Team 6 | TALICO
Preliminary Design Review

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1. Mission Overview

1.1. Mission Statement

The mission seeks to comprehensively explore and understand the distribution, composition, and origin of water ice deposits within the Lunar South Pole Region.

The collected data will offer valuable insights into permanently shadowed regions (PSRs) in the Lunar South Pole Region in preparation for the Artemis III, and any subsequent mission. This data will also shed new light on the ancient sun and its astronomical environment and history.

In-situ measurements will be employed to gather high-resolution data on PSRs near the lunar south pole. This will be done by scientific instrumentation on a rover transmitted to an orbiting spacecraft. Data collected includes surface mapping, photogrammetry, geolocation, LiDAR, temperature, and mass spectrometry.

More broadly, TALICO will leverage and seek to better understand the potential use of lunar water resources for future human exploration and colonisation efforts, ultimately contributing to the broader goals of sustainable space exploration and utilisation.

1.2. Science Traceability Matrix

The broad science goal of TALICO will expand upon the goals (NASA/SP-20205009602, n.d.) set by the ARTEMIS III mission by NASA, to seek a better understanding of the character and origin of lunar polar volatilities. While past missions have confirmed the existence of volatiles on the lunar surface, the depth, distribution, abundance, temperature, and properties of the lunar volatiles remain unknown; data on volatiles regarding the characteristics is difficult to obtain in and immediately surrounding PSRs (Smith et al., 2017).

Table 1 provides an overview of the science goals of TALICO, along with the associated instrumentation and mission requirements to achieve this goal and subsequent objectives.

Table 1. Science Traceability Matrix

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements*	Predicted Instrument Performance*	Instrument*	Mission Requirements*
		Physical Parameters	Observables				
Understanding the character and origin of lunar polar volatiles	Determine the water ice abundance in PSRs.	Analyse the lunar surface with ground-based photogrammetry and mapping.	Light and depth measurements for digital reconstruction of water ice distribution within the top one metre of the regolith.	Capture High-resolution of TBR.1 images with sufficient illumination over imaging FOV.	High-resolution images using tri-band fibre lasers and CCD imaging. Has an accuracy of 0.1 to 0.2% wt of water ice.	Tri-band LiDAR	360 degree surface images around the rover at regular time intervals.
		Map of the lunar surface with geolocation data linked to sample data at a scale of a few kilometres for the PSRs.		Depth sensors must have an acceptable range of TBR.1 to produce quality depth maps of the surface within an accuracy of 5%.	Detection up to a depth of 3 feet with an accuracy of 0.5% wt of hydrogen.	Neutron Spectrometer System (NSS)	First measurement taken at a spot to identify the concentration (and presence) of subsurface hydrogen, used to determine if TRIDENT needs to be activated.
	Accurately measure the temperature of the subsurface environment within a PSR.	Measure the temperature of sampled regolith in degrees Celsius to two decimal places	10 cm incremental depth samples up to 1 metre of regolith within a PSR and their corresponding temperatures in degrees Celsius	Must drill 1 metre into the lunar surface and take regolith samples in 10 cm increments.	Collect samples of lunar regolith in 10 cm increments up to 1 metre. As well as obtain temperature readings for each sample.	The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)	The tool must drill a total of 1m into the lunar surface. Temperature measurements accurate to TBD.1
				Temperature measurements accurate to TBD.1 must be taken during the sampling to reduce change of temperature.			
Understanding the character and origin of lunar polar volatiles	Characterise the properties of lunar water ice.	Determine the purity and composition of lunar water ice deposits and the abundance of all elements detected.	Spectral analysis to identify mineral compositions associated with water ice	The tool must isolate and identify all the different compositions in the water ice sample.	Sample measurements accurate to 3 microns Has a range of 10nm across 40 bands.	Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES)	The tool must isolate and identify all the different compositions in the water ice sample
				Remove and discard unwanted fragments if needed.	Vertical stack of samples on the surface (from TRIDENT) left behind.		
	Collect evidence for the hypothesised lunar "water cycle".	Measure the concentration of water ice on the lunar surface at regular intervals over the same region.	Spectral analysis of the surface images.	Repeated surface imaging.	N/A	N/A	N/A
	Assess the potential for lunar water ice utilisation.	Assess the accessibility and resource potential of lunar water ice per cubic metre.	Analyse ice concentration, depth and characteristics to assess resource availability and applications.	N/A - analysis completed using captured data.	N/A	N/A	N/A

1.3. Summary of Mission Location

TALICO will explore the abundance of lunar water ice in areas near the lunar South Pole, particularly in PSRs, employing surface missions and orbital assets for comprehensive data collection. (Sathyan et al., 2024) argue that the lunar south polar region is crucial as it contains some of the most extensive and persistent PSRs on the moon’s surface. These areas are believed to harbour water ice deposits (Cohen et al., 2024) due to the extremely cold temperatures (Kloos et al., 2021) and lack of sunlight, making them prime targets for scientific investigations, including TALICO’s.

Specific PSRs within the lunar South Pole region shall be targeted and selected based on their proximity to suspected water ice deposits and geological characteristics conducive to ice preservation. In-situ instruments deployed via rovers or landers allow for detailed analysis of surface features and morphology, as well as thermal properties. The selection criteria for surface mission sites shall be as follows:

Proximity to PSRs. The investigation would strategically be conducted in areas near PSRs where ice is suspected due to the prolonged absence of sunlight and where nearly constant temperature is indicated (Zhong et al., 2023). Instruments onboard the lander or rover shall be used to detect, analyse and characterise any water ice deposits within the areas.

Geological context. Geological features such as crater forms, terrain roughness, and surface composition will be assessed to identify regions of interest. Craters with steep sidewalls and low lighting conditions are primary candidates for water ice deposits (Eke et al., 2014).

Accessibility. Surface mission sites shall be chosen to ensure feasible access for rovers or landers, accounting for terrain complexity and surface roughness. Such accessible sites facilitate safe landing and mobility for more effective scientific explorations.

Connecting Ridge 1 (CR1) has been selected for the mission's landing site due to its close proximity to multiple PSRs, craters of interest and the ease of access to sunlight, all essential to the mission's success.

The connecting ridge is situated between the de Gerlache, Shackleton and Sverdrup craters connecting the three regions and is in close proximity to several PSRs. CR1 is located within a 10km distance from multiple small PSRs that range from hundreds of metres in diameter to several kilometres in diameter and is at a distance of 15 kilometres from a large PSR. Several of the small PSRs reach a maximum summer temperature that remains cool enough to retain ice water on their surfaces (Spudis et al. 2008). This gives the team a broad spectrum of PSRs to consider allowing room to amend the targeted location if necessary and redirect to a different PSR in close proximity.

The location of CR1 between both Shackleton and de-Gerlache craters offers access to potential ejecta resultant from the formation of both craters. This allows the rover to more manageably gain samples of crater ejecta if the mission requires it whilst traversing a smaller distance.

Several locations on the surface of the CR1 at a height of 10m above ground can be identified for receiving sunlight 92.3% and 95.66% of the time, with the elevation of 2m receiving illumination 88.1% and 87.9% of the time (Gläser et al., n.d.). The CR1 is the most illuminated location at the south pole, with an average maximum illumination of 88% (Spudis et al., 2008). The longest continuous periods of darkness will generally last 3-5 days at these locations, making the use of solar panels for longer missions achievable. A rover or lander will benefit from the extreme illumination present at the CR1 landing site and would only need to survive a period of less than 5 days in darkness. Elevating the solar panels would raise the hours of sunlight received significantly, according to (Gläser et al., n.d.) accumulated illumination map.

According to Spudis et al. (2008), seven out of eight of the main science concepts from the National Research Council's report on The Scientific Context for the Exploration of the Moon can be achieved at or near the CR1 landing site. These are as follows: bombardment history, polar volatiles, lunar interior, crustal diversity, regolith processes, impact processes, and the atmosphere and dust environment. The CR1 can also help to understand the formation and differentiation of the moon by sampling the feldspathic highlands crustal materials.

Whilst CR1 is a promising candidate for the mission many obstacles will have to be overcome. Though CR1 is on the edge of the Shackleton crater, to access the crater and the PSR within, the rover must be large and nimble enough to manage the steep entry slopes of >30° (Sathyan et al. 2024). Whilst this adds difficulty to the access of Shackleton crater, it does not necessarily make CR1 a poor option as slopes around the ridge average <10° with slopes further down the ridge averaging <20° (J. E. Gruener et al., 2020).

Another challenge that arises and is not unique to CR1 is the extreme cold the rover must endure. Due to the uneven topography of the south pole coupled with the very low axial inclination of the moon ~1.5°, temperatures below 110K are evident in broad areas. Temperatures this low cause issues in both material structure and electrical longevity (Sathyan et al., 2024).

Communication is also an obstacle that must be considered, as the rover may fall within an area with no direct link to Earth during the mission timeframe. Leverage of a communications satellite will be used to alleviate the severity of this issue; however a communication relay system may be implemented if the mission calls for constant real-time transmission of data and a science support team that can support operations with near real-time feedback.

The Connecting Ridge 1 landing site is the most suitable location for the mission, with its central location between many PSRs and craters alongside the access to sunlight providing a readily available power source. Though challenges in an area with rugged terrain, extreme temperatures and communication difficulties will be present, the team is confident that the goals of TALICO are completable at CR1.

1.4. Mission Requirements

TALICO is tasked to design a lunar rover to collect and transmit scientific data regarding water ice deposits on the lunar surface. The deposits are situated near the poles and the rover will be designed to tolerate extreme temperatures (Sathyan et al., 2024) and terrain (J. E. Gruener et al., 2020) conditions. The collected data will be transmitted to an orbiting spacecraft assisting the mission. Being a part of a larger mission, the rover has weight and size constraints of 180 kg and 3.375 cubic metres, respectively. A summary of all mission requirements has been provided in Table 2.

Table 2. System Requirements of the Lunar Water-Ice Strategic Science Investigation Project

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
SYS-01	The system shall not exceed 180 kg mass	Design requirement	Customer		Inspection	Payload, Thermal, CDH, Electrical, GNC, Mechanical	Met
SYS-02	The system shall not exceed the dimensions 1.5mx1.5mx1.5m	Design requirement	Customer		Inspection	Mechanical	Met
SYS-03	The system shall be able communicate with the orbiting spacecraft directly	Design requirement	Customer		Demonstration	GNC, CDH, Electrical	Blank
SYS-04	The system shall survive the lunar environment for the mission duration	Design requirement	Customer		Demonstration	Mechanical, Thermal	Blank
SYS-05	The system shall be able to capture science data focused on water-ice deposits	Design requirement	Customer		Demonstration	Mechanical, Electrical, GNC, CDH	Met
PAY - 01	The system shall carry scientific instrumentation	We will need to take samples and collect data to fulfil the scientific objectives	SYS - 05		Demonstration	Payload	Met
PAY - 02	The system shall be able to capture images	To observe the local space environment and navigate immediate obstacles	SYS - 05		Demonstration	Payload	Met
PAY - 03	The system shall have in-built GPS system	Able to navigate/ collect specific data points	SYS - 04		Demonstration	Payload	Not met
TCS - 01	The system shall protect its instruments from temperature swings from daytime to PSR's	The system needs to move between the PSR's and daytime at the poles which means extreme 250+ degree temperature swings	SYS - 04		Test	Thermal	Met
TCS - 02	The system shall retain a consistent internal temperature at all times	Electronics and computing systems have certain environment requirements for optimal operation	SYS - 04		Test	Thermal	Met
TCS - 03	The system shall ensure the negative effects of radiation are not felt	The moons exposure to EM radiation from the sun is considerably worse than Earths	SYS - 04	CDH - 05	Test	Thermal	Blank

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH - 01	The system shall have on board transmission system to negotiate data collection	Due to the many factors at play during missions the system will need to prioritise its computing power during data collection	CDH - 02		Test	CDH	Met
CDH - 02	The system shall be able to regularly send data to an orbiting spacecraft	The information collected must be relayed back to earth	SYS- 03		Test	CDH	Met
CDH - 03	The system shall be able to receive and process messages	The system will need to be able make adjustments during the mission to its path and sample collection	SYS - 03		Test	CDH	Met
CDH - 04	The system shall have built in software redundancies	In software error, having a separate but identical process in place will make our data far more reliable	SYS - 04		Inspection	CDH	Met
CDH - 05	The system shall protect itself from data corruption via radiation	The radiation can scramble the memory of the system	TCS - 03		Analysis	Thermal	Blank
SYS-ELEC-01	The system shall have the ability to move to different measuring sites	System needs to be able to move to different locations	SYS-05		Demonstration	Electrical	Met
SYS-ELEC-02	The system shall have the ability to collect and store relevant data	System needs to be able to collect and store measurements for the mission	SYS-05		Demonstration	Electrical	Met
SYS-ELEC-04	The system shall have the ability to receive and transmit information	System needs to be able to send measurements and receive commands	SYS-03		Demonstration	Electrical	Met
SYS-ELEC-05	The system shall have the ability to generate power to operate as intended	System requires power to drive, collect measurements and communicate with command centre	SYS-03, SYS-04, SYS-05		Demonstration	Electrical	Met
SYS-ELEC-06	The system shall have enough power to operate at all times	System needs to be powered 24/7 to ensure continuous operations	SYS-03, SYS-04, SYS-06		Demonstration	Electrical	Met
SYS-ELEC-07	The system shall have control systems able to regulate needed parameters	System has to be able to regulate parameters (speed, power consumption, torque) to adapt to the environment	SYS-03, SYS-04, SYS-07		Demonstration	Electrical	Met
SYS-MEC-01	The system shall have chassis able to survive in a lunar environment	The system needs to remain functional for the duration of the mission	SYS-04		Analysis	Mechanical	Met
SYS-MEC-02	The system shall have the ability to navigate through rough terrain	System needs to capable of reaching different locations	SYS-04		Demonstration	Mechanical	Met
SYS-MEC-03	The system shall have the ability to collect and store relevant data	System has to be able to do scientific research	SYS-03, SYS-05		Test	Mechanical	Met
SYS-MEC-04	The system shall have the ability to carry the needed scientific equipment	System shall be able to perform necessary measurements	SYS-03, SYS-05		Demonstration	Mechanical	Met
SYS-MEC-05	The system shall be able to effectively navigate through rough terrain (stable)	The system shall be designed in such a way that it is effective in navigation through rough terrain (protected from tipping over)	SYS-03, SYS-05		Demonstration	Mechanical	Met
SYS-MEC-06	The system shall be built from materials capable of surviving temperature swings	The system needs to remain functional for the duration of the mission	SYS-04		Analysis	Mechanical	Met
SYS-GNC-01	System needs to operate autonomously when needed	System needs to be able to drive between locations autonomously	SYS-03		Demonstration	GNC	Met

1.5. Concept of Operations (ConOps)

The mission commences operations from the Moon's surface at the Connected Bridge, a proposed landing site for the Artemis III. As the third mission under NASA's ARTEMIS program, the mission is to conduct a strategic scientific investigation to collect information on the spatial distribution and properties of lunar water ice. The Concept of Operations (ConOps) outlines the operational procedures and activities from the mission start through to the completion of the mission objectives.

Lunar Surface Mission Operations

Upon landing on the surface of the moon, the rover will establish communications with the orbital spacecraft, transmitting all vital system telemetry and verify its position on the moon. The rover will be provided navigation instructions via the orbiter to the first PSR (as decided by mission control) of exploratory interest. With provided coordinates the rover will use onboard sensors/camera to navigate hazardous terrain and defer to human input from mission control as needed.

