNEL	$ 2,896,110	$ 3,426,119	$ 4,273,515	$ 4,487,364	$ 4,168,555	$ 3,345,848	**$ 22,597,513**
TRAVEL							

Total Flights Cost	$ 10,800	$ 13,200	$ 14,400	$ 14,400	$ 12,400	$ 9,200	**$ 74,400**
Total Hotel Cost	$ 36,450	$ 44,550	$ 48,600	$ 48,600	$ 41,850	$ 31,050	**$ 251,100**
Total Transportation Cost	$ 2,700	$ 3,300	$ 3,600	$ 3,600	$ 3,100	$ 2,300	**$ 18,600**
Total Per Diem Cost	$ 20,250	$ 24,750	$ 27,000	$ 27,000	$ 23,250	$ 17,250	**$ 139,500**
Travel Margin	$ 3,510	$ 4,290	$ 4,680	$ 4,680	$ 4,030	$ 2,990	**$ 24,180**
Total Travel Costs	$ 73,710	$ 92,432	$ 103,391	$ 105,946	$ 93,432	$ 70,953	**$ 539,863**
OUTREACH							
Total Outreach Materials	$ 10,000	$ 363,413					**$ 373,413**
Total Outreach Venue Costs	$ 50,000			$ 50,000			**$ 100,000**
Total Outreach Travel Costs	$ 19,890	$ 19,890		$ 19,890			**$ 59,670**
Total Outreach Services Costs	$ 5,000	$ 5,000					**$ 10,000**
Total Outreach Personnel Costs	$ 567,980	$ 567,980					**$ 1,135,960**
Outreach Margin	$ 6,529	$ 9,563	$ -	$ 699	$ -	$ -	**$ 16,790**
Total Outreach Costs	$ 659,399	$ 990,958	$ -	$ 76,095	$ -	$ -	**$ 1,726,452**
DIRECT COSTS							
Mechanical Subsystem	$ -	$ 506,386	$ 7,216,006	$ 4,937,267	$ -	$ -	**$ 12,659,659**
Power Subsystem		$ 139,540	$ 1,988,451	$ 1,360,519			**$ 3,488,510**
Thermal Control Subsystem	$ -	$ 536,292	$ 7,642,154	$ 5,228,842	$ -	$ -	**$ 13,407,288**
Comms & Data Handling Subsystem	$ -	$ 54,806	$ 780,991	$ 534,362	$ -	$ -	**$ 1,370,160**
Guidance, Nav, & Control	$ -	$ 18,484	$ 263,392	$ 180,216	$ -	$ -	**$ 462,092**

Subsystem							
Science Instrumentation	$ -	$ 750,068	$ 10,688,466	$ 7,313,161	$ -	$ -	**$ 18,751,695**
Spacecraft Cost Margin	$ -	$ 601,673	$ 8,573,838	$ 5,866,310	$ -	$ -	**$ 15,041,821**
Total Spacecraft Direct Costs	$ -	$ 2,675,038	$ 39,085,271	$ 27,403,491	$ -	$ -	**$ 69,163,799**
Manufacturing Facility Cost	$ -	$ 802,511	$ 11,725,581	$ 8,221,047	$ -	$ -	**$ 20,749,140**
Test Facility Cost	$ -	$ 802,511	$ 11,725,581	$ 8,221,047	$ -	$ -	**$ 20,749,140**
Facility Cost Margin	$ -	$ 240,753	$ 3,517,674	$ 2,466,314	$ -	$ -	**$ 6,224,742**
Total Facilities Costs	$ -	$ 1,893,766	$ 28,371,216	$ 20,383,265	$ -	$ -	**$ 50,648,247**
Total Direct Costs	$ -	$ 4,568,804	$ 67,456,487	$ 47,786,756	$ -	$ -	**$ 119,812,047**
Total MTDC	$ -	$ 2,675,038	$ 39,085,271	$ 27,403,491	$ -	$ -	**$ 69,163,799**
FINAL COST CALCULATIONS							
Total F&A	$ -	$ 267,504	$ 3,908,527	$ 2,740,349	$ -	$ -	**$ 6,916,380**
Total Projected Cost	$ 3,629,219	$ 9,345,817	$ 75,741,920	$ 55,196,510	$ 4,261,987	$ 3,416,801	**$ 151,592,254**
Total Cost Margin	$ 220,039	$ 1,098,415	$ 12,390,753	$ 8,639,843	$ 277,822	$ 217,690	**$ 22,844,562**
	6.1%	11.8%	16.4%	15.7%	6.5%	6.4%	
Total Project Cost	$ 3,849,257	$ 10,444,232	$ 88,132,672	$ 63,836,353	$ 4,539,809	$ 3,634,491	**$ 174,436,816**

The team utilized the following table (Table 33) to use the percentages for ERE, F&A, and inflation rate. Each of these rates have been pre-set into the template. ERE is employed in personnel, F&A in the final calculation of “Total F&A”, and inflation rate in different categories to illustrate the price increase each year.

Table 33. ERE, F&A, and Inflation Rate Percentages

F&A %	10%	10%	10%	10%	10%	10%
ERE - Staff	28%	28%	28%	28%	28%	28%
Inflation Rate	0.0%	2.6%	5.2%	7.8%	10.4%	13.0%

5.3.3. Personnel Budget

A total of 36 personnel are expected to be onboarded. The Team will consist of scientists, engineers, technicians, administrators, and managers.
During the mission phases, different skill sets will be required, changing the number of personnel in different working groups (Table 34). Phase A and B will be excluded from this personnel breakdown.

This allocation is within the $22.6 million budget dedicated to personnel.

Table 34. Personnel Breakdown by Phase

	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:	5	5	5	5	7	7
Engineering Personnel:	7	8	12	12	12	7
Technicians:	8	11	11	11	5	2
Administration Personnel:	3	3	3	3	3	3
Management Personnel:	4	4	5	5	4	4

The customer-provided estimated salaries for scientists and engineers are $80k, technicians and administrators are $60k, and project managers are $120k annually.

With phases C-F lasting 6 years, the total cost for the personnel is estimated to be in range of $22.6 million (Table 35). Estimated salary is within the allocated budget to satisfy the mission needs. This budget already accounts for an ERE of 28%, inflation, and a margin of 5% (calculated before ERE).

Table 35. Personnel Budget

PERSONNEL							
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative**
Science Personnel	$ 400,000	$ 410,400	$ 420,800	$ 431,200	$ 618,240	$ 632,800	$ 2,913,440
Engineering Personnel	$ 560,000	$ 656,640	$ 1,009,920	$ 1,034,880	$ 1,059,840	$ 632,800	$ 4,954,080
Technicians	$ 480,000	$ 677,160	$ 694,320	$ 711,480	$ 331,200	$ 135,600	$ 3,029,760
Administration Personnel	$ 180,000	$ 184,680	$ 189,360	$ 194,040	$ 198,720	$ 203,400	$ 1,150,200
Project Management	$ 480,000	$ 492,480	$ 631,200	$ 646,800	$ 529,920	$ 542,400	$ 3,322,800
Total Salaries	$ 2,100,000	$ 2,421,360	$ 2,945,600	$ 3,018,400	$ 2,737,920	$ 2,147,000	**$ 15,370,280**
Total ERE	$ 586,110	$ 675,802	$ 822,117	$ 842,435	$ 764,153	$ 599,228	**$ 4,289,845**
Personnel Margin	$ 210,000	$ 242,136	$ 294,560	$ 301,840	$ 273,792	$ 214,700	**$ 1,537,028**
TOTAL PERSONNEL	$ 2,896,110	$ 3,426,119	$ 4,273,515	$ 4,487,364	$ 4,168,555	$ 3,345,848	**$ 22,597,513**

5.3.4. Travel Budget

Within the timeframe of the mission, each personnel has one travel request per fiscal year, which can adapt according to the need. Travels will include traveling to different sites to see the building or testing of the rover, and for the presentation of Standing Review Boards. Calculations were made with the highest prices found. In this way, it is ensured to stay within the budget for the budget planning. Margins are determined to be 5% of the calculated fiscal year cost and can cover the necessary travel costs.

Table 36. Travel Budget

TRAVEL							
Total	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative**
Total Flights Cost	$ 10,800	$ 13,200	$ 14,400	$ 14,400	$ 12,400	$ 9,200	**$ 74,400**
Total Hotel Cost	$ 36,450	$ 44,550	$ 48,600	$ 48,600	$ 41,850	$ 31,050	**$ 251,100**
Total Transportation Cost	$ 2,700	$ 3,300	$ 3,600	$ 3,600	$ 3,100	$ 2,300	**$ 18,600**
Total Per Diem Cost	$ 20,250	$ 24,750	$ 27,000	$ 27,000	$ 23,250	$ 17,250	**$ 139,500**
Travel Margin	$ 3,510	$ 4,290	$ 4,680	$ 4,680	$ 4,030	$ 2,990	**$ 24,180**
Total Travel Costs	$ 73,710	$ 92,432	$ 103,391	$ 105,946	$ 93,432	$ 70,953	**$ 539,863**

The mission will utilize JPL and Goddard Space Flight Center. The travel will also include airfare to Kennedy Space Center.

A total of 36 people will have 5 days of stay in total for travel in an FY. Although, during FY 6 there is no projected travel, it has been included in the budget estimations.

A roundtrip ticket costs $400 (“Travel Resources” 2024), and the maximum flight ticket has been determined to illustrate the maximum travel cost.

A hotel is $270 a day. The hotel price has been found to be the maximum for Greenland, Maryland (“FY 2024 per Diem Rates for Greenbelt, Maryland” 2024).

According to the American Driving Survey: 2022, the average miles driven for work is estimated to be 20.0 miles (“American Driving Survey: 2022” 2023). The “Standard mileage rates for moving purposes” is determined to be $0.21 for each mile (“Privately Owned Vehicle (POV) Mileage Reimbursement Rates” 2024). From this data, the maximum for a daily trip is determined to be $20, including necessary public transportation.