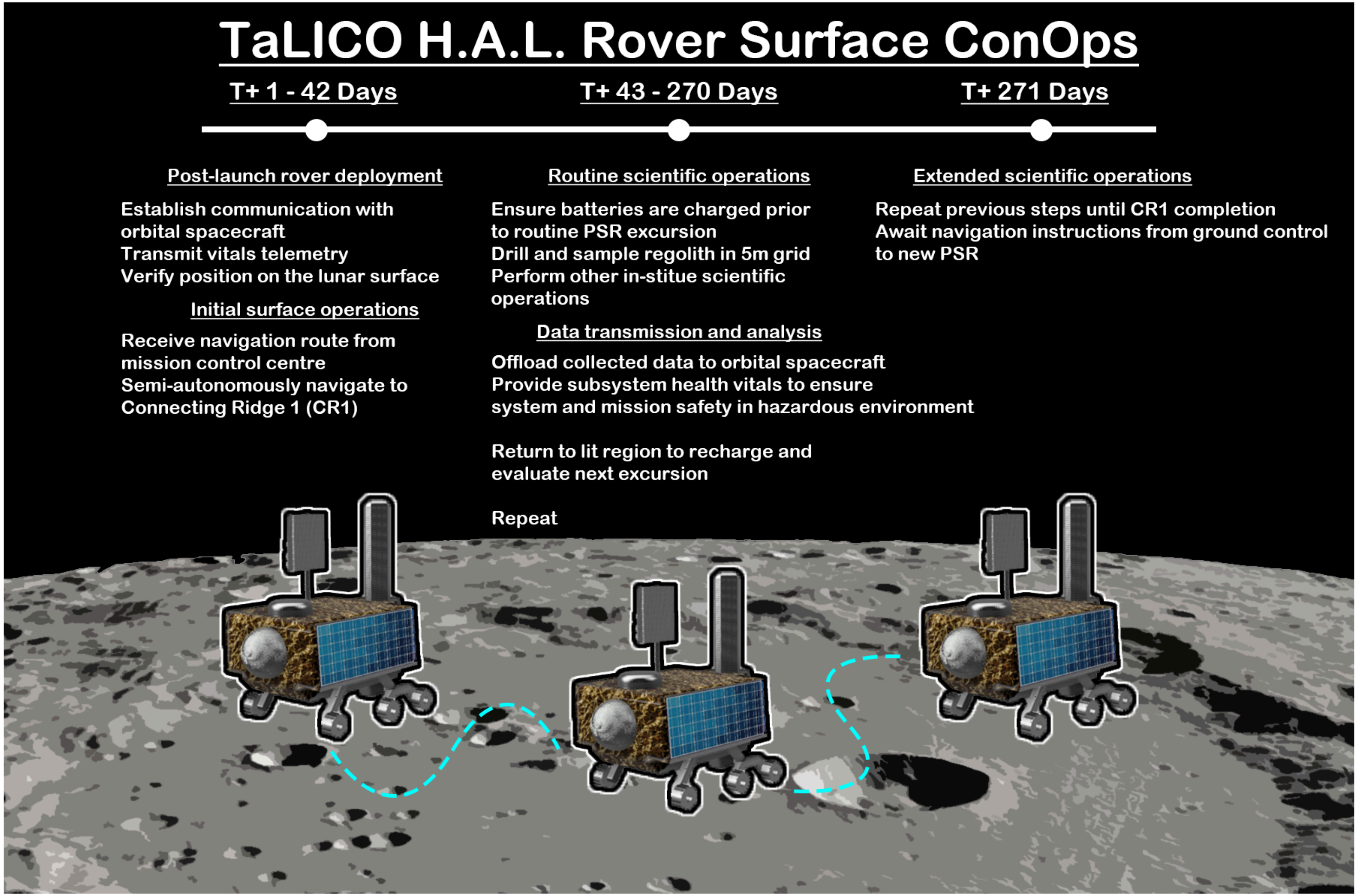
Prior to Lunar surface arrival each PSR will have been segmented into grid patterns of 5m. The rover will navigate the grid, capture LiDAR data, and perform in-situ measurements by drilling down one metre into the regolith. Samples will be taken every 10cm up to the one metre requirement. The temperature at each increment will also be tested and recorded. The collection of this data will enable the construction of a mesh based map, containing RGB, LiDAR and surface water ice information (distribution, abundance, temperature, and properties). Where a particularly high density of surface water ice is detected the rover may be tasked (by mission control) with capturing data at a reduced grid pattern size local to the detection (for increased data fidelity).

Data Analysis and Interpretation

To reduce the need for large onboard processing power where possible data will be offloaded and sent via the orbiter to mission control. Mission control can then rely on available ground computing resources to compile and process maps and data. This data will be analysed by mission scientists on the ground to achieve scientific objectives and inform future mission guidance.

Mission Monitoring and Management

Throughout the course of the mission the rover maintains communication with its orbital counterpart. Through this communication link the mission can be monitored by mission control to provide guidance and tasking. In addition to onboard autonomy the rover will use human verification and assistance to ensure mission adherence, assurance and success.



TaLICO H.A.L. Rover Surface ConOps

T+ 1 - 42 Days

Post-launch rover deployment

Establish communication with orbital spacecraft
Transmit vitals telemetry
Verify position on the lunar surface

Initial surface operations

Receive navigation route from mission control centre
Semi-autonomously navigate to Connecting Ridge 1 (CR1)

T+ 43 - 270 Days

Routine scientific operations

Ensure batteries are charged prior to routine PSR excursion
Drill and sample regolith in 5m grid
Perform other in-stitue scientific operations

Data transmission and analysis

Offload collected data to orbital spacecraft
Provide subsystem health vitals to ensure system and mission safety in hazardous environment

Return to lit region to recharge and evaluate next excursion

Repeat

T+ 271 Days

Extended scientific operations

Repeat previous steps until CR1 completion
Await navigation instructions from ground control to new PSR

Figure 1. CONOPS for TaLICO H.A.L. Rover, outlining post-launch deployment, routine scientific operations, and extended mission activities on the lunar surface.

Mission Monitoring and Management

Throughout the course of the mission the rover will maintain communication with its orbital counterpart. Through this communication link the mission will be monitored by mission control to provide guidance and tasking. In addition to onboard autonomy the rover will use human verification and assistance where needed to ensure mission adherence, assurance and success.

Mission Completion/ Decommissioning

Mission completion can be defined by the completion of the science objectives as set out by the STM. These include the successful determination of the water ice abundance in PSRs, including mapping, the successful characterisation of the distribution of water/OH within a PSR, the accurate measurement of the temperature of the subsurface environment within a PSR, characterisation of the potential of lunar volatiles, and the analysis of evidence pertaining to the proposed lunar water cycle.

These missions can be categorised in terms of their relative importance to the broader Artemis mission goals; as such they provide multiple levels of mission completion. At mission completion, the TALICO mission shall continue to map nearby PSRs, to provide larger data sets for later research. If at any stage a critical failure occurs, the mission success can be rated in terms of the number of science objectives achieved and to what quality and quantity of the data obtained. Mission termination will occur in the event of a critical malfunction that prevents the operation. The system will not be recovered—except in the case that Artemis missions land in the same region and recover samples.

1.6. Vehicle Design Summary

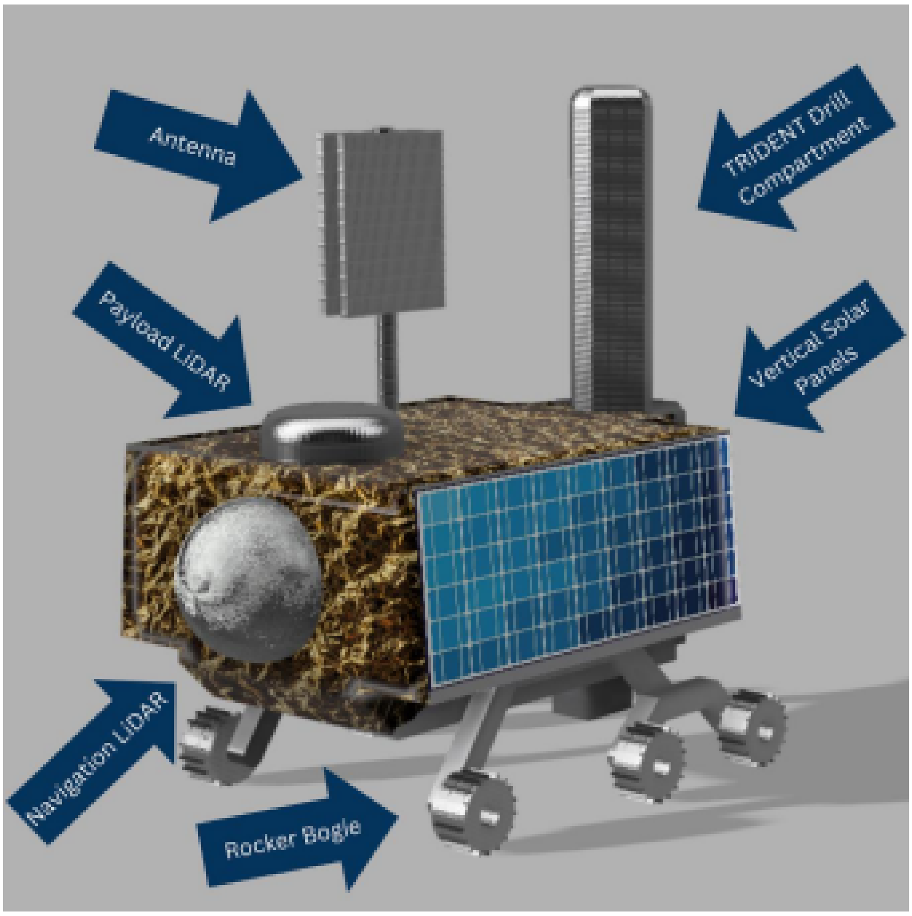


Figure 2. Rover CAD Conceptual Model

The design of the rover has several requirements it must meet for the mission. This includes weight, volume, and price restrictions (800kg, 1.5x1.5x1.5m) as provided by the client and launch provider. Several more requirements are dictated by the environment of the mission location.

From a high-level, It must be able to survive the harsh temperatures, radiation, and terrain as it traverses the mission location; it must be able to communicate with a station on Earth; it must be able to capture pertinent science data relevant to the mission; and it must be able to generate power for its relevant components.

Table 3. System Volume, Mass, and Power Budgets

Subsystem	Mass	Volume (percentage)	Power Budget (500 W)
Mechanical	80kg	60%	280 W (when active)
Power	60kg	15%	Generates
Thermal	10kg	10%	120 W
CDH	5kg	5%	40
GNC	5kg	5%	60
Payload	30kg	15%	280 (when active)

Mass & Volume Budget Distribution

The overall mass of the rover is constrained by client requirements. In its distribution, the bulk of the rover mass falls under the mechanical subsystem of the rover (80kg), responsible for the traversing, suspension, and containment of the rover body. It consists of the wheels, wheelbase, and the body frame. The next largest contribution to mass is the power subsystem (60kg), coming primarily from the large and heavy batteries necessary to store power for long periods within the PSR. The payload is the next most significant mass budget (30kg) with at least 67% of the mass coming primarily from the TRIDENT drill; other scientific instruments are not expected to require much mass budget. Thermal, GNC, and CDH subsystems require much smaller mass budgets in comparison due to the miniaturised nature of the instruments. Volume distributions are extrapolated from mass distributions.

Power Budget Distribution

Power is another major constraint due to the shadowed nature of the mission location. An expected 500W is to be provided. The mechanical subsystem, primarily the wheels, is expected to consume a maximum of 280 W of power with several previously developed wheelbases produced in the same laboratory (NASA-JPL, ex. Curiosity & Perseverance Mars Rovers) consuming 100-300 W of power. The thermal system is required to consume a maximum of 120 W of power during cold winter conditions. CDH and GNC are given somewhat significant power budgets. CDH consists of low-power high efficiency electronics, and communications while GNC mainly consumes power through navigational LiDAR which typically consumes 25-55 W. The payload is expected to draw a maximum 280 W of power in full operational use, with a large share coming from the rover. The rover is not expected to move while using the maximum share of scientific instruments, thus the highest expected consumption would be equal to the combined consumption of CDH, Thermal, GNC along with either payload or mechanical subsystems (500 W total).

1.7. Science Instrumentation Summary

TALICO utilises four scientific instruments on board, the tri-band lidar, The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT), The Broadband InfraRed Compact High-Resolution Exploration Spectrometer (BIRCHES) and the Neutron Spectrometer System (NSS), for mapping the distribution (abundance) and temporal evolution of the surface concentration of water ice.

Tri-band lidar is an imaging instrument that repeatedly images the surroundings of the rover to measure the surface concentration of water ice. It exploits the ratio in surface reflectance at the three wavelengths (532 nm, 1064 nm, and 1560 nm) of light used. This allows TALICO to possibly determine patterns and factors affecting the redistribution of surficial water ice, like the hypothesised lunar water cycle.

NSS is used to detect and characterise the abundance of subsurface water ice. It utilises the measurement of the local thermal and epithermal neutron flux. Where there is a sufficient amount for investigation, the TRIDENT rotary-percussive drill is activated to extract subsurface samples, which simultaneously measures their temperatures. These samples are exposed to the BIRCHES, which performs a high-resolution infrared spectral analysis to determine the chemical composition of the sample. The sample is also subjected to the tri-band lidar to determine the concentration of water ice. These instruments work together to provide a geo-positioned 3D map of water-ice distribution and its characteristics.

1.8. Programmatic Summary

The TALICO mission team, comprising a diverse group of experts from various disciplines and geographic locations, is dedicated to the success of the mission. The team structure ensures efficient coordination and execution, with clearly defined roles and responsibilities for each member. The mission schedule, meticulously planned to align with NASA's standards, includes critical milestones and built-in schedule margins to mitigate potential delays. With a budget cap of $225 million, the final cost estimate ensures the mission remains within budget while accommodating unforeseen expenses. Detailed planning covers all aspects, from personnel and travel to outreach and direct costs, ensuring a comprehensive approach to mission success.

1.8.1. Team Introduction

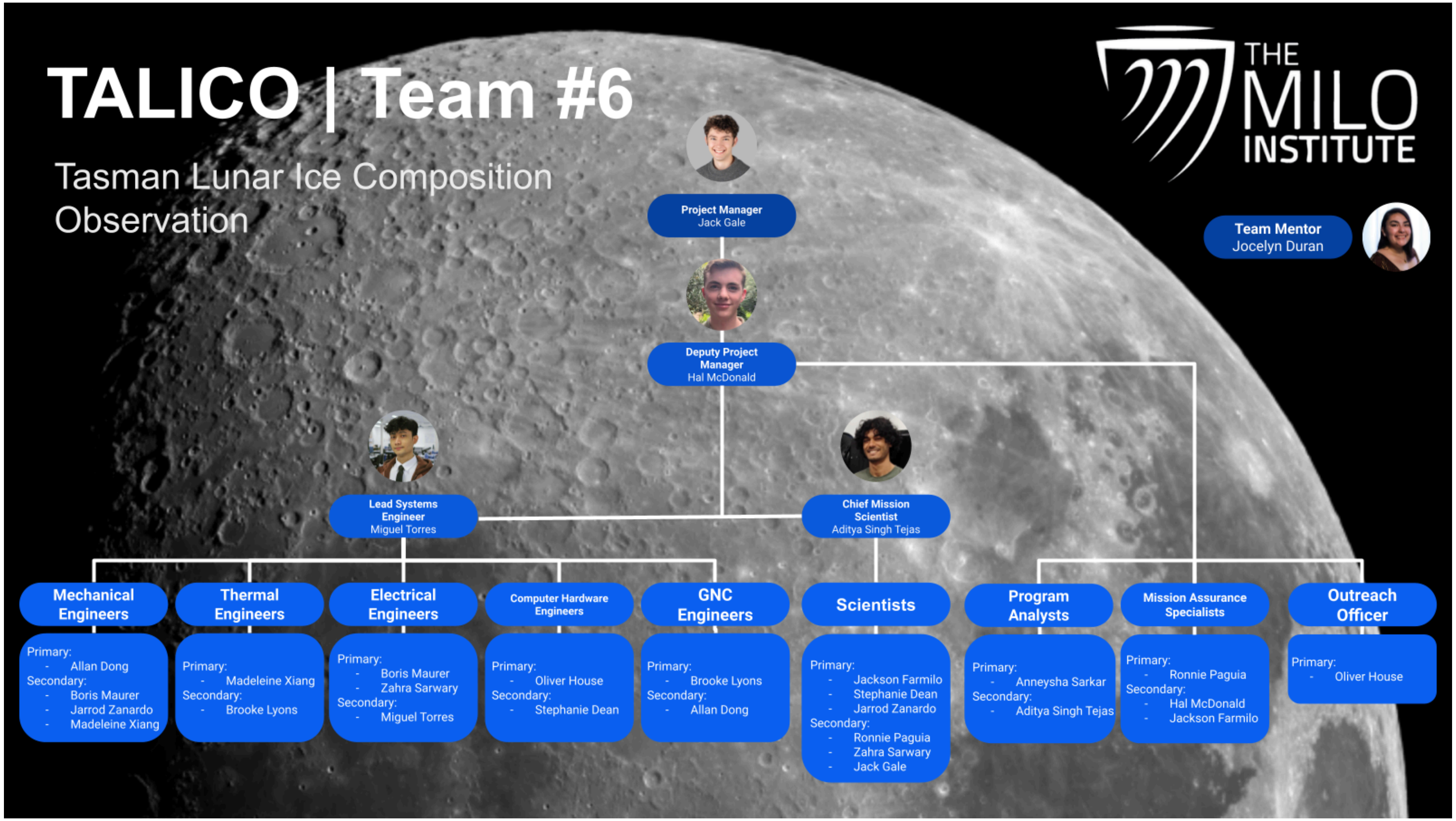
The current team behind TALICO is diverse in background, expertise, and geographic location. They are as follows:

Table 4. TALICO Team Introductions

Member	Expertise
Aditya Singh Tejas BSc (Advanced) (Honours) (*ANU, AU)*	Advanced Physics and Astronomy Instrumentations
Allan Dong Bachelor of Engineering, Aeronautical, and Space (*USYD, AU)*	Interplanetary Rovers
Boris Maurer Bachelor of Electrical/Electronic Eng'g, Int'l Business (RMIT, AU)	Expert in Electronics and Electrical Systems
Brooke Lyons Bachelor of Space Science (*RMIT, AU)*	Guidance navigation and control, and Subsystem Cost Estimation
Jack Gale Bachelor of Space Science (*RMIT, AU)*	Lunar Sciences and Mission Control
Jackson Farmilo Bachelor of Space Science (*RMIT, AU)*	
Jarrod Zanardo Bachelor of Space Science (*RMIT, AU)*	Lunar Scientific Instruments and Rover Subsystems
Madeleine Xiang Bachelor of Engineering (Aerospace) *(UNSW, AU)*	
Miguel Torres BE (Honours) in Electrical/Electronic Engineering (*UoA, NZ)*	System Verification and Design and Geographic Information Systems
Oliver House Bachelor of Engineering and Bachelor of Arts, (UoQ, AU)	Experience in Embedded Systems
Ronnie Paguia Master of Aerospace Engineering (*UoA, NZ)*	Manufacturing Planning and Project Control
Stephanie Dean Certificate in Science and Technology (*MA)*	Plant Biology and Animal Science
Team Mentor: Jocelyn Duran BSc in Electrical Eng'g, Minor in Mathematics (*UTA)*	2x Intern for the NASA L'SPACE Mission Concept Academy Program, Undergraduate Researcher for Physics

1.8.2. Team Management Overview

The TALICO mission team is structured to ensure efficient coordination and execution of the project, leveraging a diverse array of expertise across various domains essential for the mission's success. The team is organised into several key functional groups, each responsible for specific aspects of the mission. This section provides an overview of the team management structure, roles and responsibilities.



TALICO | Team #6

Tasman Lunar Ice Composition Observation

THE MILO INSTITUTE

Team Mentor
Jocelyn Duran

Project Manager
Jack Gale

Deputy Project Manager
Hal McDonald

Lead Systems Engineer
Miguel Torres

Chief Mission Scientist
Aditya Singh Tejas

Mechanical Engineers
Primary:
- Allan Dong
Secondary:
- Boris Maurer
- Jarrod Zanardo
- Madeleine Xiang

Thermal Engineers
Primary:
- Madeleine Xiang
Secondary:
- Brooke Lyons

Electrical Engineers
Primary:
- Boris Maurer
- Zahra Sarwary
Secondary:
- Miguel Torres

Computer Hardware Engineers
Primary:
- Oliver House
Secondary:
- Stephanie Dean

GNC Engineers
Primary:
- Brooke Lyons
Secondary:
- Allan Dong

Scientists
Primary:
- Jackson Farmilo
- Stephanie Dean
- Jarrod Zanardo
Secondary:
- Ronnie Paguia
- Zahra Sarwary
- Jack Gale

Program Analysts
Primary:
- Anneysha Sarkar
Secondary:
- Aditya Singh Tejas

Mission Assurance Specialists
Primary:
- Ronnie Paguia
Secondary:
- Hal McDonald
- Jackson Farmilo

Outreach Officer
Primary:
- Oliver House

Figure 3. TALICO Organisational Chart

TALICO members' primary and secondary roles were chosen individually then rearranged and finalised as a team, this ensured all roles were occupied with each member having appropriate positions. TALICO implemented four team leaders; Lead systems engineer, chief scientist, project manager and deputy project manager. Having two project managers ensures efficiency and allows for less chance of an oversight by a single manager as workload is distributed. Multiple project managers also will ensure communication is efficient and gives leniency if one member is unavailable. The role of the lead systems engineer and chief scientist are important as they give the team more guidance and promote more structure within the group.

The four team leaders were chosen after consideration of each member's previous experiences and future goals to ensure an ideal fit for every role and individual was achieved. Each member applying for a lead role was evaluated by the team after giving a short speech, then anonymously voted on to ensure equality amongst the team. The TALICO team ensured each member was in a role which would be most beneficial for the mission while accounting for future personal goals.

The team has organised and approached the mission task by delegating sub-tasks to every individual, ensuring all tasks are assigned. Tasks are assigned by the team leaders. Shared google documents are used so the team can view each other's progress and work on any sections that may need extra help. This make working much more efficient than if we were to all work offline and

The Milos Mission Academy team is equipped to address the TALICO mission. However, to enhance readiness, ongoing training and skill development programs are implemented. Programs to develop skills cover; Teaming, requirements, systems topics, project management, risk management and heat transfer. The TALICO team holds a general meeting every Monday at 3pm to discuss and distribute new and pending tasks. This was voted on as a team to ensure all members are available.

Table 5. TALICO Leadership Team

Leader	Role	Function	Job Description
Project Manager	Responsible for the overall planning, execution and delivery of the TALICO mission.	Coordination and Oversight	Ensures all teams are working in alignment with mission goals and timelines.
		Budget Management	Controls and monitors the budget to keep the project within financial constraints.
		Risk Management	Identifies potential risks and implements mitigation strategies to minimise delays or failures.
		Stakeholder Engagement	Serves as the primary point of contact between the project team and external stakeholders, including NASA, ASA and other partnering organisations.
Deputy Project Manager for Resources	Leads a team focused on resource management, mission assurance and outreach.	Resource Allocation	Manages resource allocation, including budget, personnel and materials, to ensure their efficient use and prevent any shortages.
		Mission Assurance	Oversees the mission assurance specialist to ensure all mission activities adhere to safety and quality standards, and identifies potential risks to mission success.
		Outreach and Engagement	Leads the outreach officer in developing and executing outreach programs to engage the public and stakeholders, and promotes TALICO;s goals and achievements.
		Program Analysis	Works with the program analyst to monitor the progress of the mission, analyses performance metrics, and provide reports to the Project Manager and other stakeholders.
Chief Scientist	Leads a team of scientists responsible for scientific integrity and mission success.	Scientific Strategy	Defines scientific objectives and ensures their integration into the mission planning.
		Instrument Selection and Calibration	Oversees the selection, testing and calibration of scientific instruments to ensure accurate data collection.
		Data Analysis	Leads the analysis of collected data to achieve the mission's scientific goals, including but not limited to understanding the distribution, composition, and origin of water ice deposits on the lunar surface.
		Public Dissemination	Ensures that the findings are published in credible and high-quality scientific journals, and shared with the broader scientific community.
Lead Systems Engineer	Oversees the team of engineers and technicians responsible for the technical aspects of the Rover and its systems.	System Integration	Ensures that all subsystems are property integrated and functioning.
		Design and Development	Leads the design, development and testing of the Rover to meet mission requirements.
		Technical Problem Solving	Addresses any technical challenges or issues that may arise during the development and operational phases of the mission.
		Quality Assurance	Implements quality assurance processes to ensure that all components and systems meet rigorous standards and performance criteria.

1.8.3. Major Milestones Schedule

The schedule was meticulously planned to align with the NASA Mission Life Cycle, commencing from Phase C (Final Design and Fabrication) through Phase F (Mission Operations and Closeout). The estimates were derived based on historical data from similar missions, collective judgement, and best practices outlined in the NASA Systems Engineering Handbook and the NASA Space Flight Program and PMI’s PMBOK. Each phase includes built-in schedule margins to mitigate any potential delays and risks.

The critical path, representing the shortest time to complete the mission without delays, includes several essential phases: Critical Design Review (CDR), Procurement and Manufacturing, System Integration, Operational Readiness Review (ORR), Mission Readiness Review (MRR), Launch, Mission Operations, and Decommissioning Review. The critical path tasks amount to a total of 1328 days (approximately 44 months), ensuring that each phase transitions smoothly into the next, adhering to NASA's rigorous standards and guidelines.

In summary, the mission schedule is designed to meet all critical milestones (Table X) within the estimated timeframe, with built-in schedule margins to mitigate potential delays and ensure mission success.

1.8.4. Budget Overview (1 page recommended)

The budget is meticulously planned to ensure the efficient allocation of resources while achieving all mission objectives. The budget cap is set at $225 million, with the total estimated costs carefully calculated attempting to stay within this limit.

Table 6. Budget Summary of TALICO Mission

Category	***Amount (in millions)***
Personnel	*USD 44.53*
Outreach	*0*
Travel	*1.07*
Direct Cost	*183.24*
Total Project Cost	*188.18*
Total Cost margin	*50.55*
Total Project Cost	***USD 238.73***

Key Budget Elements

- Personnel Costs: Total personnel costs amount to $44.53m, covering salaries, benefits, and other compensation for all team members. This includes Science Personnel, Engineering Personnel, Technicians, Administration Personnel, and Management Personnel, reflecting competitive salaries for highly skilled professionals over the duration of the mission.
- Travel Costs: Travel costs are estimated at $1.07m, covering expenses for flights, accommodation, transportation, and per diem for team members travelling to various NASA centres, vendor sites, and scientific conferences. This ensures effective collaboration, integration, and dissemination of mission findings.
- Outreach Costs: Currently, there are no allocated costs for outreach in this budget overview. Future considerations for outreach activities may require adjustments.
- Direct Costs: Direct costs are the most substantial part of the budget, totaling $183.24m. This includes costs for mechanical, power, thermal control, communication and data handling, guidance, navigation, and control subsystems, as well as science instrumentation and facility costs for manufacturing and testing.

A contingency margin totaling $50.55m is included to account for unforeseen expenses and risks, ensuring the mission remains within budget even in the face of unexpected challenges. This margin represents approximately 21.1% of the total project cost, providing a buffer for potential cost overruns. The budget is periodically reviewed and adjusted to reflect any changes in assumptions or project scope, ensuring continued alignment with mission goals and constraints. The meticulous planning and comprehensive cost estimation ensure that the TALICO mission can achieve its objectives efficiently and effectively within the allocated budget. The total project cost of $238.73m slightly exceeds the budget cap. Thus, there is a need for cost-saving measures or additional funding to ensure the financial viability.

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

Generally, the decisions made for the ancillary systems were done with reliability, functionality, flight heritage, and client/launch restrictions in mind. Mechanically, the rover, mainly made of aluminium, shall traverse the lunar surface using rigid wheels placed on a rocker-bogie capable of moving through steep terrain while keeping the main body level. In the Power subsystem, power shall be generated using near vertically mounted Gallium Arsenide (GaAs) solar panels with no actuation necessary due to the virtually constant angular elevation of the sun close to the horizon of the PSR.

Aforementioned systems shall support the function and transport of a Warm Electronics Box (WEB) kept thermally stable at an operational temperature of above -20C generating heat using thermal heaters. Calculations outlined in the thermal section of the document show that cooling is the main concern and will be done through the use of thermal louvres with thermal distribution within the rover conducted by a Variable Conductance Heat Pipe (VCHP). Insulation shall be provided using a layer of Aerogel within the interior of the WEB. Several flight-heritage and radiation-hardened components have been chosen for the onboard computer hardware contained in the WEB

Communication shall be handled using a state-of-the-art One Phase Array, while data handling will be done using VxWorks Real Time Operating System (RTOS) with flight heritage from Mars rover missions. Navigation will be done using an Inertial Measurement Unit and LiDAR capable of visualising the lunar environment despite a lack of light in specific regions. Lastly, the payload consists of flight-proven TRIDENT, a rotary-percussive drill used to expose regolith 1m deep into the lunar surface, and BIRCHES, an infrared spectrometry system to analyse the extracted material.

2.1.1. Mechanical Subsystem Overview

TALICO is tasked to design a lunar rover to collect and transmit scientific data regarding water ice deposits on the lunar surface. The deposits are situated near the poles and the rover will be designed to tolerate extreme temperatures (Sathyan et al., 2024) and terrain (J. E. Gruener et al., 2020) conditions. The collected data will be transmitted to an orbiting spacecraft assisting the mission. Being a part of a larger mission, the rover has weight and size constraints of 800 kg and 3.375 cubic metres, respectively. A summary of all mission requirements has been provided.

2.1.1.1. Mechanical Subsystem Requirements

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

SYS MECH 1	Body	The system shall be constructed form a material with high strength to weight ratio	The chassis must be able to withstand the unpredictable conditions of the lunar environment and remain structural	SYS MEC 01		Demonstration	Mech	Yes
SYS MECH 2	Body	The rover shall be made of materials resistant to extreme temperatures	Ensures that the system is operational und durable					Yes
SYS MECH 4	Wheels	The system shall use wheels made of a material able to resist lunar dust and extreme temperatures	The wheels should resist damage from traversing the lunar terrain as much as possible			Blank	Mech	Yes
SYS MECH 5	Suspension System	The system shall use a suspension system able to absorb impact from rough lunar terrain				Blank	Mech	Yes
SYS MECH 6	Suspension System	The suspension system shall be made of durable and light materials						Yes
SYS MECH 7	Suspension System	The system shall maintain stability up to a tilt angle of 30 degrees an any axis without tipping over	Ensures that the system remain operational and doesn't tip over					Yes
SYS MECH 8	Assembly Joints and Connectors	The joints and connecters should provide sufficient degrees of freedom and stability				Blank	Mech	Yes

SYS MECH 13	Sealing Mechanisms/Dust mitigation	The system shall have a Dust Proof Enclosure	Ensures that the sensitive electronic components are protected			Blank	Mech	Yes
SYS MECH 15	Sample Collection System	The system shall be able to store sample in a contamination free environment	System to be able to collect and safely store samples			Blank	Mech	Yes
SYS MECH 17	Sample Collection System/ mechanical arm	The Arm has to be able to lift object up to 2kg	System to be able to collect samples			Blank	Mech	Yes
SYS MEC 01		The system shall have chassis able to survive in a lunar environment	The system needs to remain functional for the duration of the mission (protection of internal components)	SYS 04		Analysis	Mechanical	Yes
SYS MEC 02		The system shall have the ability navigate through rough terrain	System needs to capable of reaching different locations	SYS 04		Demonstration	Mechanical	Blank
SYS MEC 03		The system shall have the ability to collect and store relevant data	System has to be able to do scientific research	SYS 03, SYS 05		Test	Mechanical	Blank
SYS MEC 04		The system shall have the ability to carry the needed scientific equipment	System shall be able to perform necessary measurements	SYS 03, SYS 05		Demonstration	Mechanical	Blank

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SYS MEC 05		The system shall be able to effectively navigate through rough terrain (stable)	The system shall be designed in such a way that it is effective in navigation through rough terrain (protected form tipping over)	SYS 03, SYS 05		Demonstration	Mechanical	Blank
SYS MEC 06		The system shall be build from materials capable of surviving temperature swings	The system needs to remain functional for the duration of the mission	SYS 04		Analysis	Mechanical	Blank

2.1.1.2. Mechanical Sub-Assembly Overview

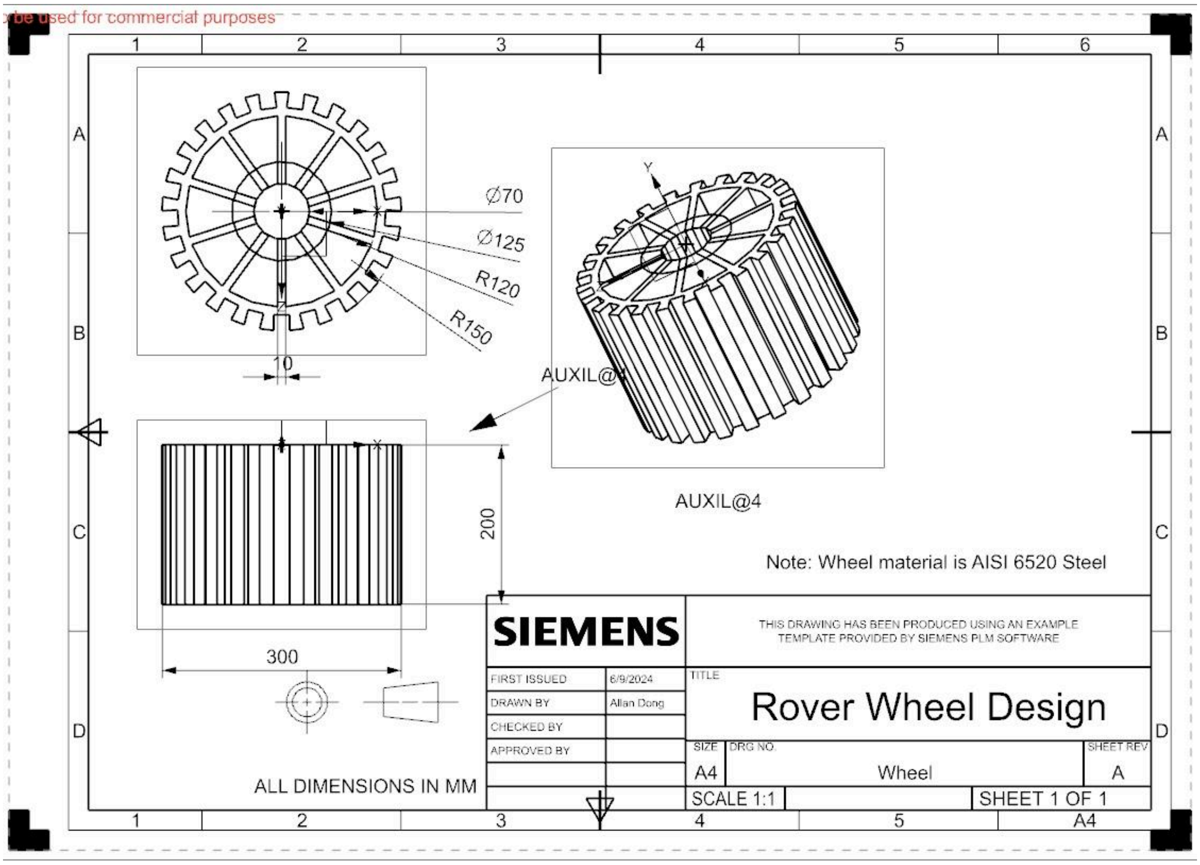

Figure 4.Rover Wheel Design using AISI 6520 Steel.