Daily spending for food is calculated as $100 and breakfast or dinner for the extra day is calculated as $50. Another $200 will be given to the personnel for any personnel travel needs. A total of $539,863 will be spent on the travel section of the outreach.

5.3.5. Outreach Budget

The outreach activities have been planned to promote the mission according to the past successful mission outreach plans. The outreach cost is 0.98% of the total cost with a total of $1,726,452. To stay within the budget constraints the planned outreach budget was 1% of the total budget. After the given budget cut from the customer, the budget replanned to stay within the constraint where outreach did not affect the total budget overall. The total budget can be seen in Table 32.

Table 37 Outreach Budget

OUTREACH							
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative**
Total Outreach Materials	$ 10,000	$ 363,413					**$ 373,413**
Total Outreach Venue Costs	$ 50,000			$ 50,000			**$ 100,000**
Total Outreach Travel Costs	$ 19,890	$ 19,890		$ 19,890			**$ 59,670**
Total Outreach Services Costs	$ 5,000	$ 5,000					**$ 10,000**
Total Outreach Personnel Costs	$ 567,980	$ 567,980					**$ 1,135,960**
Outreach Margin	$ 6,529	$ 9,563	$ -	$ 699	$ -	$ -	**$ 16,790**
Total Outreach Costs	$ 659,399	$ 990,958	$ -	$ 76,095	$ -	$ -	**$ 1,726,452**

One of the expenses that is expected is the personnel cost for the outreach activities. The total cost and the number of personnel can be seen in Table 38. Total of 9 personnel with the average salary for each profession is to be calculated as $567,980 a year.

Table 38. Salary of Personnel

Personnel Responsibility	# of Personnel	Salary
Photographer	1	$40,760 (U.S. Bureau of Labor Statistics 2023)
Camera Operator	2	$65,070 (U.S. Bureau of Labor Statistics 2023)
Social Media Manager	1	$56,770 (U.S. Bureau of Labor Statistics 2016)
Moderator	1	$57,300 (U.S. Bureau of Labor Statistics 2020)
Instructional Coordinators	1	$77,200 (U.S. Bureau of Labor Statistics 2023)
Outreach Manager	1	$77,030 (U.S. Bureau of Labor Statistics 2023)
Teacher Trainer	2	$64,390 (U.S. Bureau of Labor Statistics 2023)
Total	9	$567,980

As it can be seen the outreach will be working for two fiscal years to ensure the other costs are covered in the mission. There will be two conferences, the first one before the launch date. This is estimated to be in July 2028. The second one will be in Phase E to discuss with the public about the findings and will be held in July 2029. The conferences will include the science objectives, progress, and mission results. Conferences are projected to be $50,000 for one venue.

For the conferences, media, and educational purposes the travel budget was calculated using the highest per diem, and flight prices. A total of 9 people will have 4 days of stay in total for travel in an FY. The cost estimations are followed by the travel budget sources. Three FY will be projected to be traveled throughout the mission timeline. A roundtrip ticket costs $400, a hotel is $270, and transportation is $100. Daily spending for food is calculated as $100 and breakfast or dinner for the extra day is calculated as

$50. Another $200 will be given to the personnel for any personnel travel needs. A total of $59,670 will be spent on the travel section of the outreach.

Merchandise will be published for the public to buy mission-related stuff. 58,000 materials will be ordered and will be sold. These materials will be promoted on social media accounts. The costs are determined by wholesale brands. Table 39 represents the number of orders and the cost of the order. A total of $363,413 will be spent on the merchandise.

Table 39. Merchandise order and cost

Good	Wholesale Cost with Print	Order Size	Cost	Sell Price
T-shirt	$6.67 (“RushOrderTees Classic T-Shirt | Design Online” 2024)	2,500 for each S, M, L, XL 2,000 for each 2XL, 3XL	$93,420	$24.99-30.99
Hoodie	$20.53 (“Custom Gildan Heavy Blend Hoodie | Design a Hoodie Online” 2024)	2,500 for each S, M, L, XL 2,000 for each 2XL, 3XL	$287,420	$40.99-60.99
Hat	$10.52	4,000 for each S/M and M/L 2,000 for each L/XL	$63,100	$17.89-37.59
Pins	$0.64	20,000	$12,800	$4.00-7.25
Total			$363,413	

5.3.6. Direct Costs

The direct costs of the rover are allocated a large part of the budget. Currently, around 35% of the total mission budget is allocated to direct costs, and the breakdown between systems will be further discussed below.

The cost of specific components is based on a few methods. Some components that can be found in COTS have prices listed by manufacturers. Otherwise, NICM formulas are used to estimate prices based on mass and power draw. Additionally, all costs listed here are adjusted for inflation, whether that be 2004 (for components estimated with the NICM formulas), or another year (depending on when the component was contracted).

Table 40. Direct Costs Table

System	Component	2004 Dollars	2024 Dollars
Mechanical	Chassis	$500,000.00	$830,400.00
	Drive Train	$1,240,000.00	$2,059,392.00
	Suspension	$5,632,627.22	$9,354,667.29
	Wheels	$250,000.00	$415,200.00
			$0.00
			$0.00
		Total	$12,659,659.29
Power	Batteries	$250.00	$415.20
	Power Distribution Unit	$250,000.00	$415,200.00
	Solar Panels	$800,000.00	$1,328,640.00
			$0.00
		$1,050,250.00	$1,744,255.20
		Total	$3,488,510.40
Thermal	ACT HP	$5,000,000.00	$8,304,000.00
	Heater	$10,000.00	$16,608.00
	Radiators	$3,032,789.00	$5,036,855.97
	MLI	$20,000.00	$33,216.00
	Paint	$10,000.00	$16,608.00
		Total	$13,407,287.97
CDH	CPU	$300,000.00	$498,240.00
	Antennas	$200,000.00	$332,160.00
	Memory	$25,000.00	$41,520.00
	Transcievers	$300,000.00	$498,240.00
			$0.00
			$0.00
		Total	$1,370,160.00
Nav	SQRLi	$427,863.00	$462,092.04
			$0.00
		Total	$462,092.04
Science	TRIDENT	$4,800,000.00	$6,096,000.00
	Sampling Suite	$7,930,000.00	$10,071,100.00
	Sample Arm	$1,000,000.00	$1,660,800.00
	SQRLIx2	$855,366.00	$923,795.28
		Total	$18,751,695.28

For the power and CDH subsystems, the “Electronics subsystem” NICM formula was used. For the Thermal subsystem, the “Thermal Subsystem” NICM formula was used. For the Mechanical subsystem, the “Mechanical/Structures Subsystem” NICM formula was used.

For the Chassis, because it had no power draw, the cost was estimated based on price of material plus manufacturing costs. The team used similar methods to estimate the costs of thermal paint, and MLI.

For scientific and navigational components, the team used actual quotes (not requested by the team), because the team believed they represented the cost of the components more accurately.

5.4. Scope Management

5.4.1. Change Control Management

When the team receives feedback from stakeholders on a deliverable, any requests for change are registered as RFAs or ADVs. Often, these are related to a specific section of a deliverable or a certain system, and those working on that section or system address the request. By the next deliverable, any requested changes will have been made, and a table of all requested changes are listed in the appendix. (Appendix A)

Additionally, if a person believes the mission should be modified, they can refer it to their system, and systems related by the change. The risk of the change will also be assessed before being proposed to a Change Control Board (CCB). The CCB involves the team presenting and defending their suggested change to a board of stakeholders and experts in the subject. This will result in the change eventually being denied or accepted by the CCB.

When a change is performed, or a metric re-assessed, the team member that made the change would bring it up to the rest of their team / system. Additionally, any systems that need the updated information (commonly budget & risks) will also be notified of the change. This can occur within the weekly general meeting, or occur on text. Of course, if the change conflicts with other plans, there will be a discussion about the change, often requiring an additional meeting with involved members.

5.4.2. Scope Control Management

The Lunar Vanguard mission has already gone through a descoping. The original budget of $225 Million was lowered to $175 Million, all online members began planning immediate changes. At this point, the mission was already severely under budget, but because the budget was assumed to increase, the team still decided to descope the mission objectives. Redundant components from the rover and payload were removed and additional budget was taken out of the outreach section. The team logged the increased risk these changes would bring, and continued with changing the mission.

Of course, the mission continued to change after the downscoping. Once the team reassessed the costs of rover components and approached final estimates, the mission had been found to be severely over budget. In this scenario, one person reached out to the engineers designing expensive systems, and requested that the system is made cheaper. The engineers responded with suggestions, and the team eventually came back to a design that was within our expected budget. Part of this took place in the team's general meetings, where any member can talk to the entire team, make requests, and ask questions. In the future, a similar process would be followed when changes must be made between subteams.

If the team is making a change in scope that is not suggested by a stakeholder, a change request must be made. When this change is requested, the team will attend a CCB, along with relevant experts in the topic. Through the CCB, the team will defend their change decision,

5.5. Outreach Summary

The team has developed a multifaceted strategy to enhance public awareness during the first two years of the mission. Within the constraints of the allocated outreach budget, the team will optimize efforts to maximize appreciation of the mission

The target groups have been separated into three categories and subcategories:

- Education
    - Young Learners

  - Parents
  - Educators
- Scientists & Engineers
- Public
  - General Public
  - Space Enthusiast

Each category has its own unique approach for utilizing material from outreach activities. To meet the projected demands of these activities, nine additional personnel have been added to the team, each assigned to a different area.

Table 41. Outreach Personnel Counts

Personnel	# of Personnel
Photographer	1
Camera Operator	2
Social Media Manager	1
Moderator	1
Educational Planner/Consultant	1
Outreach Manager	1
Teacher Trainer	2
Total	9

One of the initial activities to increase mission awareness is the creation of a school curriculum designed to teach the necessity of the mission. This curriculum will feature tailored content for different age groups.