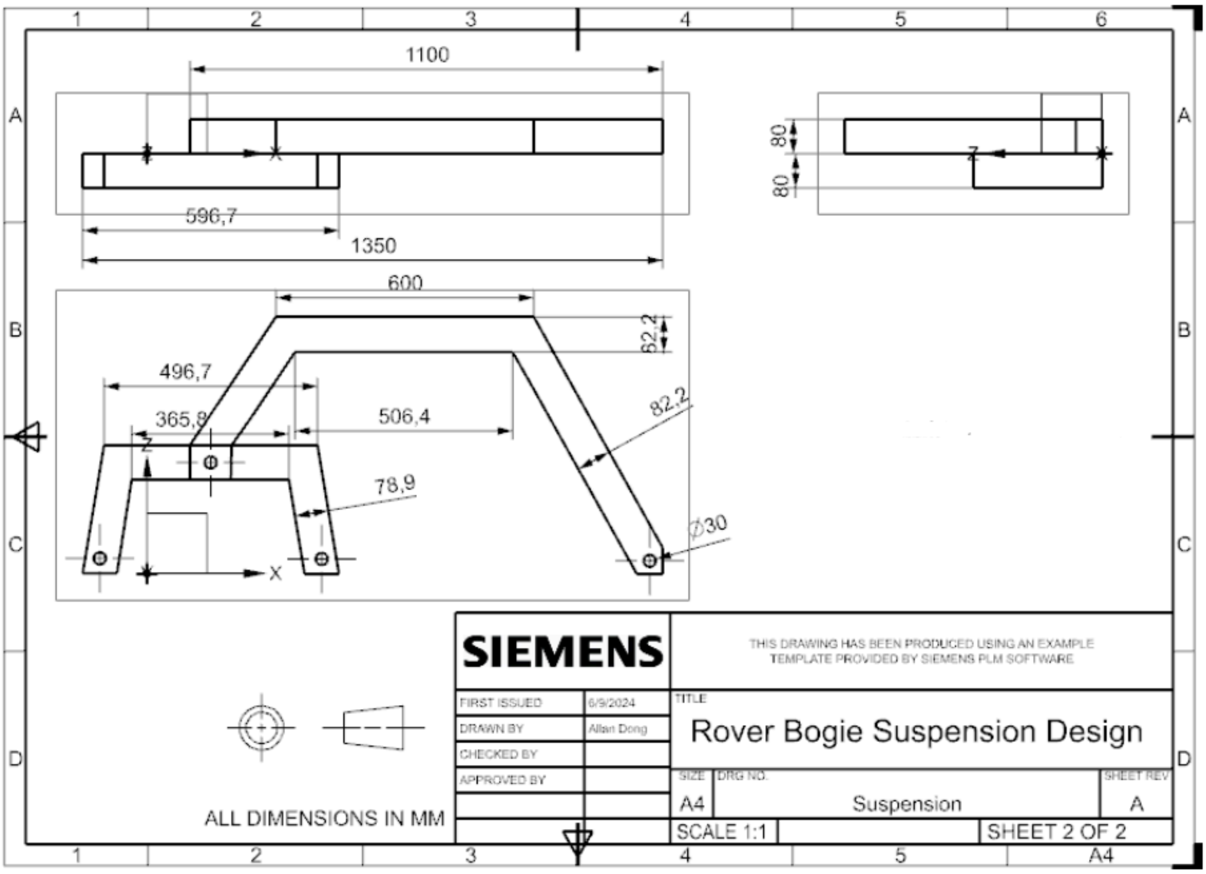

Figure 5. Rover Bogie Suspension Design

2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans

The mechanical subsystem will utilise the IMU as fault detection between the left and right sides of the rover, periodically checking if the input direction is the same as the actual output. Afterwards, any bias found in movement may be compensated for in software. The rocker bogie is designed to have an even distribution across the body with a redundant pair of wheels present, minimising the impact of a broken wheel on the stability of the rover.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans

The mechanical subsystem is responsible for ensuring the rover can effectively traverse across the lunar landscape and carry out its tasks successfully. All mechanical subsystem parts will be manufactured in NASA's JPL due to their expertise in precision engineering and space-grade materials for space missions. Prototypes of critical mechanical components, such as the rocker bogie suspension, rigid wheels and steel body will undergo extensive testing to validate performance under simulated lunar environmental conditions including radiation exposure, mechanical stress and thermal stress testing to ensure the system is functional, reliable and consistent with NASA standards and spaceflight requirements.

Upon successful qualification, mechanical components will be assembled according to the detailed engineering drawing of the model. This involves attaching the rocker bogie suspension to the body of the rover and attaching the rigid wheels to the rocker bogie suspension. Assembly of mechanical components of the rover will be conducted in close collaboration with mechanical engineers to ensure seamless functionality of the mechanical subsystem. The mechanical subsystem will undergo comprehensive system-level testing to ensure compatibility.

Verification of the subsystem involves testing and analysis to confirm compliance with size and weight restrictions, agility requirements, durability goals and mission objectives. This includes the verification of suspension capabilities and the rover's ability to traverse rough terrain. Verification activities will be documented, reviewed, and validated to ensure alignment with mission goals and mechanical subsystem standards. Validation results will be analysed to confirm the readiness of the subsystem for deployment on the lunar surface and sustained mission operations. As specialised components sourced from NASA centres may have longer lead times due to fabrication and qualification processes as well as shipping, the estimated lead times will be around 12-months considering procurement, testing, integration, and validation phases.

2.1.1.5. Mechanical Subsystem Verification Plans

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2.1.2. Power Subsystem Overview

The power subsystem is a crucial component of TALICO’s lunar rover, providing all the energy required to operate and function, through multiple sources of power, throughout the mission. This subsystem integrates solar panels, batteries, a power distribution unit (PDU), and the wiring and connection all into a resilient power management system capable of generating, storing, and distributing energy to meet the needs of all operational capabilities of the lunar rover.

To understand the power subsystem that supports TALICO’s lunar rover, it is important to detail each of the critical subassemblies and how they work individually and together to maintain the rover’s energy needs.

Two large solar panels are positioned on each side of the rover to allow for power generation through solar energy received from the Sun. These solar panels are designed to be rotatable to allow for sun tracking, ensuring that maximum energy can be captured and used by the rover and all its instruments. These solar panels will be installed flush against the rover’s body, and movement in 2 dimensions will allow for the solar panels to first, extend outwards and upwards to be horizontal relative to the rovers body, and once fully extended, can then rotate around the horizontal axis, tiling forwards and backwards when necessary. This dual movement of extending and rotating will enable continuous tracking of the sun and therefore continuous power generation. Dust accumulation on the solar panels would mean that they would be less and less effective as more dust gathered, however with the inbuilt mitigation system the dust can be vibrated or wiped off the solar panel.

The battery on the rover will store energy from the solar panels to use when solar power generation can not support all the rover’s energy needs. The battery is a solid state battery, chosen for its XXX features and XXX capacity. The batteries work with the solar panels during sunlight, being charged with the excess energy generated; However, during low-light or no-light situations, the battery is the main power source to ensure continuous operation of all components and instruments. Low-light and no-light situations include when the rover cannot produce solar power either during the lunar night or when travelling within PSRs.

The power distribution unit (PDU) will manage and distribute power between the source and the varying instruments and components on the rover. The PDU will make sure that the right amount of power is delivered efficiently and timely where needed most. The PDU will be able to manage the power from the solar panels and the battery interchangeably allowing for a smooth flow of power.

The wiring and connectors between the instruments and components are like the veins of the system. Without these the power could not flow throughout the vehicle. Working with the PDU, the network of wires allows the power to be sent to any component or instrument on board. Multiple pathways are made for critical components to ensure any damage sustained will not affect the distribution of power.

Efficient power management is essential during operational use of the rover. During each operational phase, the power subsystem must accommodate varying energy demands for the subsystems and instruments to ensure smooth operations. There are several operational phases that the rover will go through during a typical cycle: traversal, data collection, data analysis, data relaying and recharging. Each phase will only require some instruments or subsystems to be powered while others will be switched off to be more efficient.

During all operational phases, some subsystems and components will be considered crucial, such as the OBC, battery, etc, and these will have a priority in power use to ensure the rover can function properly. During the traversal phase, the rover will be travelling across the lunar surface which will require a lot of power for the motors to move the rover. The GNC subsystem will take priority in the energy demand to guide the rover and provide terrain monitoring and path planning. Connection to an orbiter can be used for GPS to get absolute position information, requiring power for the antenna. Once the rover has reached its desired location, it will enter a data collection phase in which the rover will shift power to the scientific instruments. This phase requires a lot of power to ensure the equipment functions properly, does not fail or damage samples mid operation, or does not damage the instrument itself. The data analysis phase is less power intensive than traversal or data collection. The on board computer will process and prepare the data for transmission to the orbiter. Data preparation can be done during other phases if necessary and power is available, so this phase could take place at any time. The Data relay phase requires that mission critical data is able to be transferred uninterrupted. Power can be prioritised to the CDH subsystem to ensure safe and reliable transmission. This phase is also not as power intensive as other phases, and could operate simultaneously with other phases if the OBC can ensure stable power supply to all active subsystems. Recharging of the rover's battery can be done whenever excess power is generated by the rover's solar panels. However, considering that the rover will spend a lot of time in PSRs where no solar power can be generated the rover will need to enter a recharging phase after reaching a sun lit location. In the recharging phase the rover should power down all other subsystems to maximise power generation and battery recharging.

This figure shows a conceptual power vs time plot for TALICO's rover. It outlines the power levels consumed by the rover during different operational phases. Power levels are based on each operational phase running separately.

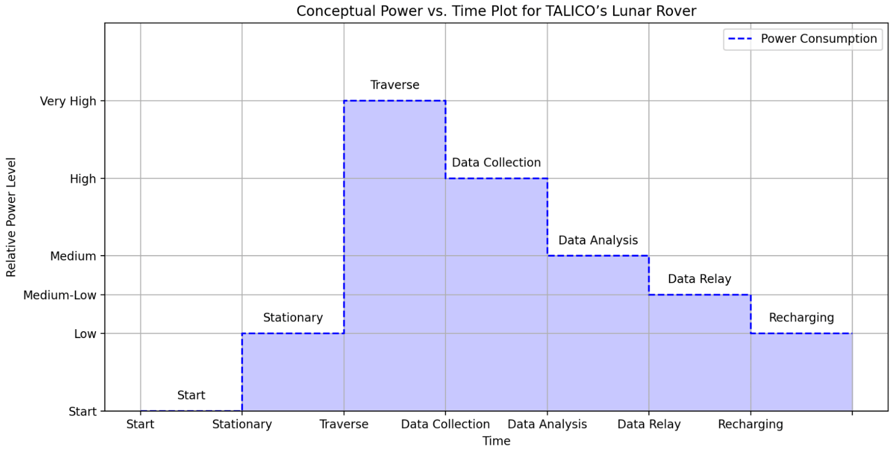


Figure 6. Conceptual Power vs. Time Plot for TaLICO's Lunar Rover, illustrating power consumption levels across various operational phases

2.1.2.1. Power Subsystem Requirements

Requirement ID	Subsystem	Requirement Description	Parent Req	Child Req	Rationale	Verification Method
SYS ELECL2-01	All	The System shall use different power Sources	SYS-04, SYS-ELEC 06		Ensures that the System is always operational, protected against failure of one of the systems	Demonstration
SYS ELECL2-02	Solar Panels	The Solar panels shall be able to survive the Lunar environment	SYS-04	SYS ELECL2-04 SYS ELECL2-03	Ensures that the System is operational	Demonstration
SYS ELECL2-03	Solar Panels	The Solar panels shall resist dust accumulation	SYS ELECL2-02, SYS-04		Ensures that the solar panels can efficiently collect solar energy	Demonstration
SYS ELECL2-04	Solar Panels	The Solar panels surface shall be able discharge static build-up	SYS ELECL2-02, SYS-04		Prevents sudden discharges that can damage the system	Demonstration
SYS ELECL2-05	Solar Panels	The Solar panels used in the system shall provide minimum XXX Watts of power at all times	SYS-04, SYS-05, SYS-03		Ensures that enough Energy is collected to maintain the rover operational	Demonstration
SYS ELECL2-06	Solar Panels	The Solar Panels used in the system shall provide minimum XXX Watts of power at peak sunlight	SYS-04, SYS-05, SYS 04,SYS ELEC-06		Ensures that enough Energy is collected to maintain the rover operational	Demonstration
SYS ELECL2-07	Solar Panels	The System shall have the ability to orient the Solar Panels towards the sun within X degrees accuracy.	SYS-04, SYS-05, SYS 05,SYS ELEC-06		Ensures the maximization of solar energy collection	Demonstration
SYS ELECL2-08	Battery System	The batteries used in the System shall maintain a minimum of XX% of total capacity over XXX charge/discharge cycles.	SYS-04, SYS-05, SYS-06, SYS-ELEC 06		Ensures the longevity and continuous operation of the system	Demonstration
SYS ELECL2-09	Battery System	The batteries used in the System shall be able to operate at temperatures between XX°C and XX°C.	SYS-04, SYS-ELEC 06		Ensures that the batteries are able to operate within Lunar temperatures	Demonstration
SYS ELECL2-10	Power Distribution Unit	The System shall include a PDU		SYS ELECL2-12 SYS ELECL2-11	Ensures that the system is able to switch between different power sources	Demonstration

SYS ELECL2-11	Power Distribution Unit	The System shall have multiple electrical paths to critical Systems	SYS ELECL2-10		Ensures the System is operational if one path gets damaged	Demonstration
SYS ELECL2-12	Power Distribution Unit	The systems PDU shall have minimal to no interruption time when switching between power sources	SYS ELECL2-10		Ensures that there is no data loss, disruptions in measurements and communication etc.	Demonstration
SYS ELECL2-13	Thermal Management	The system shall have a thermal control system	SYS-ELEC 07	SYS ELECL2-14	Ensures that the system is able to control temperatures to protect from overheating or freezing	Demonstration, Analysis
SYS ELECL2-14	Thermal Management	The thermal control system shall regulate the temperature to oscillate between XX°C and XX°C.	SYS ELECL2-13		Ensures that the electrical and electronic components are protected against thermal conditions	Analysis, Inspection
SYS ELECL2-15	Power Monitoring	The System shall inform of low power conditions or any failures within XXs from detection	SYS-ELEC 04		Ensures a fast response in case of power delivery issues	Demonstration
SYS ELECL2-16	Power Safety	The system shall be able to detect component failures or short circuits	SYS-04	SYS ELECL2-17	Prevention of failures, ensures operational continuity	Demonstration
SYS ELECL2-17	Power Safety	The system shall be able to isolate damaged components or shut down when a short circuit is detected	SYS ELECL2-16		Limits the impact on the entirety of the System	Demonstration
SYS ELECL2-18	Wiring and Connectors	The systems electrical connectors shall be resistant to physical degradation and corrosion	SYS-04		Increases the longevity of wiring	Analysis, Inspection
SYS ELECL2-19	Wiring and Connectors	The systems wiring shall use mechanism preventing disconnections	SYS-04		Ensures stable operation of the system	Demonstration
SYS ELECL2-20	Power Regulation	The systems voltage regulator shall be able to maintain a stable voltage output	SYS-04		Ensures stable operation of the system	Demonstration

2.1.2.2. Power Sub-Assembly Overview

The Power system will generate the energy needed through solar panels. The energy collected will be stored in batteries which are needed in case that the solar panels cannot produce enough energy consistently (lowered power generation caused by dust on the panels, travelling through regions without sunlight etc.). The energy used for the operation of the rover would therefore come from the battery and the solar panels. This process will be managed by the Power Management and Distribution (PMAD) system, which would distribute energy from the solar panels and the battery to other systems. The power system will also include a power monitoring subsystem which will measure all power related data to ensure the functionality of the system.