Table 42. Different levels of curriculum plan

Education Level	Curriculum
Elementary School	• Animation about the mission • A little overview of the mission using little to no terminology
Middle School/High School	• Overview of the mission • Usage of similar scientific ways to connect into the class environment • Establishment of an experiment related to the science objective of the mission
High School/College	• Technical document on how a rover can be designed in little details • Focused class methodology on science and engineering • Design/Build competition in a class environment using materials from the classroom and writing a document related to their design of a rover as an end-of-the-year project. This can also include 3D designs as well as programming.

An educational planner and two teacher trainers will be primarily responsible for developing and training teachers and community groups on the mission-related materials, as detailed in Table 41. Each educational level will have its own set of challenges and time schedules tailored to the mission's various aspects. The majority of the curriculum's focus will be on high school and college students, who will learn about the processes involved in designing a rover for the mission. This will help students understand the mission's underlying rationale. Ultimately, the curriculum will culminate in a competition where students design a rover, either through small physical models or in 3D models.

This outreach initiative aims to impact students, parents, and educators across all educational levels. Initially, only a few schools will plot the curriculum, but the program will eventually expand to all community educational institutions, serving the entire community, including minority groups. To enhance awareness among underrepresented groups, teacher training will prioritize these communities, fostering education in future innovations as part of the Artemis generation. While reaching out to underrepresented communities, information and detailed descriptions of the mission will be available for visually impaired with audio. For the people with hearing problems, subtitles and ASL interpreters will be available. This focus will align with the mission's goal of promoting inclusivity and ensuring that the benefits of the mission reach all segments of society.

Educational planners will also accumulate data from schools and their impact. During the first two fiscal years, it is projected to reach 102 educational institutions across the U.S. Table 42 illustrates the projected numbers while Figure # and Figure # demonstrate the projected participants throughout the mission with an educational plan. It is projected to impact 847 educators, and 40,402 students during the mission process with the educational plan.

Table 43. Projected Numbers

	School Number	Administrators in Each School	Teacher in Each Schools	# of Students in Each School
Elementary Schools	29	2	8	11,223
Middle Schools	26	2	6	6,292
High Schools	35	3	10	20,055
University	12	5	3	2,832

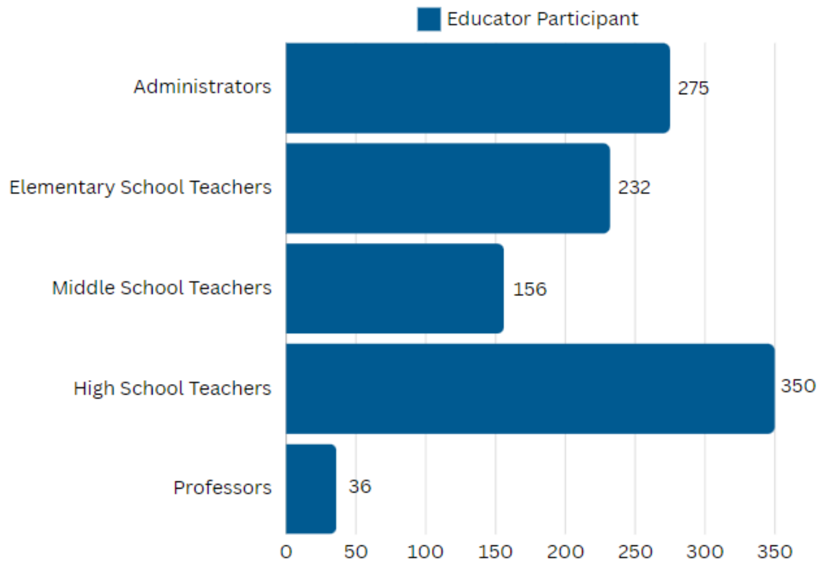


Figure #27. Educator Participant Numbers

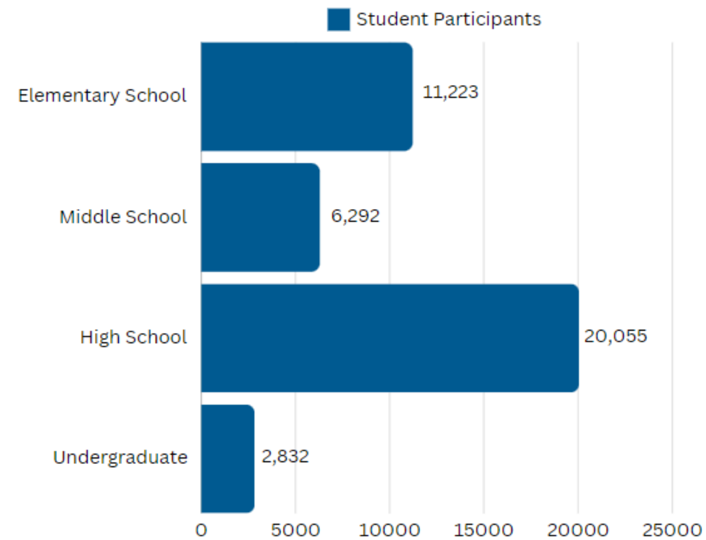


Figure #28. Participant Numbers

As the education plan expands, an outreach manager will organize competitions for high school and college students, creating research opportunities for them to engage with the mission. While this competition will impact mostly on students, research opportunities will be available through third-party companies such as Bay Area Environmental Research Institute and university labs. Some universities will utilize resources from scientists and engineers from different industries to work on some research topics that need to be addressed but have been put off to meet customer launch date. Through including current scientists and engineers of the workforce into collaboration with the colleges, this will create a dynamic to prepare the next generation of innovators as well as involving the STEM community in the process of the mission. This helps to gather more information relevant and helpful for the future missions. An example of these can be illustrated in science:

> Research more Carbon Hydrogen Oxygen and Nitrogen (CHON) containing volatiles through stable isotopes to get a better and more encompassing understanding of lunar volatile origins.

The outreach manager will also oversee two conferences during the first two fiscal years to promote the mission both in person and online related to the science objectives of the mission. This conference will be aired on NASA's Youtube account and on NASA TV for the general public to watch.

A social media manager, along with other professionals such as photographers, camera operators, and moderators, will be integral to this stage. These individuals will work at the conferences, with the photographer and social media manager specifically tasked with promoting the mission on platforms such as Instagram, YouTube, Facebook, Twitter, and LinkedIn. Each platform has its own unique audience, and the social media team will analyze and develop a tailored schedule to maximize engagement.

The outreach activity is measured by the interactions over social media and streams. Outreach manager will be responsible for gathering the data. It is projected to have an engagement of 248 million from NASA Official/NASA Artemis social media accounts and mission specific accounts.

Table 44. Major Post Schedule

Date	Post Caption/Themes	Post Goal
9/30/2024	A mystery in progress!	This will announce to the general public a way to

	A new mission has just entered a new phase. Can you find what the Artemis generation is up to? #NASA #newphase #artemisgeneration	interact with them. Through utilizing a question, people can predict the mission name and search through NASA.
11/1/24-9/1/25	Announcement of the mission in a public manner. Series of information about PSR will be available.	Lunar Vanguard mission will be known by everyone. Followed by series of information about lunar surface and PSRs, it will help people to understand the general objective of the mission.
9/2/25-6/30/28	Photos from building facilities and interviews from engineers and scientists.	This will show the general public the progress.
7/1/28-9/10/28	Posts about launch! As the day will get closer, the intensity of the posts will increase to increase the spirit for the mission.	More engagement will public about the mission and launch will increase the awareness of Lunar Vanguard mission.
9/30/28-3/29/30	Information and photos from the mission will be available and will be posted. The findings will become available through interviews done for the social media and NASA website.	It will illustrate the progress of the mission and the results.

Outreach personnel will work to promote the mission to the general public and space enthusiasts. For the broader population, activities similar to those from the Mars Perseverance mission will be implemented (NASA 2020b). A competition will be held for students across America to name their rover, involving an essay and video challenge. Students will explain their reasons and motivations for their proposed names in these essays.

Additionally, the mission will incorporate recent NASA initiatives that allow individuals to send their names to space (NASA 2021), further engaging the public and fostering a personal connection to the mission.

There will be tours in the Goddard Space Flight Center during the building process of instrumentations. The outreach efforts will also include mission-specific merchandise and patches. These merchandise will be available after the tours as well. In the second fiscal year, this merchandise will be made available in NASA stores for the public and space enthusiasts to purchase. A total of 58,000 different merchandise items will be produced and sold throughout the mission. The total cost for the merch and personnel can be found in the Outreach budget section. The merch will include the following patch that is designed by the team:

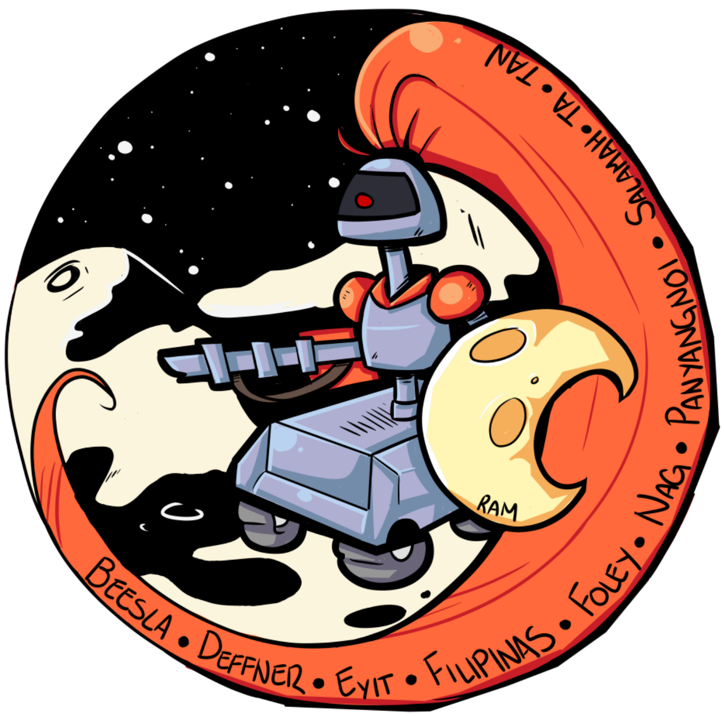


Figure #29. Lunar Vanguard Mission Patch

The patch has been implemented into several merch designs that the mission will provide to the public.