Solar Panels

The solar panels subsystem is part of the power system which is responsible for the power generation needed to power the rover. The solar panels would preferably be made from a material able to withstand the extreme conditions and temperatures present on the lunar surface. Depending on the mission length it may be needed to include protective measures to prevent the accumulation of dust on the solar panels. To achieve this goal the Solar panels will either be layered with protective coating, or the rover will include equipment preventing dust accumulation (electrodynamic dust shield, mechanical wipers, air cleaning system, vibration system). The Panels will be mounted on top of the rover and will feature the ability to adjust its angle to maximise the collection of solar energy.

Table 7. Solar panel specifications

	Mass	Volume	Max power	Technology Readiness Level (TRL)
Solar Panels	10-15kg	0.1m3	300W	7

Battery system

The Battery System will be responsible for storing the energy collected by the solar panels. The battery used will probably be a lithium-ion or lithium-polymbattery which has a high energy density. The type of battery has been chosen due to their efficiency and reliability, long life cycle, and ability to deliver high power. The battery will need to be insulated to survive the extreme temperatures of the moon. The battery system will include a controller and power management system to optimise the charging of the battery.

Table 8. Battery specifications

	Mass	Volume	Power	Technology Readiness Level (TRL)
Battery	20-40kg	12l	200-250Wh/kg or 442-800Wh/l	8

Power Management and Distribution Unit

The Power Management and Distribution Unit (PMDU) subsystem will be responsible for the management and distribution of energy from the solar panels and batteries to other instruments onboard the rover such as scientific measurement equipment. The PDU will include:

DC-DC converters: Responsible for converting the voltage from the solar panels to levels required by other components. The Converters ensure that all electronic equipment is provided with stable and suitable voltages regardless of the magnitude of the input power magnitude.

Solid state power controllers (SSPCs) will be used inside the PMDU in order to protect the rover's electrical circuit from high voltages. The SSPC have been selected opposed to mechanical circuit breakers due to their precise control and fast reaction time

Power Monitoring sensors integrated in the SSPC will provide real time measurements of electrical parameters of the rovers power system. These sensors will measure parameters such as voltage,current, temperature and power consumption across different circuits allowing the PDMU to distribute the energy in the most efficient way. The measurements will also allow for a quick identification of potential faults and anomalies within the system. The monitoring will help in extending the operational lifespan of the rover and all the instruments

Table 9. PDMU specifications

	Mass	Volume	Power	Technology Readiness Level (TRL)
PMDU	10kg	0.005m3	500W	7

Wiring and Connectors

Durable wiring is crucial in establishing connections of different subsystems of the rover. The wiring must be made from durable materials that are resistant to temperature and potential mechanical stress.

The wiring and connectors will have to be able to survive the extreme conditions of the lunar surface in choosing a suitable material with the priority being durability and minimal mass. Suitable materials include aluminium, copper, gold and carbon/graphene. The insulation of the wiring will be chosen to optimally protect the wires from external conditions. The connector will be sealed to block lunar dust. Connectors will be shielded against electromagnetic interference which can negatively affect the operation of sensitive electronic components.

Table 10. Wiring and connector specifications

	Mass(kg)	Volume(cm3)	Power losses	Technology Readiness Level (TRL)
Wiring and Connectors	2	200	1	8

Power Monitoring Subsystem

The power monitoring subsystem will be responsible for measuring and reporting power related data. The primary function of this subsystem includes measuring, reporting, and managing the flow of electrical power within the rover. The Subsystem will also be responsible for assessing the systems health by monitoring all power related components such as batteries and solar panels. The power monitoring subsystem is critical in ensuring the effective management and reliability of the rover's power supply.

Table 11. Power monitoring specifications

	Mass(kg)	Volume(cm 3)	Power losses	Technology Readiness Level (TRL)
Wiring and Connectors	2	1000	5	6

This subsystem includes power monitoring sensors which are responsible for measuring key electrical parameters (voltage, current, temperature). The measurements provide data which is necessary in controlling and optimizing the rovers power system. The sensors operate in real time constantly providing measurements enabling operators or autonomous systems to make informed decisions and adjustments.

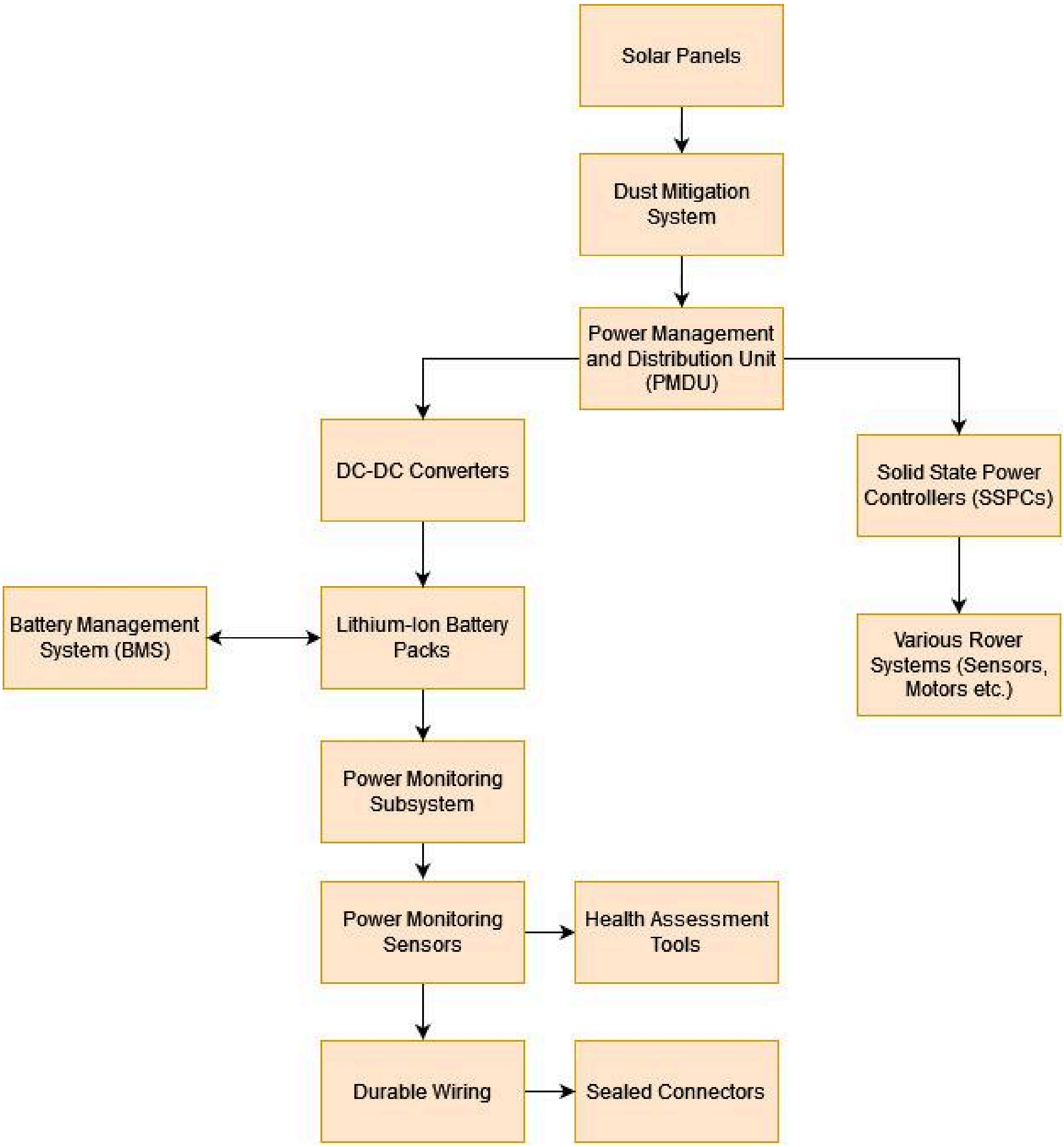


Figure 7. Power Subsystem Flow Diagram for TaLICO's Lunar Rover

Description

1. Solar Panels with Dust Mitigation System are responsible for collection solar energy

2. The energy is then transported to the PMDU, where DC-DC Converters adjust voltages and SSPCs manage the distribution of power in the circuit.
3. The energy is then distributed to various rover systems (e.g., scientific instruments, communication, and motors etc.).
4. The excess energy that has been collected is stored in Lithium-Ion Battery Packs, managed by the BMS which will be responsible for maximising the Batteries lifespan and protect it against overcharging, deep discharging, and other potential failures, ensuring the overall safety of the system
5. The Power Monitoring Sensors will measure system performance of all subsystems of the power system. The data obtained by the sensors will be used by the Health Assessment Tools to provide diagnostics.
6. The Durable Wiring and Sealed Connectors will be responsible for ensuring that all components are securely connected and protected from lunar conditions (duct, temperature, radiation etc.). It will connect the PMDU with all subsystems ensuring reliable power transmission.

2.1.2.3. Power Subsystem Recovery and Redundancy Plans

Table 12. Recovery and Redundancy Plans

Subassembly	Recovery	Redundancy
Solar Panels	If the solar panels experience an issue in power generation, it may be due to dust build up on the panels. The rover may regularly dust off its panels with the integrated dust mitigation equipment (wipers or vibration system). If power is not being produced temporarily, the battery system will still have a supply to continue operations until the solar panels are back online.	There are no redundant solar panels on board the rover that can be replaced if damage or failure occurs; However, there are multiple panels on board the rover and each is maintained separately. If one panel fails then the others can continue to operate.
Battery System	Constant monitoring of the battery is important as extreme damage can occur when outside the normal operating temperatures. The power management and distribution unit will safely isolate the battery to prevent damage to other instruments while the problems are diagnosed.	The main battery is made up of smaller batteries which will ensure redundancy if certain cells fail or degrade during the mission. Overall battery capacity may decrease but the rover will still be able to access backup power if needed.
Wiring and Connectors	The wiring can be monitored to ensure that all connections are online and working. If components are not responding, temperatures are too high, or too much current is being passed through them, the rover may disconnect certain instruments or components temporarily to try and restore the connection to normal operation.	Multiple connections and paths to critical instruments and components can be duplicated to ensure that the failure of a wire will not result in the loss of that component or instrument. Wiring should be insulated to be better protected and connectors seal from lunar dust.

2.1.2.4 Power Subsystem Manufacturing and Procurement Plans

The power subsystem is responsible for the management and distribution of energy from the solar panels and batteries to other instruments onboard the rover such as scientific measurement equipment. A combination of NASA centres and COTS suppliers are enlisted to fulfil the component requirements of the power subsystem. Components such as the power management unit will be manufactured at NASA’s Jet Propulsion Laboratory (JPL) due to their expertise in precision engineering and space-grade materials for space missions. Components such as solar panels and batteries will be purchased from Space Power Inc. (SPI) as they specialise in advanced power solutions for space missions.

Prototypes of critical power components, such as the solar panels, battery, power management unit, wiring and connections will undergo extensive testing to validate performance under simulated lunar environmental conditions. This includes thermal stress testing and radiation exposure to ensure the system is functional, reliable and consistent with NASA standards and spaceflight requirements. Upon successful qualification, power subsystem components will be integrated according to the detailed integration plans. This involves integrating solar panels, batteries, power management unit, wiring and electrical connections to the rover. Assembly of power subsystem components will be conducted in close collaboration with electrical engineers to ensure seamless functionality and compatibility of the power subsystem. The power subsystem will undergo comprehensive system-level testing to ensure compatibility.

Verification of the subsystem involves testing and analysis to confirm compliance with the rover's power needs, safety requirements, weight restrictions and mission objectives. This includes the verification of battery capacity, solar panel efficiency and wiring reliability and durability. Verification activities will be documented, reviewed, and validated to ensure alignment with mission goals and power subsystem standards. Validation results will be analysed to confirm the readiness of the power subsystem for deployment on the lunar surface and sustained mission operations.

Specialised components sourced from NASA centres may have longer lead times due to fabrication and qualification processes as well as shipping, while COTS components will typically have shorter lead times. Considering the fabrication process, procurement, testing, integration, and validation phases and adding extra time to account for margin and worst-case scenarios the expected average lead time is 12-15 months. Using the longest lead times ensures that the project plans accommodate potential delays, allowing for unforeseen delays while still meeting deadlines.

Table 13. Power Subsystem Supplier Details

Subsystem	Potential Major Supplier	Justification	Lead Time (Est.)
Power	Space Power Inc. (SPI)	Specialised in advanced power solutions for space missions.	12-15 months

Manufacturing Plans for Rover Power Subsystem

Solar Panels

The manufacturing of solar panels will be outsourced to a specialised manufacturing shop as the production of space-grade photovoltaic cells requires experience and specialised tools. The inhouse manufacturing of solar panels is too complex and lies beyond the capabilities of our in-house facilities. Companies such as Spectrolab specialise in production of photovoltaics for space application and have a proven track record. The estimated time of the entire process is estimated to take 9 months and includes around 1000 person-hours. The integration of the solar panels with other systems will be conducted at NASA centre.

https://www.spectrolab.com/

Battery System

The manufacturing of batteries will be outsourced to a specialised manufacturing shop. The battery system will be sourced primarily from suppliers such as Saft who produces long lasting and reliable batteries. The company also has a proven track record producing space-grade lithium-ion batteries used by NASA and the ESA in their vessels. The estimated time of the entire process is estimated to take 6-8 months and includes around 1000 person-hours. The integration of the batteries with other systems will be conducted at a NASA centre.

https://saft.com/media-resources/our-stories/how-saft-batteries-made-space-travel-possible

Power Management and Distribution Unit (PMDU)

The PMDU will be partially manufactured in-house and outsourced. Components requiring specialised equipment will be outsourced. Components such as DC-DC converters and SSPCs will be sourced from companies such as Vicor whose products are known for their reliable and robust design. The estimated time of the entire process is estimated to take 8-10 months and includes around 1200 person-hours. The integration of the PMDU with other systems will be conducted partially in house and partially at a NASA centre.

https://www.vicorpower.com/resource-library/articles/aerospace-and-defense-faqs

Wiring and Connectors

The wiring and connectors will be manufactured in-house as it needs to be directly fitted to the rover structure, with the inhouse manufacturing the control over the custom specifications is maintained. Materials such as aluminium and copper will be sourced from specialised suppliers. The estimated time of the entire process is estimated to take 4-6 months and includes around 800 person-hours. The integration of the Wiring and connectors with other systems will be conducted in house with final checks being made at a NASA Centre.

Power Monitoring Subsystem

The power monitoring subsystem will be outsourced. Companies such as Honeywell which has a proven track record and is known for their robust and reliable sensors and electronics for space applications. The estimated time of the entire process is estimated to take 8 months and includes around 900 person-hours. The integration of the Monitoring subsystem with other systems will be conducted partially in house and partially at a NASA centre.

https://aerospace.honeywell.com/us/en/products-and-services/industry/space

2.1.2.5 Power Subsystem Verification Plans

Requirement ID	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan	Expected Outcome
SYS-ELECL2-01	The system shall use different power sources	Demonstration	To demonstrate that the system can switch between different power sources effectively during operations.	Programming the rover to switch between the different power sources while ensuring the performance and stability of the system.	The rover can utilise all available power systems on board.
SYS-ELECL2-02	The solar panels shall be able to survive the lunar environment	Testing	To ensure the solar panels can survive the lunar environment.	Exposing the solar panels to a vacuum and extreme temperature differences to simulate the lunar environment.	The solar panels are in operational condition.
SYS-ELECL2-03	The solar panels shall resist dust accumulation	Testing	To maintain solar panel power generation efficiency.	Exposing the solar panels to dust to test the resistance and test the dust mitigation systems.	Dust accumulation can be dealt with.
SYS-ELECL2-04	The solar panels surface shall be able to discharge static build-up	Testing	Static build up can be dangerous for the rover.	Applying static charges to the solar panels surface and ensuring that it does discharge safely.	Static charge build up is discharged safely.
SYS-ELECL2-05	The solar panels used in the system shall provide at minimum 600 watts of power at all times	Testing	To ensure the solar panels can produce the required power levels.	Test power generation from the solar panels under similar conditions to the lunar surface.	600 watts of power are produced

SYS-ELECL2-06	The solar panels used in the system shall provide minimum 300 watts of power at peak sunlight	Testing	Testing the panels minimum output to ensure satisfactory results.	Testing the solar panels in a simulated lunar environment with peak sunlight levels.	A minimum of 300 watts are produced during peak sunlight.
SYS-ELECL2-07	The system shall have the ability to orient the solar panels towards the sun within 3 degrees of accuracy	Demonstration	Demonstration will prove that the solar panels can rotate and align with the sun correctly to provide the required energy.	Programming the solar panels to track the movement of the sun and measuring the accuracy to verify good results.	The solar panels are able to orient within 3 degrees of accuracy
SYS-ELECL2-08	The batteries used in the system shall maintain a minimum of 90% of total capacity over 600 charge/discharge cycles	Testing	Testing the lifecycle of the batteries for repeated charging and discharging.	Charging the discharging the battery to simulate operational use and measuring the results.	After 600 battery cycles, there remains 90% battery capacity.
SYS-ELECL2-09	The batteries used in the system shall be able to operate at temperatures between -20°C and 30°C	Testing	Ensuring that the batteries can operate within the determined temperature range.	Batteries can be placed into a thermal testing chamber to simulate changes in temperature expected during operation.	The batteries withstand temperatures between -20°C and 30°C
SYS-ELECL2-10	The system shall include a PDU	Inspection	Inspection will ensure proper installation of the PDU.	Physically inspecting the rover and verifying a secure attachment and placement.	The PDU is installed properly.
SYS-ELECL2-11	The system shall have multiple electrical paths to critical systems	Inspection	Inspection will ensure proper installation of redundant paths.	Physically inspecting the rover and verifying installation to all critical systems.	Multiple electrical paths are installed properly.
SYS-ELECL2-12	The systems PDU shall have minimal to no interruption time when	Demonstration	Ensuring that the rover can switch between	Simulating a transfer of power sources and monitoring any	There is minimal interruption during power

	switching between power sources		various power sources without causing issues.	power fluctuations during the change.	source switching.
SYS-ELECL2-13	The system shall have a thermal control system	Inspection	Inspection will ensure proper installation of the thermal control system.	Physically inspecting the rover to verify the installation of the thermal control system.	The thermal control system is installed correctly.
SYS-ELECL2-14	The thermal control system shall regulate the temperature to oscillate between -55ºC and 30ºC	Testing	Testing the thermal control system to confirm its ability to maintain safe temperatures.	Simulating changes in external temperatures and monitoring internal rover temperatures in a lunar-like environment.	Temperature is regulated between -55ºC and 30ºC by the thermal control system.
SYS-ELECL2-15	The system shall inform of low power conditions or any failures less than 1 second from detection	Testing	Testing the system to ensure that it can indeed detect failures or low power conditions in less than 1 second.	Simulate lower power conditions and power failures and monitoring the response from the system.	Low power or power failure is detected in less than 1 second.
SYS-ELECL2-16	The system shall be able to detect component failures or short circuits	Testing	Testing the system's ability to detect failures in components or short circuits.	Introducing random faults and failures within components and monitoring the response from the system.	Any component failure or short circuit is detected by the system.
SYS-ELECL2-17	The system shall be able to isolate damaged components or shut down when a short circuit is detected	Demonstration	Demonstrating the rovers ability to isolate components when needed.	Simulating damage to components requiring the system to isolate them and monitoring the results.	Damaged components are isolated or shut down by the system.
SYS-ELECL2-18	The systems electrical connectors shall be	Testing	Confirming that the electrical	Putting the electrical connections	Electrical connectors are resistant

	resistant to physical degradation and corrosion		connections will be able to withstand the lunar surface.	through harsh environmental conditions that may cause degradation or corrosion.	to degradation and corrosion.
SYS-ELECL2-19	The systems wiring shall use mechanisms preventing disconnections	Inspection	Inspection will confirm that disconnections will be prevented with the proper mechanisms.	Inspection of the rover and all internal connections that may come loose or disconnect completely.	Disconnections are prevented.
SYS-ELECL2-20	The systems voltage regulator shall be able to maintain a stable voltage output	Testing	Confirming that the voltage is stable and usable for the rovers needs.	Testing the voltage regulator by varying the load on the system and monitoring the results.	Stable voltage output is achieved and maintained.

2.1.3 CDH Subsystem Overview

The Command and Data Handling (CDH) Subsystem is the rover's central nervous system, managing commands, tasks, and data communication. The CDH system is a crucial component of TALICO's rover that serves as the central location for data processing and system management and control. It is responsible for all the rover's behaviour including receiving and actioning commands received from the orbiter, processing and preparing data for transmission, and managing system checks to ensure the rover and all components are operating as intended. The CDH system contains 6 main subsystems outlined below.

Microcontroller*:* Space grade microcontrollers are commercially available at this point, and have gone through rigorous radiation testing. The RAD750 is tried and tested being priced at $200,000, with use on Perseverance and James Webb Space Telescope. The CPU can clock 200MHz operating at 200 Mips and is above and beyond what we would need as a bare minimum. We can discount a CPU as a point of failure on our rover if we utilise the RAD750. It can operate between -55C and 70C whilst only drawing 10 Watts of power.

Table 14. Microcontroller specifications

Microcontroller	**Mass**	**Volume**	**Power**	**Technology Readiness Level**
RAD750	1kg	0.00059m^3	10 Watts	9

Internal Networking System: The internal networking system will run on VxWorks RTOS due to its tried and tested reliability in the Mars Rover program. In terms of the internal network, we need to prioritise certain messages carrying important real time information that will allow our rover to operate autonomously. This is why the CAN networking protocol is favourable due to its compatibility with VxWorks, as demonstrated in the Automobile industry (BMW iDrive). We are also able to detect low level communication errors with the CAN bus, which increases the reliability of our data. Its ability to facilitate a multi-node bus drop system is ideal as it allows for the most important message to be handled which allows safe operation of our rover. As a technology it was developed initially for automobiles. A downside is the hardware reliance as we have a number of wires and an additional transceiver for every node on our system, this can be handled through careful design. We will also need to develop a CAN bus connection to the PCI bus on the RAD750 Microcontroller if we are to use that, this is relatively simple with a number of commercial options.

Table 15. RTOS+CAN specifications

RTOS + CAN	**Mass**	**Volume**	**Speed**	**Technology Readiness Level**
VxWorks + CAN	-	-	8Mbs	6

Data Storage System: Our lunar rover needs to be able to handle a relatively large amount of data, early estimates for LIDAR in a comfortable terrain is about 1Mb/s if we are storing the mapped data. In terms of photography, a 12 megapixel photo will cost us around 4MB of data. This will obviously add up fairly quickly and change with the type of instruments attached to the rover. We need to design with redundancy in mind, but also recognise that the data can be uploaded to the satellite. We have two options of SSD's, which are the most reliable storage systems for space exploration, both of which have received NASA >6 TRL's, and have been designed for operating under high levels of radiation. They are able to operate in temperatures as low as -40C, and store up to 400Gb of data. They are both built with failsafe's, and fault tolerances which is how Mars Perseverance (2011) was able to stay in operation even after a storage system failure.

Table 16. SSD specifications

SSD	Mass	Volume	Speed (Reads)	Technology Readiness Level
RH3480 SSDR	1kg	~0.001m^3	8Gb/s	6

Protocols: The rover will use the Consultative Committee for Space Data Systems (CCSDS) standard protocols with NASA's Interplanetary Overlay Network (ION) implementation with the Delayed Transmission Network Bundle Protocols (DTN BP) architecture, to manage file transmissions between itself and the orbiter. This encompasses the File Delivery Protocol (ION CFDP), which allows for reliable file transmission (Manning, 2023). Access to the Class 1 and Class 2 transfer systems (unacknowledged and acknowledged respectively), which allows for transmission of non-critical data (Class 1) and mission critical data (Class 2) to ensure data integrity. The DTN protocol allows for 'store and forward' capabilities, which means data can be sent partially to a receiver when there is a connection and the receiver will store that information while waiting for the connection to restore. Once all data has been sent and received an acknowledgment message is sent back. The moon's location provides some obstacles for data transmission, including the noisy space environment, loss of signal between the transmitter (rover) and receiver (orbiter), etc (Schauer, 2020). The ION CFDP is designed exactly for this type of environment. ION CFDP also allows for lossless data compression ensuring reliability and faster transfers of mission critical data from onboard the rover.

Antenna: The rover will use only one antenna for communication, one phased array antenna that encompasses a low gain antenna (LGA) and a high gain antenna (HGA). The LGA will provide a wide angle of coverage by sending out signals in a wide beam in all directions. In doing so the signal strength is weaker but able to cover a much wider area. This antenna will be used for 'housekeeping' data, sending commands to and from the rover along with system status and other mission non-critical data. This antenna will transmit on the S-band around 2-4 GHz with speeds of around 4Mbps. The high gain antenna (HGA) will transmit all mission critical data because of its ability to focus the signal beam much narrower allowing for precise targeting of the signal and allowing for more information to be sent. A phased array antenna is able to electronically steer the signal beam which means there are no moving parts controlling the antenna which allows for less mechanical risk of parts failing. This antenna will transmit on the Ka-band at around 20-30GHz and allow for upload speeds of around 20Mbps. Phased array antennas are considered to be the next generation of communication technology within the space sector (Nessel et al., 2020). Phased array antennas in a planar style are made up of smaller antennas placed onto a sheet, the number of antennas that make up the whole antenna can vary based on the required usage and needs making them adaptable to the required circumstance (Electronics Notes, n.d.). The smaller antennas can range from several up to hundreds and more. The way in which it works is by taking advantage of constructive and destructive interference patterns in the radio waves. As all the antennas transmit their separate signals they interfere with each other as they propagate, small timing delays can be made between the antennas which cause different interference patterns within the signals (Jackson, 2018). Destructive patterns can create a narrower beam while constructive patterns increase the strength. Depending on the timing between signals the direction of the beam can also be controlled through the use of these interference patterns (He et al., 2023). The use of this antenna allows for the beam to be steered without any mechanical movements on the rover which decreases the possibility of parts failing within the system.

Table 17. Antenna specifications

Antenna	**Mass**	**Volume**	**Power**	**Technology Readiness Level**
Phased Array Antenna	<5kg	~0.0045m^3	<10W	9

On Board Computer (OBC): The rover will be equipped with two separate operating systems installed on the hard drive. This will ensure that if there are any major faults in the system, such as file corruption within the rover's primary software, then a backup system will be ready to take control and manage the rover and all its subsystems. The rover will be able to detect these faults automatically to ensure a seamless transfer of control from each operating system. When this happens, the fault will be diagnosed by software engineers on Earth and the corrupted software can be isolated and wiped. This allows a new copy of the software to be downloaded from the orbiter and reinstalled on the rover to ensure that the redundancy of the system is renewable and operational.

The technology readiness level of each subsystem within the Command & Data Handling system. The total TRL is level 6.

Table 18. Technology readiness level summary

Technology Readiness Level					
Antenna	Microcontroller	Networking System	Internal Storage	Communications Protocol	**Total TRL**
9	9	6	7	9	**6**

Software Architecture Flow Chart:

Figure 8. Software Architecture Flow Chart

2.1.3.1 CDH Subsystem Requirements

Req #	**Requirement**	**Rationale**	**Parent Req**	**Child Req**	**Verification method**	**Relevant Subsystem**	**Req met?**
CDH 01	The system shall handle all data onboard the rover	A centralised place for all data processing		CDH-02 CDH-03 CDH-04 CDH-05 CDH-06 CDH-07		OBC	
CDH 02	The system shall receive and perform commands from the orbiter and transmit back	Communication with the rover to control it remotely	CDH-01			antenna	

CHD 03	The system shall store 400Gb of data	Storage of mission data on board the rover before transmission and during times with no link to the orbiter	CDH-01			storage	
CDH 04	The system shall process data onboard the rover in preparation for transmission to the orbiter	Processing raw data ready for transmission and analysis (compressing files)	CDH-01			OBC	
CHD 05	The system shall transmit data to the orbiter at maximum speeds of 20Mbps	High speeds in order to transfer large and numerous files	CDH-01			antenna	
CHD 06	The system shall have built in software redundancies	Ensuring the critical data is not lost in the event of an error, increasing reliability	CDH-01			software	
CDH 07	The CPU? shall monitor the health of the rover and all sub systems	Ensuring the rover and all subsystems are within their temperature limits, instruments operating at optimal power levels, battery levels are adequate, etc	CDH-01			OBC	

2.1.3.2 CDH Sub-Assembly Overview

The CDH subsystem can be thought of as a negotiator between all the components on board the lunar rover. We negotiate all the data through a central CPU which will facilitate communication with a high gain antenna via S and KA band protocols. The embedded systems on a lunar rover have to be incredibly reliable and to facilitate this the data being received from the sensors such as LiDAR or the Path Planning Algorithms (PPA) will be sent on a CAN bus. The CAN bus gives us many advantages, namely the bus negotiation will allow for the prioritization of messages. This can help us preserve the rover in the unpredictable terrain found on the south pole. By allowing us to assign a high priority header to data that can ensure the safety of the rover, over data from the TRIDENT drill , which can be sent later. For other sections such as reading and writing to storage, Ethernet is sufficient. We will use a TCP protocol for the Ethernet data internally.

The transmission of data will be done through the KA and S band as is standard among space communications. We find that we have sufficient storage space to transfer data to the orbiting satellite every 24 hours. We will also store a backup of the past 3 days of data onboard the lunar rover in the event of an emergency, or fault in transmission.

In order to optimize data collection, we will limit data handling onboard. By doing this we can optimize the amount of samples collected as we will send the data out, and then proceed with the next task. This is ideal for the single core RAD750.

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans

In order to ensure the integrity and execution of critical components within the CDH subsystems, the TALICO team has several redundancy and recovery systems. The CDH is comprised of 6 main subsystems, those being the On Board Computer (OBC), Internal Networking System, Data Storage System, Antenna, Protocols and Microcontrols. The TAILCO team has run extensive risk assessments for all options relating to each subsystem, ensuring the most effective hardware and software has been implemented. This ensures effective communication and data transfer to the orbiter.

<u>On Board Computer (OBC):</u> For operational redundancy, the rover will be equipped with two separate operating systems installed on the hard drive. This will ensure that if there are any major faults in the system, such as file corruption within the rover's primary software, then a backup system will be ready to take control and manage the rover and all its subsystems. The rover will be able to detect these faults automatically to ensure a seamless transfer of control from each operating system. When this happens, the fault will be diagnosed by software engineers on Earth and the corrupted software can be isolated and wiped. This allows a new copy of the software to be downloaded from the orbiter and reinstalled on the rover to ensure that the redundancy of the system is renewable and operational.

<u>Internal Networking System:</u> CAN has some error potential when it comes to the transceiver, if the RHU fails and the temperature drops to -200C TALICO will have a failure mode. TALICO contains bit error checking which will allow the team to run data through again if there is a loss. Ethernet can also be error checked through a TCP protocol. A backup protocol makes no sense and is not readily executable. TALICO's protocol will be thoroughly tested on Earth and therefore should not be a point of total failure. The internal networking system will run on VxWorks RTOS due to its tried and tested reliability in the Mars rover program. In terms of the internal network, TALICO needs to prioritise certain messages carrying important real time information that will allow the rover to operate autonomously. This is why the CAN networking protocol is favourable due to its compatibility with VxWorks, as demonstrated in the Automobile industry (BMW iDrive). TALICO is also able to detect low level communication errors with the CAN bus, which increases the reliability of our data. Its ability to facilitate a multi-node bus drop system is ideal as it allows for the most important message to be handled which allows safe operation of our rover. One flaw is the hardware reliance as we have a number of wires and an additional transceiver for every node on our system, this can be handled through careful design.

Data Storage System: The TALICO team will segment our memory in case of any certain errors within parts of the data storage system. If the system goes down fully the team is confident that the data storage system should be able to use the CPU memory to redownload data from the satellite. The TALICO team believes It would be financially irresponsible to implement a backup data storage system. Instead an effective recovery system will be implemented. The best way to store data generated on the rover is a digital storage system. RH3480 SSDR and the 3U TRRUST-Stor VPX RT were assessed for reliability, storage space, reading and writing speeds, and flash memory. The RH3480 SSDR was chosen due to the higher overall score and will support TALICO's rover in collecting and storing rover generated data. TALICO's lunar rover needs to be able to handle a relatively large amount of data. We need to design with redundancy in mind, but also recognise that the data can be uploaded to the satellite. TALICO have two options of SSD's, which are the most reliable storage systems for space exploration, both of which have received NASA >6 TRL's, and have been designed for operating under high levels of radiation. They are able to operate in temperatures as low as -40C, and store up to 400GB of data. Both are built with failsafes, and fault tolerances.

Protocols: Recovery is built into the CCSDS and NASA's protocols. The rover will use Consultative Committee for Space Data Systems (CCSDS) standard protocols with NASA's Interplanetary Overlay Network (ION) implementation with Delayed Transmission Network Bundle Protocols (DTN BP) architecture, to manage file transmission between itself and the orbiter. This encompasses the File Delivery Protocol (ION CFDP), which allows for reliable file transmission (Manning, 2023).CCSDS allows for acknowledged notifications to ensure data has been transmitted in full and not lost. The DTN protocols will allow for partial data transfer to pause when signal is lost and to resume when signal is re-established. The protocols will not require a redundant subassembly as this is all handled through the use of software.