Figure #30. T-Shirt Merch

Figure #31. Hoodie Merch

6. Conclusion

Lunar Vanguard is a discovery-class rover mission that aims to investigate the origin and composition of volatile substances located in a permanently shadowed region (PSR) at the lunar south pole in the area known as the Amundsen Rim.

The next steps for the team is to get the PDR reviewed and accepted, or edited and re-submitted. Next, the mission will enter phase C, begin working on the CDR (Critical Design Review), which will be the last major milestone before beginning fabrication. In order to complete this, every system must be inspected in additional scrutiny, the team would gather direct quotes for components instead of estimations, and begin producing outreach material.

Given additional time, the team would've reconsidered many technical decisions in order for the rover to fit more within basic requirements. Additional interfaces between systems would be considered, and budgets corrected.

Generative AI Statement:

While preparing this document, Lunar Vanguard utilized ChatGPT and QuillBot to rephrase the original statements drafted by the team. This approach enhanced the overall professionalism and academic tone of the sections. Following the use of these tools, the team conducted thorough editing and assumed full responsibility for the content in this deliverable.

In addition to ChatGPT and QuillBot, Lunar Vanguard employed Perplexity.AI to search for relevant scientific papers. This allowed the team to access credible sources that could be easily cited and provided valuable insights for the sections. After utilizing Perplexity.AI, the team conducted a comprehensive background check on each paper and assumed full responsibility for the content in this deliverable.

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Generative AI Statement:

While preparing this document, Lunar Vanguard utilized ChatGPT and QuillBot to rephrase the original statements drafted by the team. This approach enhanced the overall professionalism and academic tone of the sections. Following the use of these tools, the team conducted thorough editing and assumed full responsibility for the content in this deliverable.

In addition to ChatGPT and QuillBot, Lunar Vanguard employed Perplexity.AI to search for relevant scientific papers. This allowed the team to access credible sources that could be easily cited and provided valuable insights for the sections. After utilizing Perplexity.AI, the team conducted a comprehensive background check on each paper and assumed full responsibility for the content in this deliverable.

Appendix A - Table of Changes

RFA ID	PDR Section #	Action
MDR-RFA-1	1.4	Expanded upon the narrative in the mission requirements section.
MDR-RFA-2	2.1.x.4	This section has been moved out of table format, and added back as narratives.
MDR-RFA-3	4.1.1	Added a section describing how RIDM and CRM is used in the mission.
MDR-RFA-4	4.1.3	Added information about OSMA and OSHA
MDR-RFA-5	5.3.3	Directly Added Budget Template.
MDR-RFA-6	5.3.6	Added Excerpt from Budget Template.
MDR-RFA-7	5.4.1	Added an actual change control plan for the team.
MDR-RFA-8	5.4.2	Added an actual scope control plan for the team, described previous descoping procedure.
MDR-RFA-9	5.5	Elaborated on outreach activity metrics.
MDR-RFA-10	5.5	Added information about how the team's planned outreach activities will be accessible to non-native english speaking communities, and those with disabilities.
MDR-RFA-11	6.	Provided more information about how the team will move on into PDR Reviews, CDR, and fabrication.
MDR-ADV-1	1.4	Assessed requirements.
MDR-ADV-2	4.1.1	Added updates for all risks.
MDR-ADV-3	5.3.4	Provided sources & re-assessed travel costs.
MDR-ADV-4	5.5	Added additional merch examples as visuals.
MDR-ADV-5	5.5	Created a posting schedule.

Appendix B - Supplementary Subsystem Information

Mechanical Subsystem

Trade Studies

Wheels						
Criteria	**Explanation**	**Grade**	**Weight**	**Mecanum Wheels**	**Aluminum Wheels**	**Omni Wheels**
Weight	The wheels can't be too heavy or else the rover might exceed the weight limit	10 = light weight 0 = heavy weight	10%	9	8	10
Cost	The wheels can't be very expensive or else they will go over budget	10 = cheap, doesn't effect the budget 0 = expensive, effects the budget	15%	8	6	9
Traction	The wheels need to grip the ground to be able to move the rover	10 = can move on inclines of up to 15 degrees and on any lunar surface 5 = can move on parts of the lunar surface and no steep inclines 1 = can only move on flat ground 0 = cannot move on the moon's surface	25%	8	10	5
Maneuver ability	How well the wheels are able to move about the lunar surface	10 = can move and turn in all directions effectively 5 = can only partially move in certain directions or turn	30%	7	9	6

		0 = can't move or turn				
Strength	How much weight can be carried by the wheels	10 = can support the rover while traversing the lunar surface 0 = can not properly support the rover	20%	7	10	6
		TOTALS:	**100%**	79.50%	81.00%	73.50%

Chassis						
Criteria	**Explanation**	**Grade**	**Weight**	**Steel**	**Galvanized Steel**	**Aluminum**
Weight	The overall system can't exceed a weight of 85kg. It is important to pick a metal that is not too heavy since other parts of the robot such as the science tools will weigh a lot.	10 = overall weight of the system and of the metal is equal to or less than 85kg 0 = overall weight of the system and of the metal is more than 85kg	15%	6	6	9
Durability	The metal must be resistant to wear, deformation, and fracture while performing its mission on the moon.	10 = metal can resist damage and has a high strength 5 = metal can resist some damage 0 = metal easily breaks	35%	8	8	7

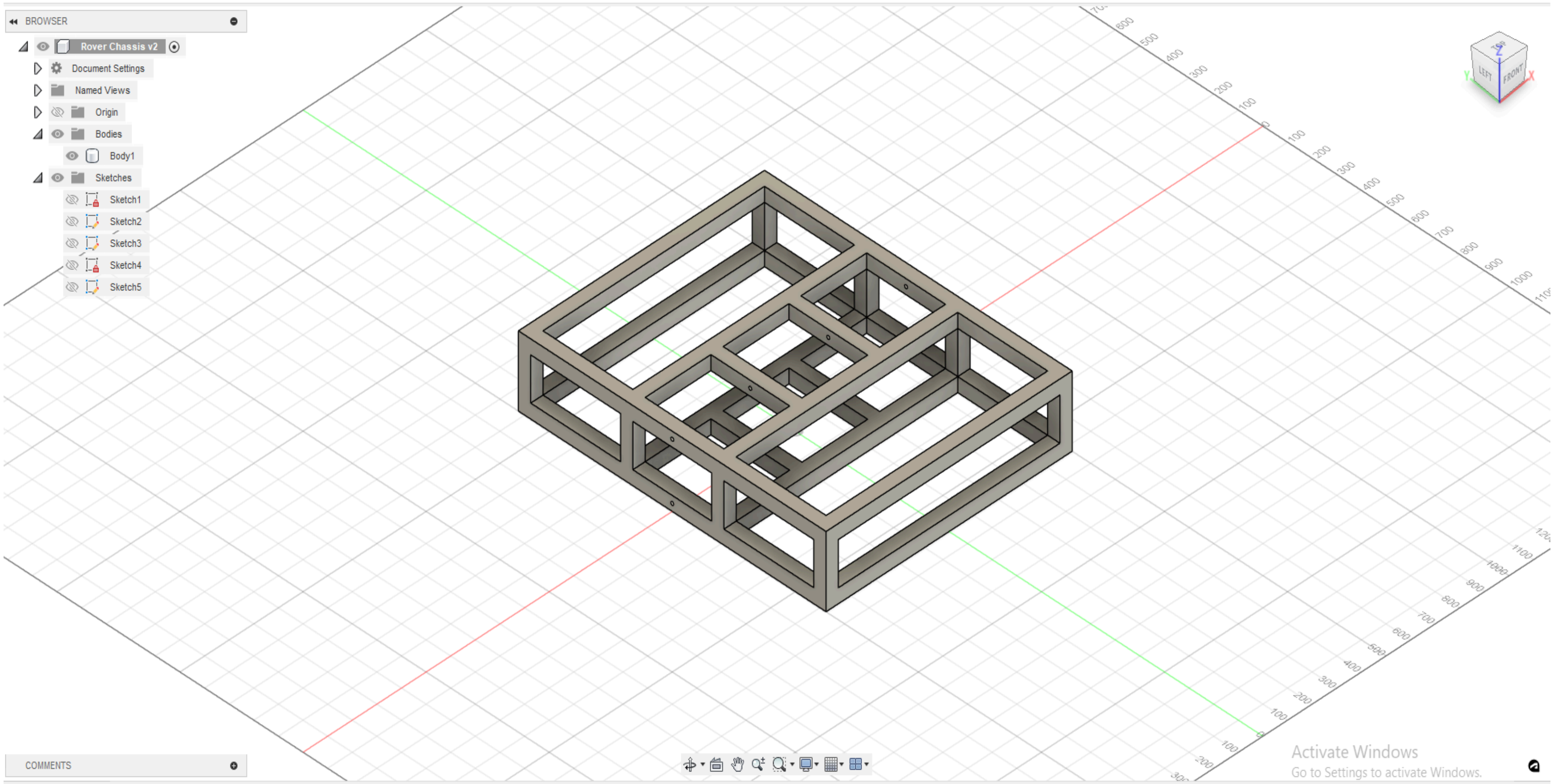
Ductility	The metal must be able to deform (bend or stretch) before breaking, since the temperature on the moon is very low, materials tend to be more brittle and thus break more easily/ suddenly.	10 = the material is ductile and easy to shape 0 = the material is brittle and can't be shaped	30%	6	7	10
Cost	Cost of material is important for the budget.	10 = cheap which doesn't affect the budget 0 = too expensive which strains the budget	20%	8	7	6
		TOTALS:	**100%**	71.00%	72.00%	80.00%