Antenna: The antenna will not require any redundant software features as this will be handled by the other subassemblies. The phased array antenna consists of many smaller antennas all working together to produce a signal. When one of these antennas fails the others can all adapt to the lost antenna and continue to produce a signal. Although the strength of the signal will weaken as more antennae fail, it will still be able to function allowing for graceful degradation of the subsystem. SPF's. Due to the need to steer the beam to establish a connection with the rover, both the patch array and parabolic reflectors would need to be attached to a gimbal. The phased array scored highest in the three categories for its slim profile, highly steerable beam, and durability for having no physically moving parts. No moving mechanical parts on the antennas allow for lower risk of mechanical failure.

Microcontroller: As mentioned above, space grade microcontrollers are commercially available at this point, and have gone through rigorous radiation testing. The RAD750 is tried and tested, with use on the Perseverance and James Webb Space Telescope. The CPU can clock 200MHz operating at 200 Mips and is above and beyond the specs needed at a bare minimum. We can discount CPU as a point of failure on our river if we utilise the RAD750. It can operate between -55C and 70C whilst only drawing 10 WAtts if power.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans

The manufacturing and procurement plan (Table 19) ensures that the CDH subsystem of the mission is entrusted to reputable suppliers with proven expertise in space hardware development. Byn leveraging both in-house capabilities and external partnerships, TALICO aims to optimise cost, schedule and performance to achieve its mission success.

Table 19. High-Level Overview of Manufacturing and Procurement Plans for CDH

Subsystem	**Potential Major Supplier**	**Justification**	**Lead Time (Est.)**
CDH	JPL, JSC, Intel, Micron, Electro Optic Systems (EOS)	To ensure close integration with other mission components, tailoring the CDH system according to the mission requirements.	6 months

The command and Data Handling (CDH) subsystem is the rover's central nervous system, managing commands, tasks and data communication. The manufacturing and procurement plan for the CDH subsystem covers component sourcing, testing, integration, verification, validation and schedule milestones. The manufacturing and procurement plan for the CDH subsystem covers component sourcing, testing, integration, verification, validation and schedule milestones. Critical components, such as flight computers and data storage units, will be sourced from NASA’s JPL and JSC, with Intel’s space-grade processors, Micron’s radiation-hardened SSDs, and EOS communication interfaces chosen for their reliability in space. This blend of specialised NASA components and COTS suppliers balances stringent requirements and cost-efficiency (Table 20).

Extensive prototype testing under simulated lunar conditions (thermal stress, radiation) ensures reliability. NASA components undergo rigorous qualification testing, while COTS components meet industry standards. Integration of CDH components in a cleanroom ensures precise assembly and compatibility. System-level tests validate computational performance, data handling and communication reliability. Verification and validation confirm design compliance and mission readiness. Component lead times range from 6 to 12 months, ensuring the subsystems reliability for lunar exploration.

Table 20. Manufacturing and Procurement Plans Overview of CDH Subsystems

Subsystem	**Component**	**Description**	**Supplier Type**	**Potential Supplier**	**Reason**

CDH	Flight computers	Central processing units for executing commands and processing data.	Contractor	JPL	JPL's expertise in space mission hardware ensures high reliability and performance.
CDH	Data storage	Devices for storing mission data securely.	Contractor	JPL	Ensures access to reliable and high-capacity data storage solutions.
CDH	Space-grade Processors	These are processors designed to withstand harsh space conditions.	COTS	Intel	Intel's space-grade processors offer reliability and performance.
CDH	Radiation-hardened SSDs	Solid-state drives resistant to space radiation for data storage.	COTS	Micron	Ensures data integrity and endurance in space missions.
CDH	Onboard Computing Systems	Integrated hardware and software systems for onboard data handling and processing.	Contractor	JSC	JSC's tailored solutions ensure compatibility with mission requirements.
CDH	Memory Modules	Storage modules for temporary data processing and storage.	COTS	Intel	Provides cost-effective and reliable memory solutions.
CDH	Communication Interfaces	Hardware for data transmission between the rover and mission control.	COTS	EOS	Ensures reliable communication systems for data transmission.
CDH	Software Redundancies	Backup systems for fault tolerance	In-house	TALICO	Customization and control over software development
CDH	Radiation Shielding	Protects electronics from radiation	Contractor	Northrop Grumman	Expertise in developing radiation-hardened components

Table 21. TALICO Mission Risk Analysis for CDH subsystems

ID	*Summary*	*L*	*C*	*Trend*	*Approach*	**Risk Statement**	**Status**
19	CDH	1	2	NEW	R	Due to the lack of an electromagnetic field protecting the Moon from space radiation, it is possible that data storage corruption may occur causing loss in scientific measurements causing a delay in the mission.	Active
20	CDH	2	5	NEW	M	Due to the presence of regolith dust, obstructions from build up may occur causing interference in the use of antenna affecting the ability of the rover to communicate.	Active
21	CDH	2	5	NEW	M	Due to workmanship error, vibration from drilling may cause spacewiring to become compromised, potentially affecting the operability and connectivity of internal circuitry.	Active
22	CDH	2	5	NEW	M	Due to workmanship error, it is possible for outgassing to occur from some materials in reaction to the vacuum of space, creating debris around electronic components that may cause malfunction, possibly to the extent of mission failure	Active

2.1.3.5 CDH System Verification Plans

The management of the rover's communication, storage, and data processing processes depends on the Command and Data-Handling (CDH) subsystem. To make sure its requirements are satisfied, the verification plans entail an extensive set of tests, analyses, demonstrations, and inspections. The strategies listed below guarantees that the CDH subsystem satisfies all of its needs. All requirements will be thoroughly tested, analysed, and shown to ensure that the system functions as intended in a variety of scenarios. These steps ensure that the CDH subsystem can process data onboard for efficient communication with the orbiter, store a sizable amount of mission data, transmit and receive orders with reliability, and handle data efficiently.

Table 22. TALICO Mission Verification plans for CDH subsystems

Requirement ID	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan	Expected Outcome
CDH-01	System shall handle all	Functional	A Centralised Place For	Simulate data processing	System correctly

Requirement ID	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan	Expected Outcome
	data on board the rover	Testing	Data Processing	operations and verify all data is correctly handled onboard	processes and manages all onboard data
CDH-02	The system shall receive and perform commands from the orbiter and transmit back	Command and Telemetry Testing	Communication with the rover to control it remotely	Send commands from a simulated orbiter and verify the rover's response and data transmission back	System successfully receives commands and transmits data back to the orbiter
CHD-03	System shall store 400Gb of data	Data Storage Capacity Testing	Storage of mission data on board the rover before transmission and during times with no link to the orbiter	Load 400Gb of dummy data into the storage system and verify storage integrity and retrieval	System can store, maintain, and retrieve 400Gb of data
CDH-04	The system shall process data on board the rover in preparation for transmission to the orbiter	Data Processing Testing	Processing raw data ready for transmission and analysis(compressing files)	Perform data processing tasks including compression and verify processed data is ready for transmission	System successfully processes and prepares data for transmission
CDH-05	The system shall transmit data to the orbiter at maximum speeds of 20Mbps	Performance Testing	High speeds in order to transfer large and numerous files	Conduct transmission tests to measure data rate under various conditions, ensuring the system can achieve and maintain 20Mbps	System successfully transmits data to the orbiter at 20Mbps under expected operational conditions
CDH-06	System shall have built in software redundancies	Redundancy Testing	Ensuring the critical data is not lost in the event of an error increasing reliability	Simulate software failures and verify system recovery and data integrity	System maintains data integrity and continues operation during software failures
CDH-07	The CPU monitor the health of the robot and all subsystems	Health Monitoring Testing	Ensuring the rover and all subsystems are within the temperature limits, instruments operating at optimal power levels, battery levels are adequate etc	Simulate various operational scenarios and verify the health monitoring system reports accurate status and alerts	System accurately monitors and reports the health status of all rover subsystems

2.1.4 Thermal Control Subsystem Overview

The Thermal subsystem consists of a Thermal Link, Insulation, and Heater. The thermal link chosen is a Variable Conductance Heat Pipe (VCHP), commonly used spacecraft due to its efficient use of heater power in cold environments, acting as a “Thermal Superconductor.” VCHPs suit the restrictions of the mission environment while being passive, reducing the risk of overheating electronics and keeping temperature consistent and stable. Overheating is not seen as a risk under this thermal link thus thermal dumping mechanisms such as Louvres are not necessary. Insulation will be done primarily through a thin, brittle, yet effective insulator of Aerogel within the rover body, protected by metal exterior. A thermal blanket of Aluminized Kapton surrounds the body exterior. Lastly, a baseline of heat generation is established using an RHU with an emergency electric heater that can be deployed during unexpectedly long periods of cold.

Operating temperatures of components:
RAD750: 218.15 - 398.15 K
RH3480: 233.15 - 343.15 K
IMU: 233.15 - 358.15 K
Battery: 223.15 - 398.15 K

Thus, the temperature inside the rover must be kept between 233.15 - 343.15 Kelvins at all times to ensure all components remain operational.

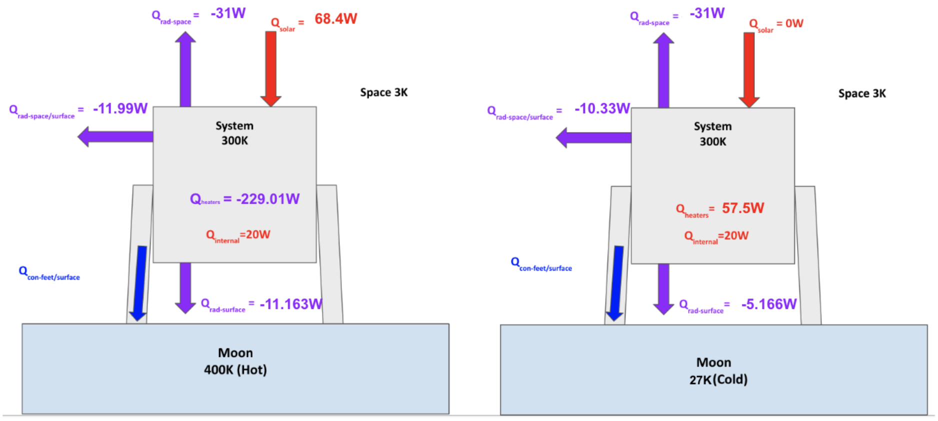


Figure9. Heat Flow Map

6.1.1.1. Thermal Control Subsystem Requirements

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

TCS-01	The system shall protect its instruments from temperature fluctuations from daytime to PSR's	The system needs to move between the PSR's and daytime at the poles which means extreme 250+ degree temperature swings			Test	Thermal	
TCS-02	The system shall retain a consistent internal temperature at all times	Electronics and computing systems have certain environment requirements for optimal operation			Test	Thermal	
TCS-03	The system shall ensure the negative effects of radiation do not have significant impact	The moons exposure to EM radiation from the sun is considerably worse than Earths			Test	Thermal	
TCS-04	The system shall maintain battery temperatures to above -20 degrees C at all times	Batteries are not operable below -20 C. Heating systems along with all other systems require power storage in some form thus it is crucial these are left at an operating temperature.	TCS 02		Analysis	Thermal	
TCS-05	The system shall maintain an internal temperature of above -55 degrees C at all times	All industrial or military semiconductor electronics have operating temperatures of above minus 55 degrees C.	TCS 02		Test	Thermal	
TCS-06	The system will have insulation that can thermally isolate the system from the environment	Radiating heat to the environment poses the risk of freezing electronics to the unpredictable thermal conditions of the PSR.	TCS 01		Analysis	Thermal	
TCS-07	The system will have instruments designed to measure the temperature around the rover body	Sensors are necessary for the assessment of the thermal situation, providing evidence for the use of emergency heaters that require critical power.	TCS 01,02		Analysis	Thermal	
TCS-08	The system will proactively react to measured changes in temperature to maintain a stable operating temperature	As temperature is a mission critical factor to the function of the rover, The ability to react to alarming body temperatures is crucial in rover survival.	TCS 01,02		Demonstration	Thermal	

2.1.4.2 Thermal Control Sub-Assembly Overview

The moon is prone to extreme temperature differences between sunlit and shadowed regions due to its lack of significant atmosphere. The insulation aims to prevent temperatures inside the rover from changing drastically by attempting to thermally isolate the system from the moon's environment. This will be done primarily through a thin, brittle, yet effective insulator of aerogel within the rover body, protected by metal exterior and a thermal blanket of aluminized kapton surrounding the body exterior. The thermal blanket on the exterior of the rover must be able to withstand general wear and tear from the moon's sharp regolith in order to be successful in maintaining temperatures inside the rover. It must also be ensured that the negative impacts of radiation does not have a significant impact on the kapton blankets attached to the exterior of the rover to ensure the mission is successful. The chosen insulation method has been used in multiple successful missions in the past and is currently at TRL-9.

VCHP's will be used to remove heat from the rover when it is in the sunlit regions of the moon. The chosen insulation method has been used in multiple successful missions in the past and is currently at TRL-9.

RHU's will be used to provide heat to the rover when it is in the shadowed regions. The RHU's will be producing heat at all times but will only be vital to the mission in the shadowed regions. The chosen insulation method has been used in multiple successful missions in the past and is currently at TRL-9.

2.1.4.3 Thermal Control Subsystem Recovery and Redundancy Plans

Table 23. TALICO Mission Thermal Control Recovery and redundancy plans

Subassembly	Recovery	Redundancy
Thermal Link	In the event that the VCHP thermal link fails to regulate temperatures and keep the rover within safe limits, the rover can momentarily power down certain instruments or non-essential components to allow them to cool and reduce the thermal load. The rover will monitor temperature levels during all operations to ensure that unsafe temperatures are never reached.	A second VCHP can be installed in parallel with the first or as a backup, which will enable continued thermal load handling if one was to fail or experience errors.
Insulation	Due to the insulation of the rover being aerogel, which will use no moving parts or electrical components, there is no recovery method that can be taken. Once damage has been sustained the	There can be no redundancy of the insulation due to the practical constraints of the aerogel's application. The insulation cannot be swapped during or replaced during the mission.

	aerogel cannot be swapped, moved, or repaired while on the lunar surface. The insulation will be designed to withstand the lunar conditions, however, in the event that the insulation fails, no in-situ repair can be done.	
Heat Generation	Since the RHU is critical for holding the baseline temperature of the rover in safe operating limits, the electrical heaters on board can autonomously step in if the RHU was to fail or experience a problem during operation.	There is no redundant RHU unit, but emergency electrical heaters may be able to compensate with careful usage and constant monitoring or power consumption and temperature readings.

2.1.4.4 Thermal Control Subsystem Manufacturing and Procurement Plans

The thermal management subsystem is responsible for ensuring the temperature inside the rover is maintained within the working temperatures for instruments. A combination of reputable contractors and COTS suppliers will be enlisted to fulfil the component requirements of the thermal subsystem. Components such as the VCHP will be manufactured at NAECO PTY LTD due to their comprehensive manufacturing and engineering expertise, specifically focused on supporting high end manufacturers and designers in the Aerospace and Defence sectors. Other components such as the RHU's and kapton and aerogel blankets will be purchased from COTS and assembled in house to reduce cost and manufacturing time. Prototypes of critical thermal components, such as VCHP, kapton and aerogel blankets and RHU will undergo extensive testing to validate performance under simulated lunar environmental conditions. This includes thermal stress testing, radiation exposure and physical stress testing to ensure the system is functional, reliable and consistent with NASA standards and spaceflight requirements. Upon successful qualification, thermal components will be integrated according to the detailed integration plans. This involves attaching the kapton and aerogel blankets to the exterior of the rover, installing VCHP and RHUs. Assembly of thermal management components of the rover will be conducted in close collaboration with thermal management engineers to ensure seamless functionality and compatibility of the thermal subsystem. The thermal management subsystem will undergo comprehensive system-level testing to ensure compatibility.