Suspension						
Criteria	**Explanation**	**Grade**	**Weight**	**Rocker-Bogie Suspension**	**Torsion Bar Suspension**	**Independent Suspension with Coil Springs**
Weight	The suspension can't be too heavy or else the rover might exceed the weight limit	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	8	6
Cost	The suspension can't be very expensive or else they will go over budget	10 = high, 5 = medium 1 = low 0 = Fail	15%	6	7	7

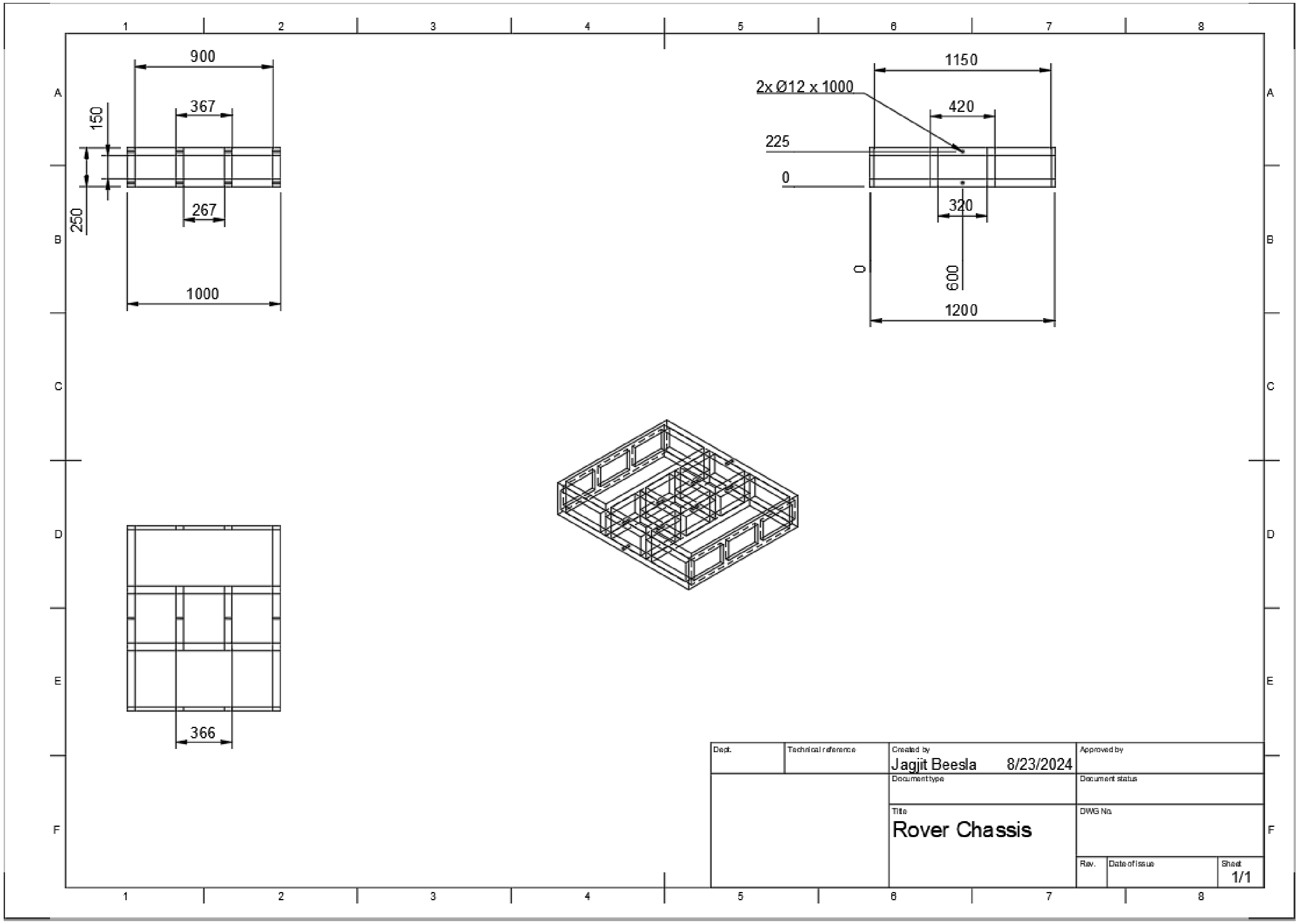
Suspension						
Criteria	**Explanation**	**Grade**	**Weight**	**Rocker-Bogie Suspension**	**Torsion Bar Suspension**	**Independent Suspension with Coil Springs**
Weight	The suspension can't be too heavy or else the rover might exceed the weight limit	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	8	6
Terrain Adaptability	The suspension system must be able to navigate obstacles on the lunar surface like craters, rocks, and loose regolith efficiently and maintain stability	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	7	8
Thermal Resistance	Suspension must be able to function reliably across the moon's extreme temperature ranges without failure	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	7	7
Dust and Contamination Resistance	The suspension system must be designed to minimize dust ingress and withstand abrasion. Effective sealing mechanisms are necessary to prevent dust from entering critical components and to protect moving parts	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	7	6
		TOTALS:	**100%**	77.50%	71.50%	71.50%

Drivetrain						
Criteria	**Explanation**	**Grade**	**Weight**	**Maxon BLDC ECX T22 Motors & GPX 26 Planetary Gears**	**Maxon DC GPX70 Planetary Gearbox & IDX70 Motors**	**Maxon DC GPX52 Planetary Gearbox & IDX56 Motor**
Weight	The system can't exceed 85 kg. Selection of the motors weight is important since it may slow down the rover while mobile	10 = low 5 = medium 1 = heavy 0 = Fail	15%	8	3	6
Cost	The cost of the system is important for remaining inside the budget.	10 = high 5 = medium 1 = low 0 = Fail	20%	7	5	6
Torque Efficien cy	High torque and low power input are ideal for the longevity and durability of the drivetrain system	10 = high, 5 = medium 1 = low 0 = Fail	25%	3	9	8
Durabili ty	Can the Motors withstand lunar night and day, and the terrain of the lunar surface.	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	7	7
Reliabili ty	Motors must be reliable to maintain mobilization for the duration of the mission	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	7	7
		TOTALS:	**100%**	61.50%	65.00%	69.00%

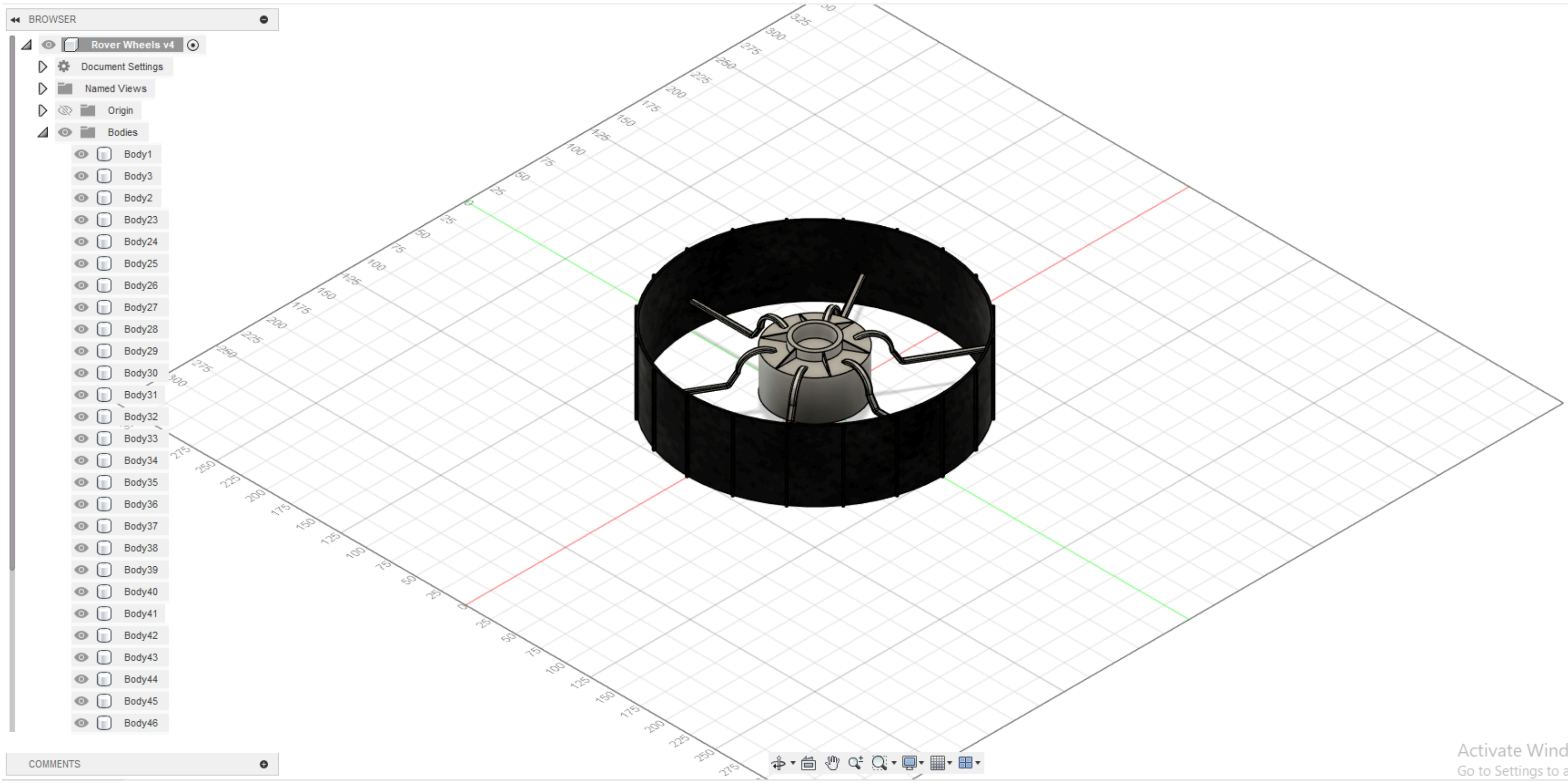
CAD Models



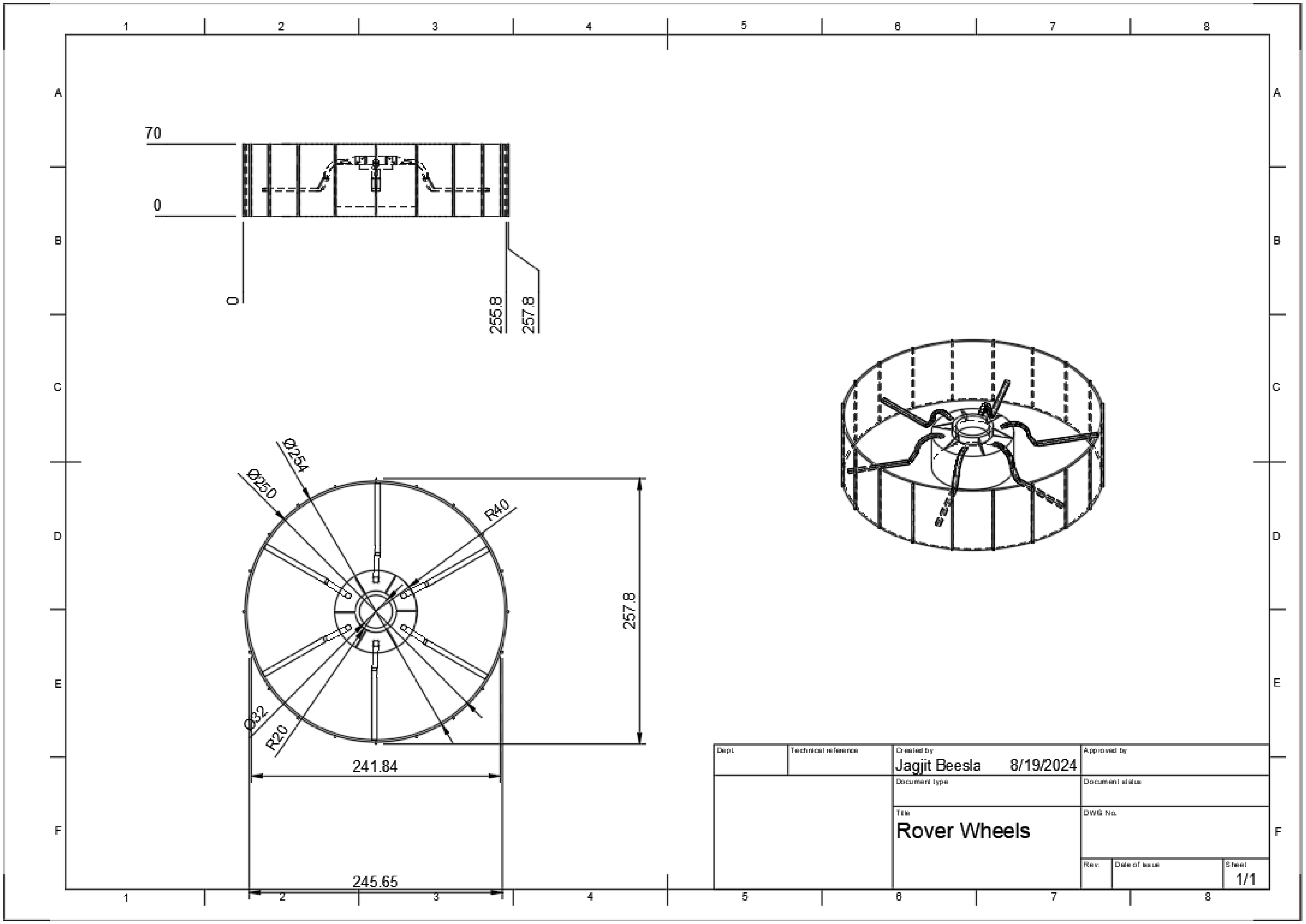
Rover Chassis



Chassis Drawing



Rover Wheels



Rover Wheels Drawing

Power Subsystem

Power Storage (Li-ion batteries)							
Criteria	**Explanation**	**Grade**	**Weight**	**Panasonic NCR18650GA**	**LG Chem LG18650 MJ1**	**EnerSys-ABSL CM1040 Lithium-ion Batteries**	**EaglePicher Rechargeable Lithium-Ion Batteries**
Energy Density	The battery must have high energy density to ensure long operational periods	10 = greater than 200 Wh/kg 5 = 150-200 Wh/kg 1 = less than 150 Wh/kg	25%	9	10	8	8
Temperature Tolerance	The battery must be able to function efficiently in extreme lunar temperatures (23-100K)	10 = Full range 5 = Partial 1 = Limited	15%	5	4	7	5
Cycle Life	Number of charge/dishcharge cycles before significant capacity degradation	10 = more than 1000 cycles 5 = 500-1000 cycles 1 = less than 500	20%	7	7	8	8

		cycles					
Efficiency	Charge/discharge efficiency impacting overall energy utilization	10 = >95% majority of energy generated from solar panels effectively stored with minimal loss 5 = 90-95% efficiency 1 = <90%	20%	9	9	9	9
Safety and Reliability	Safety features and reliability in preventing issues like thermal runaway	10 = highly reliable 5 = moderately reliable 1 = low reliability	20%	9	9	9	9
		TOTALS:	**100%**	62.00%	63.00%	64.50%	61.50%

Integrated Avionics Unit (IAU)

Criteria	Explanation	Grade	Weight	Moog IAU	Honeywell Primus Epic 2.0 IAU
Efficiency	Minimizing energy loss during transmission will help to maximize the utilization of generated power and extend the operational periods of the rover	10 = High 5 = Medium 1 = Low	25%	9	8
Reliability	Consistent power delivery without disruptions is essential in avoiding mission failure and maintaining continuous operation	10 = High 5 = Medium 1 = Low	25%	9	9
Compatibility	Compatibility with existing rover subsystems and instruments helps to minimize the need for additional modifications	10 = High 5 = Medium 1 = Low	20%	9	8
Complexity	How intricate the power distribution system is. Simpler systems are preferred since they are easier to implement and maintain	10 = Simple 5 = Moderate 1 = Complex	15%	8	7

Cost	The cost of the power distribution is important for maintaining budget	10 = Low 5 = Medium 1 = High	15%	7	7
		TOTALS:	**100%**	68.00%	63.50%

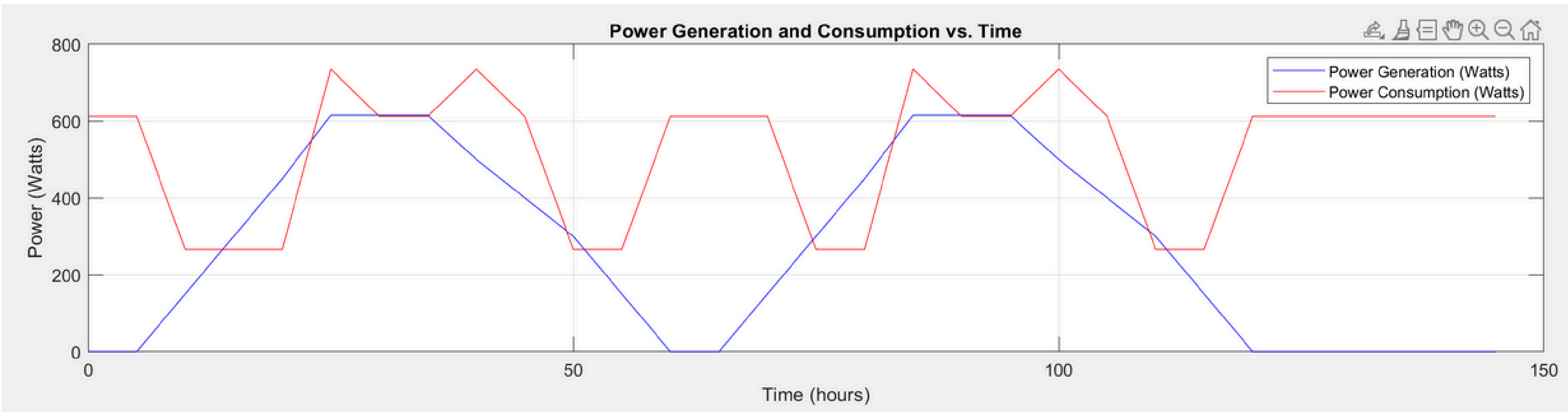
Power Generation					
Criteria	**Explanation**	**Grade**	**Weight**	**XTJ Prime Triple Junction Solar Cells**	**Azur Space 3G30 Triple Junction Solar Panels**
Energy Output	Total energy generated to ensure that rover has sufficient power for all operations	10 = High 5 = Medium 1 = Low	30%	10	9

Reliability	Consistency of power generation in lunar conditions	10 = High 5 = Medium 1 = Low	15%	9	8
Lifespan	The power generation system must ensure that the rover can last the entirety of the missions duration	10 = Long 5 = Medium 1 = Short	25%	9	8
Durability	The power generation system must withstand the harsh lunar environment, such as extreme temperatures and dust	10 = Simple 5 = Moderate 1 = Complex	15%	9	8
Cost	The cost of the power generation system is important for budget constraints	10 = Low 5 = Medium 1 = High	20%	7	6
		TOTALS:	**105%**	70.50%	62.50%

Power Distribution Unit (PDU)

Criteria	Explanation	Grade	Weight	Vicor DC-DC Converters	Pumpkin Space EPSM 1 PDU	GE Aviation PDU	Artesyn DC-DC Converters
Efficiency	Manage and distribute power with minimal losses	10 = <5% power lost as heat or other forms of energy dissipation 5 = ~5-10 % power loss 1 = >10% power loss	30%	9	8	9	9
Reliability	Dependability in continuous operation without failures	10 = failure rate <1% 5 = failure rate 1-5% 1 = failure rate >5%	25%	9	8	9	8
Scalability	Adaptability to different mission needs	10 = easily adaptable for various mission needs 1 = Not scalable, PDU has a rigid design	15%	8	9	8	9

Lunar Tolerance	Functionality in extreme temperatures and radiation environments	10 = Full range 5 = Partial 1 = Limited	30%	7	9	8	7
		TOTALS:	**100%**	66.00%	68.00%	68.00%	66.50%



Power (Wh) vs Time (h) Plot

Cycle Length: Moon experiences a day-night cycle called Lunar day last about 29.5 Earth days.

One Lunar night/day: About 14.75 Earth days.

Daytime Phase: → Lunar day (14.75 Earth days) rover can perform all active operations and powered by solar energy.

Nighttime Phase: → Lunar night (14.75 Earth days) Solar energy is unavailable. Rover must rely only batteries energy to performance on the moon or alternative power source such as radioisotope thermoelectric generator (RTGs)

Phase Within each Cycle

Mobility:

- *Daytime Phase:* Optimal for rover movement and exploration. Rover can traverse from origin to destination site.

- *Nighttime Phase:* Mobility should be restriction caused by lack of solar energy source, limited power, crutial low temperature.

Instrumentation:

- *Daytime Phase:* Perfect for deploying instruments, collecting data and conducting experience, leveraging solar energy.

- *Nighttime Phase:* limited the instrument operation due to limited power available.

Communication:

- *Daytime Phase:* Direct communication with Earth is feasible, depending on the rover's line of sight to relay satellites or Earth.

- *Nighttime Phase:* Communication may be more challenging due to limited power, low temperature.

Energy Generation Significant Factors

System Factors:

- **Array Size:** Larger solar arrays can capture more sunlight, but they must be balanced against weight and space constraints.
- **Cell Efficiency:** High-efficiency solar cells will maximize energy capture, especially during the short periods of sunlight.
- **Side Mount:** Solar arrays mounted on the sides of the rover can potentially capture light at low sun angles but may be less effective when the Sun is directly overhead.
- **Array Tilt:** Adjustable solar arrays can optimize energy capture by tilting toward the Sun, particularly as its angle changes during the lunar day.

Environmental Significant affect Factors:

- **Orbital Inclination:** Affects the angle and duration of sunlight the rover receives. The Moon's orbit around the Earth and the Earth's orbit around the Sun create variations in sunlight exposure.
- **Latitude:** The rover's Latitude of the moon will determine the angle and duration of sunlight received. Areas near the poles may experience long periods of sunlight or shadow.
- **Distance from the Sun:** The average distance of the Moon from the Sun is relatively constant, so this has minimal impact on energy generation.
- **Shadows:** Nearby terrain (craters, mountains) can cast shadows, reducing sunlight exposure. Planning must consider the topography of the landing site.
- **Atmosphere:** The Moon lacks a significant atmosphere, so there is no atmospheric scattering or attenuation of sunlight.

- **Eclipse:** Lunar eclipses, where Earth blocks sunlight from reaching the Moon, are rare but can affect energy generation for brief periods.

Calculating Power Draw:

- Max power draw for mechanical is about 100W. Max radial load is 900N

- 40W from power subsystem

- 125W from thermal

- 126.3W (CDH) + 100W (Mech) + 40W (Power) + 346W (Payload) = 612.3W (total)

KEY INFO:

- About **63 hours** of traversing to get to Amundsen A (PSR)
- Sunlight received **40-50%** of sunlight per lunar day at Amundsen rim
    - 1 moon day = 29.5 Earth days | 11.8 - 14.75 earth days w/sunlight
- Max rover weight: **85 kg**
- Moon gravity: **1.62 m/s^2**
- Rover Speed: 1 km/hr = about **0.2778 m/s**
- Max slope of **10 degrees**
- Rolling resistance estimate: **0.15 (Crr)**

    - Estimate based on Apollo 15 mission tests conducted on earth and lunar surfaces, average resistance ranged from 0.1 - 0.2
    - https://ntrs.nasa.gov/api/citations/19730008090/downloads/19730008090.pdf
- Power = Force x Velocity

EnerSys ABSL CM1040 Lithium-Ion Battery:	XTJ Prime Solar Cells:
Capacity: 36 Ah Voltage Range: 24.0V - 33.6V Energy Storage 1066 Wh per battery Possible 30% battery efficiency drop in extremely cold lunar conditions 1066Wh x 0.7 = 746.2 Wh per battery w/bad lunar conditions	Output Voltage: 0.76V - 2.406V Cell Efficiency 26.7% Standard Cell Size: 27cm^2 - 84cm^2 Mid range efficiency: 135.3mW/cm^2 Power per cell: 55.5cm^2 x 135.3mW/cm^2 = about 7.51W/cell Total Solar Cells Needed: $\frac{612.3\ W}{7.51\ W/cell}$ = 82 cells Possibly 20% or more reduction in cell efficiency if dust accumulation occurs/not enough sunlight 612.3W x 0.8 = 489.84W generated w/bad conditions

`

CALCULATION FOR TRAVERSING

126.3W (CDH) + 100W (Mech) + 40W (Power) = 266.3W

266.3W x 63hr = 16,776.9 Wh (total)

82cells x 7.51W/cell = 615.82W generated by cells

Duration on Battery Alone:

$\frac{1066\ Wh}{266.3\ W}$ = about 4 hours, then would need to recharge (assuming good lunar conditions)

$\frac{746.2\ Wh}{266.3\ W}$ = about 2.8 hours, then would need to recharge (assuming bad lunar conditions)

Recharge Time:

$\frac{1066\ Wh}{615.82\ W}$ = about 1.73 hours to recharge battery fully (assuming good lunar conditions)

$\frac{1066\ Wh}{489.84\ W}$ = about 2.2 hours to recharge battery fully (assuming bad lunar conditions)

Considering Weight/slope stuff:

85kg (max rover weight) x 1.62m/s^2 (moon gravity) = 137.7N (rover weight on moon)

137.7N (rover weight) x sin(10) (max slope rover will encounter) = about 23.91N (gravity w/slope)

0.15 (rolling resistance) x 137.7N (rover weight) = about 20.66N (needed to overcome rolling resistance)

Total required force going uphill: 23.91N + 20.66N = 44.57N

Total required force going downhill: 20.66N - 23.91N = -3.25N (negative bc gravity helping rover move downhill)

Power consumption on flat ground: 20.66N (resistance) x 0.2788 m/s (rover speed) = about 5.76W

Power consumption uphill: 44.57N x 0.2788 m/s = about 12.43W

Power consumption downhill: -3.25N x 0.2788 m/s = about -0.9061W

CALCULATION FOR SAMPLE COLLECTION

Step 1: TRIDENT Drill (200 W) for 30 minutes.

Step 2: Sampling Arm (30 W) for 10 minutes.

Step 3: Pyrolytic Oven (36 W) for 30 minutes.

Step 4: SAM GC-MS Primary (20 W) and Secondary (20 W) for 60 minutes.

Step 5: Tunable Laser Spectrometer (TLS) Primary (10 W) and Secondary (10 W) for 60 minutes.

Step 6: Data Transmission (SQRLi front and back, 20 W) for 10 minutes.

200 min total;Takes about 3.3 hours for a full cycle

Energy Consumption for Each Step:

1. TRIDENT Drill:
   200W × 0.5 hours = **100 Wh**
2. Sampling Arm:
   30W ×10/60 hours = **5 Wh**
3. Pyrolytic Oven:
   36 W × 0.5 hours = **18 Wh**
4. SAM GC-MS (Primary and Secondary):
   (20W+20W) × 1hour = **40 Wh**
5. Tunable Laser Spectrometer (TLS) (Primary and Secondary):
   (10 W+10 W) × 1 hour = **20 Wh**
6. Data Transmission (SQRLi):
   20 W × 10/60 hours = **3.33 Wh**

- 100Wh + 5Wh + 18Wh + 40Wh + 20Wh + 3.33Wh = 186.33 Wh for payload
- 126.3W (CDH) + 40W (Power) = 166.3W x 3.3 hrs = 548.79 Wh
- 548.79 Wh + 186.33 Wh = **about 735.12 Wh total for entire sample collection cycle**

Cycle Duration on Battery Alone:

$\frac{1066\ Wh}{735.12\ Wh}$ = 1.45 cycle = The rover can go through 1 sample collection cycle before needing to recharge (assuming good lunar conditions)

$\frac{746.2\ Wh\ Wh}{735.12\ Wh}$ = 1.015 = The rover can barely make it through 1 sample collection cycle before needing to recharge (assuming bad lunar conditions)

Recharge Time:

$\frac{735.12\ Wh}{615.82\ W}$ = about 1.2hrs to recharge completely (assuming good lunar conditions)

$\frac{735.12\ Wh}{489.84\ W}$ = about 1.5 hrs to recharge completely (assuming bad lunar conditions)

CDH Subsystem

Trade Studies

Antenna						
Criteria	**Explanation**	**Grade**	**Weight**	**High-gain parabolic dish**	**Medium-gain directional antenna**	**Low-gain omnidirectional antenna**
Communication distance	Orbiting spacecraft must be in the antenna's range	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	10	8
Data rate	How much data can be transported at once (how quickly it can be sent)	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	7	5
Pointing accuracy	The geographical accuracy of the antenna. This will affect how easy it is to receive data from Earth	10 = high, 5 = medium 1 = low 0 = Fail	25%	5	7	10
Power consumption	How much power is required by the antenna to function	10 = high, 5 = medium 1 = low 0 = Fail	15%	6	7	9
Cost	Cost of the antenna. Important to follow budget requirement	10 = high, 5 = medium 1 = low	20%	6	7	9

		0 = Fail				
		TOTALS:	**100%**	72.00%	77.50%	84.00%

CPU						
Criteria	**Explanation**	**Grade**	**Weight**	**RAD750**	**RAD510**	**LEON3/LEON4**
Performance	How fast the CPU can communicate with all functionalities of the rover.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	9	8
Reliability	How well the CPU can maintain proper functionality throughout the length of the mission.	10 = high, 5 = medium 1 = low 0 = Fail	30%	10	8	8
Radiation tolerance	How sufficient the CPU can withstand high levels of radiation. This will affect its level of risk of malfunctioning whlie in space.	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	9	8
Power consumption	How optimal the CPU performs in relation to how much power it consumes.	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	5	8
Cost	Cost of the CPU. Important to follow budget requirement	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	6	8
		TOTALS:	**100%**	78.00%	76.50%	80.00%

Data Storage						
Criteria	**Explanation**	**Grade**	**Weight**	**SSD**	**Flash memory**	**NVM**
Capacity	How much data can the device store.	10 = high, 5 = medium 1 = low 0 = Fail	20%	9	8	7
Reliability	How much data can be transported at once (how quickly it can be sent)	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	8	8
Radiation tolerance	How sufficient the device can withstand high levels of radiation. This will affect its level of risk of malfunctioning whlie in space.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	8	9
Power consumption	How much power is required for storage	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	9	8
Cost	Cost of the device. Important to follow budget requirement	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	9	7
		TOTALS:	**100%**	77.00%	83.50%	78.00%

Transceiver						
Criteria	**Explanation**	**Grade**	**Weight**	**L3Harris C/TT-510 Electra-Lite (UHF)**	**Endurosat X-Band Transmitter**	**Comtech EF Data XSAT-7080 (X-Band)**
Data rate	How quickly data can be transmitted/received	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	8	7
Reliability	Reliability	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7	7
Radiation tolerance	How sufficient the device can withstand high levels of radiation. This will affect its level of risk of malfunctioning whlie in space.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	8	8
Power consumption	How much power is required	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	7	8
Cost	Cost of the device. Important to follow budget requirement	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	7	8
		TOTALS:	**100%**	74.00%	75.00%	76.00%

Thermal Subsystem

Trade Studies

Thermal Heating Subsystem						
Criteria	**Explanation**	**Grade**	**Weight**	**ACT Constant Conductance Heat Pipe**	**GLAS Thermal Loop Heat Pipe**	**MINCO FEP Kapton Polymide Thermofoil Heaters**
Cost	The cost of heating system is important for maintaining the budget	10 = Perfect for Budget 5 = Feasible Expense 1 = Borderline expensive	20%	3	5	7
Power Consumption	Efficient allocation of power to the whole system is important for surviving harsh PSR environments	10 = low, 5 = medium 1 = high	25%	3	4	6
Weight	Weight shouldn't exceed 85kg, so choosing a option that is appropriate for other subsystems is important	10 = appropriate for this mission 5 = somewhat acceptable 1 = Pushing the weight constraint	15%	6	6	8
Effectivity	The system should be able to use passive and active parts of the thermal control system to regulate temperatures	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	5	6

Reliability	How well/long can the system function in the fluxation of day-night cycles.	10 = multiple tests ran, and funcitons almost perfectly 5 = can be reliable at times 1 = least reliable 0 = not reliable	20%	7	6	6
		TOTALS:	**100%**	52.50%	51.00%	65.00%

Thermal Cooling Subsystem						
Criteria	**Explanation**	**Grade**	**Weight**	**RedWire Deployable Q-Rad Radiator**	**Laird CP Series Thermo-Electric Cooling**	**NeoGraf NeoNxGen N-80**
Cost	The cost of cooling system is important for maintaining the budget	10 = Perfect for Budget 5 = Feasible Expense 1 = Borderline expensive 0 = Too expensive	15%	6	7	7
Power Consumption	Efficient allocation of power to the whole system is important for surviving harsh PSR environments	10 = low 5 = medium 1 = high	20%	8	6	9
Weight	Weight shouldn't exceed 85kg, so choosing a option that is appropriate for other subsystems is important	10 = appropriate for this mission 5 = somewhat acceptable 1 = Pushing the	15%	6	8	9

		weight constraint				
Cooling Capacity	How much heat can the subsystem remove from the system	10 = high capacity 5 = medium capacity 1 = low capcity	25%	8	7	5
Reliability	How effectively can the part function without anomalies or risks	10 = multiple tests ran, and functions almost perfectly 5 = can be reliable at times 1 = least reliable	25%	7	6	6
		TOTALS:	**100%**	71.50%	67.00%	69.50%

Thermal Insulating Subsystem						
Criteria	**Explanation**	**Grade**	**Weight**	**Dunmore 200HN MLI**	**Aptek 2711 White Coating**	**Sierra SpaceThermal Louvers**
Cost	The cost of the insulation system is important for maintaining the budget	10 = Perfect for Budget 5 = Feasible Expense 1 = Borderline expensive 0 = Too expensive	15%	6	7	7
Density	The lighter density of the material will allow us to stack more while not exceeding the 85kg limit	10 = low 5 = medium 1 = high	20%	7	8	4

Durability	How severely does the material deteriorate after exposure to certain environments	10 = little to no effect on material 5 = some deformation and effect 1 = High risk	20%	7	7	8
Emissivity	Material effectiveness in radiating thermal energy	10 = Very high emissivity (>0.90) 5 = Some emissivity (>0.50) 1 = Low emissivity(<0.25)	25%	9	10	7
Absorptivity	Material effectiveness in absorbing radiant solar energy	10 = low absorptivity 5 = some absorptivity 1 = high absorptivity	20%	9	9	3
		TOTALS:	**100%**	77.50%	82.50%	56.00%

Thermal Calculation

Known and Assumptions	
n radiating to space	1
n radiating to space/surface	4
n radiating to surface	1
space node temp, k	3
surface temp hot, k	400
surface temp cold, k	40
q_solar flux, W/m^2	1440
SA faces, m^2	1.25
emissivity base, e	0.09
abosportivity base, a	0.15
system temp, k	300
Stephan Boltzman Constant	0.0000000567

using aluminum 7075 characteristics for base

Start Here! Making no changes to assumptions and seeing what the numbers look like.

Hot Case, initial NO TCS implimented		
Q_solar, W	270	
Q_internal, W	100	
Q_rad-space, W	51.67	
Q_rad-space/surface, W	-119.92	
Q_rad-sruface, W	-111.628125	
Q_in, W	601.55	
Q_out, W	51.67	
Q_net, W	549.88	This is too high... need to reduce
if positive system is heating, if negative system is cooling. If 0 assume ss stable		

You may see some (-1) mupltipliers in the math... these are to keep the convention same! Heat goes from hot to cold. For Q_net (+)Q is heating the system and (-)Q is cooling the system.

We also have made the assumption that the radiator will not change temperature between hot/cold case. This is untrue but it is ok to state that assumption is being made for a 1st order analysis.

Hot Case, with TCS		
Q_solar, W	252	MLI! ,a = .14
Q_internal, W	100	extreme case for internals
Q_rad-space, W	28.70	MLI! ,e = .05
Q_rad-space/surface, W	-66.62	MLI! ,e = .05
Q_rad-sruface, W	-62.016	MLI! ,e=.05
Q_Rad-Radiator-space, W	106.7802739	different area, and e=.93 for paint
Q_in, W	414.02	
Q_out, W	401.97	
Q_net, W	12.04	
if positive system is heating, if negative system is cooling. If 0 assume ss stable		We can use 12.04W of cooling to make this net 0!

Cold Case		
Q_solar, W	0	no sun!
Q_internal, W	100	
Q_rad-space, W	28.70	
Q_rad-space/surface, W	57.41	cold surface temps
Q_rad-sruface, W	28.695	cold surface temps
Q-Thermofoil Heaters, W	50.00	
Q_Internal_LHP, W	75.00	
Q_in, W	225.00	
Q_out, W	287.03	
Q_net, W	-62.03	
if positive system is heating, if negative system is cooling. If 0 assume ss stable		Need 82.03W of heating to make this net 0!

Payload Subsystem

MASS SPECTROMETER					
Criteria	**Explanation**	**Grade**	**Weight**	**Tunable laser spectrometer (TLS)**	**Secondary ion mass spectrometer (SIMS)**
Cost	Is this instrument expensive?	10 = inexpensive 5 = fair 1 = expensive 0 = Fail	10%	5	1
Size	Is this instrument large?	10 = compact 5 = medium 1 = large 0 = Fail	15%	10	5
Weight	Is this instrument heavy?	10 = light, 5 = medium 1 = heavy 0 = Fail	15%	10	1

Proven In Situ Planetary Use	Has this instrument been used by a previous NASA mission to collect information about stable isotopes?	10 = Yes, it has been used to collect data in situ on other planetary bodies 5 = no, but it was designed for in situ planetary use 1 = No, it was designed for earth or remote use 0 = Fail	30%	10	10
Can detect 18O/16O, 2H/1H, and H20	Explanation 3 (i.e. ,requirement identifier, MPa, temperature, Watt, etc)	10 = high, 5 = medium 1 = low 0 = Fail	30%	10	10
		TOTALS:	**100%**	95.00%	70.00%

Navigation Subsystem

PSR NAVIGATION COMPONENT						
Criteria	**Explanation**	**Grade**	**Weight**	**SQRLi (Based on LiDAR)**	**ShadowCam**	**VIPER Rover Camera System**
Cost	Is this component expensive?	10 = inexpensive 5 = fair 1 = expensive 0 = Fail	30%	5	7	4
Size	Is this component large?	10 = compact 5 = medium 1 = large 0 = Fail	15%	10	5	5

Weight	Is this component heavy?	10 = light, 5 = medium 1 = heavy 0 = Fail	15%	10	3	1
Proven In Situ Planetary Use	Has this component been used by a previous NASA rover mission?	10 = Yes, it has been used to collect data in situ on other planetary bodies 5 = no, but it was designed for in situ planetary use 1 = No, it was designed for earth or remote use 0 = Fail	20%	5	10	5
Robust	Can component withstand 20K minimum and 100K maximum temperature?	10 = Absolutely 5 = Somewhat 1 = Hardly 0 = Fail	20%	10	10	10
		TOTALS:	**100%**	75.00%	73.00%	51.00%