2.1.4.5 Thermal Control Subsystem Verification Plans

Table 24. TALICO Mission Verification plans for Thermal Control

Requirement ID	**Requirement Summary**	**Verification**	**Rationale for Method**	**Preliminary Verification**	**Expected Outcome**

TCS-01	The system shall protect its instruments from temperature fluctuations from daytime to PSRs	Testing	The instruments must be protected and operational during temperature fluctuations.	Simulating large temperature fluctuations as seen on the lunar surface and in PSRs.	The rover is protected from temperature fluctuations.
TCS-02	The system shall retain a consistent internal temperature at all times	Testing	Maintaining a stable internal temperature will be crucial for the critical systems in the rover to stay operational.	Simulating changes in temperature and monitoring the results	The rover maintains consistent internal temperatures.
TCS-03	The system shall ensure the negative effects of radiation do not have significant impact	Testing	Radiation can have negative effects on many aspects of the rover during its operational life.	Testing the system under controlled radiation exposure and monitoring the results	Minimal impact on the rover from radiation.
TCS-04	The system shall maintain battery temperatures to above -20ºC at all times	Testing	The battery must remain above -20ºC at all times to not sustain damage.	Thermal testing of the battery by simulating the harsh environment of the lunar surface.	The battery temperature remains above -20ºC.
TCS-05	The system shall maintain an internal temperature of above -55ºC at all times	Testing	Critical components within the rover must be above -55ºC at all times to ensure longevity.	Thermal testing of the rover by simulating the cold lunar environment.	Internal rover temperatures remain above -55ºC at all times.
TCS-06	The system will have insulation that can thermally isolate the system from the environment	Inspection	Insulation is important to keep heat from escaping into space and cooling the rover below safe limits.	Inspecting the rover to see the insulation is installed properly.	Insulation is installed properly.
TCS-07	The system will have instruments designed to measure the	Inspection	Temperature sensors are important when monitoring the	Inspection will ensure the temperature sensors are	Temperature sensors are installed properly.

	temperature around the rover body		rover’s system health.	installed correctly.	
TCS-08	The system will proactively react to measured changes in temperature to maintain a stable operating temperature	Demonstration	To demonstrate that the rover can maintain stable temperatures and ensure it is always within the safe limits.	Simulating changes in temperature similar to those that will be seen on the lunar surface and in PSRs.	The systems is proactively reacting to temperature changes and the rover remains operational.

2.1.5 GNC Subsystem Overview

The Guidance, Navigation, and Control (GNC) subsystem is the core of the rover's autonomous mobility, allowing it to traverse the lunar surface, avoid obstacles, and reach target destinations efficiently and safely. This subsystem integrates several sub-assemblies, each designed to work together seamlessly to ensure the rover can navigate and operate effectively in the challenging lunar environment. The GNC subsystem includes the following key components:

a. Guidance: Determines the rover's current location and plans the optimal path to the target.
b. Navigation: Maintains real-time information about the rover's position, velocity, and orientation.
c. Control: Applies steering and movement commands to follow the planned path while maintaining stability.

Integration and Functionality

The diagram provided illustrates the interactions between the various sub-assemblies of the GNC subsystem. Below is a detailed explanation of how these components work together to ensure the rover's successful navigation and control:

- Perception Equipment Interface:
    - **LiDAR and IMU Sensors:** These sensors continuously gather data about the rover’s environment and its own movements. The LiDAR (Light Detection and Ranging) measures distances to nearby objects using laser light, providing detailed mapping of the terrain. The IMU (Inertial Measurement Unit) tracks the rover's acceleration and rotational rate.
    - **Data Processing:** The sensor data is processed by the Perception Equipment Interface, which converts raw measurements into actionable information for the rest of the GNC system.
- Localisation:
    - **Position and Orientation**: Using the processed sensor data, the localisation component determines the rover's precise position on the lunar surface and its orientation.
    - **Relative Movement:** This component also tracks changes in the rover's position and orientation over time, essential for understanding its current location relative to previous positions and planned paths.
- Terrain Monitoring and Analysis:
    - **3D Mapping:** Creates a detailed three-dimensional map of the surrounding environment using the point cloud data from LiDAR and visual data from cameras.
    - **Obstacle Detection:** Identifies and classifies features such as rocks, craters, and slopes, crucial for navigation and obstacle avoidance.

- Path Planning:
    - **Route Calculation**: Utilises localisation and terrain analysis data to calculate the safest and most efficient path to the target. This involves considering terrain features and obstacles to avoid potential hazards.
    - **Trajectory Adjustment**: Continuously adjusts the planned path in real-time based on updated sensor data and environmental changes, ensuring the rover can navigate dynamically.
- Locomotion and Manoeuvre Control:
    - **Actuator Drive Electronics:** Converts path planning commands into specific actions, controlling the rover's steering and motors.
    - **Movement Execution:** Ensures the rover follows the planned path while avoiding obstacles and maintaining stability. This involves precise control over the rover's wheels and steering mechanisms to execute smooth and accurate movements.

Workflow Overview

The integrated workflow of the GNC subsystem can be summarised as follows:

1. **Data Acquisition**: Sensors (LiDAR and IMU) collect data about the environment and the rover's movements.
2. **Data Processing and Perception**: The Perception Equipment Interface processes this data, generating detailed maps and identifying obstacles.
3. **Localisation**: Determines the rover's precise position and orientation using the processed sensor data.
4. **Terrain Monitoring**: Analyses the terrain, classifying features to inform path planning.
5. **Path Planning**: Calculates the optimal path to the target, adjusting dynamically based on new data.
6. **Control and Execution**: The Locomotion and Manoeuvre Control system applies the necessary commands to steer and drive the rover, ensuring it follows the planned path and avoids obstacles.

The GNC subsystem's parts and data flow are illustrated as a simple diagram above in figure[]. To summarise the perception sensors connecting to LiDAR and IMU sensors are the first step in the process which feeds into localisation and to terrain monitoring and analysis. Path planning receives data processed by the localisation and terrain monitoring subsystems. The paths generated by the path planning subsystems are carried out by the locomotion and manoeuvre subsystem, which is composed of actuators and drive electronics.

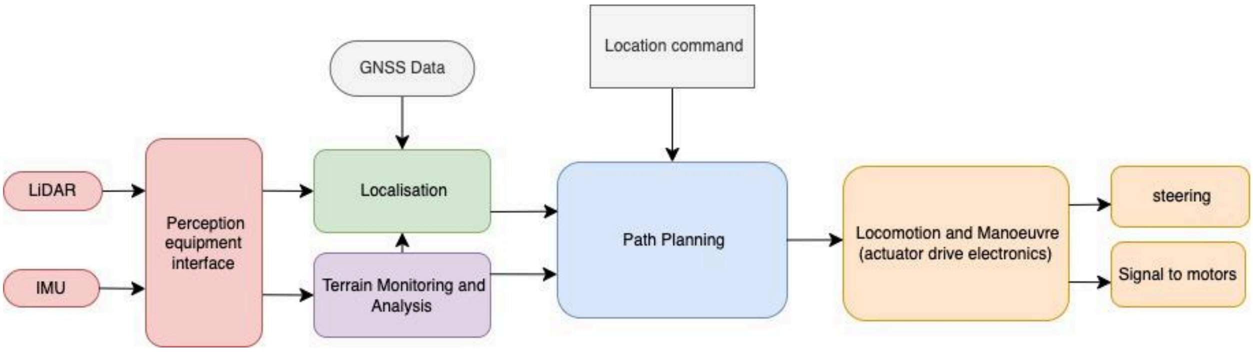


Figure 9. Flow Block Diagram of the Lunar Rover Guidance, Navigation, and Control (GNC) Subsystem

Summary

The GNC subsystem's integration of guidance, navigation, and control functions is essential for the rover's autonomous operation on the lunar surface. Each component plays a crucial role in ensuring that the rover can determine its position, plan a safe path, and execute movements accurately and efficiently. This sophisticated system enables the rover to conduct its mission successfully, navigating the lunar environment's complexities and achieving its exploratory goals.

2.1.5.1 GNC Subsystem Requirements

The GNC subsystem is integral to the successful operation of any rover on the lunar surface. This subsystem ensures that the rover can autonomously navigate, avoid obstacles, and reach designated targets or areas of interest. The requirements outlined below detail the functionalities and capabilities necessary for the GNC subsystem to effectively support the rover's mission objectives. Each requirement specifies the critical aspects such as localisation, perception, path planning, terrain monitoring, and locomotion control. These requirements have been derived to guarantee that the rover can operate safely, navigate efficiently, and perform its mission-critical tasks accurately. Verification methods such as testing and analysis are also specified to ensure these requirements are met. The table below provides a comprehensive list of the lower-level requirements that are used to design the GNC subsystem.

Requirement ID	Subsystem	Requirement description	Parent Req	Child Req	Rationale	Verification Method
SYS-GNC2-01	Localisation (Navigation)	System shall determine relative location/position of rover on lunar surface	SYS-GNC-04		Required to later determine path to conduct mission objective.	Test
SYS-GNC2-02	Perception	System shall use a sensor system, using laser light to measure distances to objects with X detection range.	SYS-GNC-04	SYS-GNC2-03	Essential for accurate perception of the environment and obstacle avoidance	Test
SYS-GNC2-03	Localisation (Navigation)	System shall extract distinct visual features from sensor/cameras		SYS-GNC2-04	Ensures appropriate information is collected for downstream applications i.e localisation or obstacle detection	Test
SYS-GNC2-04	Localisation (Navigation)	Shall use distinct visual features to provide accurate guidance to the rover.	SYS-GNC2-03		Allows rover to determine its relative location to make appropriate decisions based on mission objective, i.e direction of travel.	Test
SYS-GNC2-05	Path planning (Guidance)	System shall utilise perception and terrain monitoring subsystems to identify obstacles.			Crucial for path planning and obstacle avoidance	Analysis
SYS-GNC2-06	Perception	System shall create 3-dimensional mapping of surrounds (using point cloud mapping)			Provides a detailed understanding of the terrain for navigation and path planning	Test
SYS-GNC2-07	Terrain monitoring/analysis	System shall classify surroundings (rocks, craters slopes)		SYS-GNC2-08	Necessary for determining the nature of the terrain and avoiding hazardous areas	Test
SYS-GNC2-08	Path planning (Guidance)	System shall use classified surroundings to determine safest route	SYS-GNC2-07		Ensures the system prioritises paths with minimal steep angles to avoid tip-overs and avoids collisions etc.	Analysis
SYS-GNC2-10	Locomotion and manoeuvre Control	System shall follow determined path trajectory	SYS-GNS-01 SYS-GNC-04	SYS-GNC2-11	Ensures rover travels the safest path between locations	Test
SYS-GNC2-12	Locomotion and manoeuvre Control	Rover shall utilise IMU data to autonomously adjust its velocity.	SYS-GNS-01		Ensures rover maintains stability	Demonstration
SYS-GNC2-13	Locomotion and manoeuvre Control	System shall autonomously steer to avoid obstacles and maintain path trajectory	SYS-GNS-01 SYS-GNC2-10		Ensures rover avoids any collisions or maintains stability	Demonstration

2.1.5.2 GNC Sub-Assembly Overview

Perception Sub-assembly

Identifying and interpreting the rover's surroundings is the primary function of the perception subsystem in a lunar rover. This entails recognising scientific targets, mapping the environment, and identifying barriers using sensors like LiDAR, stereo cameras, or other optical technologies. By comprehending this data later through the terrain monitoring and analysis subsystem is able to build and categorise a comprehensive structure of its surrounding environment such as slopes, craters and any other obstacles on the lunar surface thanks to the data provided by the perception subsystem. The rover is able to move safely, avoid obstacles, and carry out mission objectives by making decisions to avoid based on the data collected by these sensors.

Components:

The best optical sensor for this task is a LiDAR sensor, light detection and ranging, is a remote sensing technique that measures a target's distance from it using laser light. LiDAR devices take measurements of the time it takes for light to return to the sensor after producing laser pulses, which allows them to produce accurate, three-dimensional maps of their surroundings (Carter et al. 2012).

This best suits TALICOs needs as compared to Hazcams, or rather stereo-cams, previously used on all mars rovers, as it does not rely on visible light to capture its surrounds which proves ideal as the rover is set to travel within PSR which will have no light in some areas.

Having been extensively used in planetary exploration missions, the LiDAR will have a TRL of 6 (Frampton et al., 203), as this technology exists and has high maturity in other applications, although its integration into lunar missions may require further validation and testing ensuring it can endure the harsh elements of the lunar environment.

Overall this Sub-assembly has a technology readiness level of 6.

Terrain Monitoring & Analysis Sub-assembly

Terrain monitoring and analysis is set to continuously assess the rover's environment on the lunar surface to guarantee safe navigation and ideal path planning through the path planning Sub-assembly. In order to support well-informed decision-making for movement and scientific discovery, it recognises and evaluates topographical elements like slopes, barriers, and surface textures collected from the perception subsystem, as previously mentioned, these classifications are then provided to both the localisation and path planning Sub-assembly.

Components:

The components necessary for this Sub-assembly are simply those included in the perception Sub-assembly including LiDAR And the appropriate software. The Terrain Monitoring and Analysis Sub-assembly software is based on components that have been extensively used and validated in other Mars missions, it is reasonable to assign a Technology Readiness Level of 8 . Indicating that the software has been thoroughly tested and proven in relevant operational environments, similar to that of the lunar surface (Winter, Barclay, Pereira, Lancaster, Caceres, Mcmanamon, et al. 2015)

Localisation (Navigation) Sub-assembly

The accurate determination of the rover's position and orientation on the lunar surface is the responsibility of the Localisation Sub-assembly. This provides accurate and real-time updates on the rover's location by combining data from its sensors, including as inertial measurement units (IMUs) and visual odometry devices. Through the integration of several data sources, the Localisation subsystem guarantees the rover's ability to manoeuvre independently, avoid obstructions, and accomplish its scientific objectives. For the mission to be successful, accurate localisation is essential since it allows the rover to carry out activities like environmental analysis and sample collecting with extreme precision.

Components

This Sub-assembly consists of Inertial Measurement Units (IMU) which is a device that monitors a body's specific force, angular rate (Grewel et al. 2007). By detecting changes in rotation and velocity, an IMU in a navigation system aids in tracking the movement and orientation of a vehicle and enables precise orientation and motion tracking even in the absence of external references. The LN-200 IMU produced by Northrop Grumman's have been used previously in several spacecraft missions, including several Mars Rover missions including Spirit and Opportunity rovers 2004, Curiosity 2012 and Perseverance 2020, proving to be an ideal selection for this component. The LN-200 IMU is an optic fibre IMU or rather a Fiber Optic Gyroscope (FOG) which utilises light interference to detect changes in orientation.

This particular model by Northrop Grumman's high performance variation: The LN-200HPS (High Performance), has a higher radiation tolerance and better gyro performance. These models are comprised of three solid-state fibre-optic gyros and three solid-state silicon Micro Electro-Mechanical Systems accelerometers in a compact package that measures velocity and angle changes in a coordinate system fixed relative to its case ("LN-200S & LN-200HPS Inertial Measurement Unit (IMU)," n.d.). Based on the previous history this component has had through several successful mission operations in the relevant environment it can be determined that the IMU has a technology readiness level of 8.

TALICO is also inclined to include a GNSS receiver which would act as a receiver designed to work with any future satellites orbiting the moon. A recent project, the

Lunar GNSS receiver experiment (LuGRE) is being done by NASA and the Italian space agency aims to demonstrate GNSS based positioning navigation and timing on the moon. As this technology is still being developed and tested and has been demonstrated in a relevant environment but not yet in space it currently has a technology readiness level of 6 (Parker et al., n.d.).

Overall this Sub-assembly has a technology readiness level of 6.

Path Planning (Guidance) Sub-assembly

The purpose of the Path Planning Sub-assembly is to find and plan the best path for a lunar rover to travel from its current position to its chosen goals. In order to comply with mission requirements including time and scientific objectives, this Sub-assembly must minimise energy consumption, avoid obstructions and other path obstacles that would be difficult to manoeuvre through or around ensuring safe navigation. This is done so by utilising the input from Perception Sub-assembly, using this categorised 3-dimensional data it is able to make the safest or most practical decision. The rover's autonomy depends on its ability to make decisions in real time in the harsh and unpredictable lunar environment, which is made possible by the path planning subsystem. As algorithms have been employed and validated in previous missions demonstrating reliability and a TRL of 9 (Goode, 2023).

Locomotion and Manoeuvre Control Sub-assembly

A lunar rover's locomotion Sub-assemblies role is to make traversing across the lunar surface as easy as possible. This subsystem oversees the rover's capacity to move over different kinds of terrain, withstand tilting without tipping over, and manoeuvre around obstacles. It is made up of parts that cooperate to guarantee that the rover can navigate effectively and dependably while completing its mission objectives. These parts include wheels, motors, suspension systems and drive actuators to convert electrical signals into mechanical motion to propel the rover.

Components:

The rover should employ a “rocker-bogie” suspension, which actually falls under the mechanical subsystem but works alongside GNC to ensure the rovers stability. This suspension design has been implemented across all Mars rovers developed by NASA. It. Consists of a differential, which connects the two “rockers” which allows the system to distribute. the load evenly (NASA 2020). It also consists of the “rocker”, which is a primary arm that connects the front wheel to the “bogie”, the. “bogie”, which is an arm that connects the middle and rear wheel together which then connects to the “rocker”. The rover can overcome difficulties thanks to its rocker-bogie suspension. As it has been employed on all previous Mars rovers it can be said the suspension system design has a TRL of 8.

Commercial off the shelf (COTS) actuators produced by the Swiss manufacturing company Maxon have also been used in previous Mars Rover missions, including Sojourner pathfinder 1997, Spirit and Opportunity rovers 2004, Phoenix lander 2008, Curiosity 2012 and Perseverance 2020 rovers. This particular company's actuators are a likely choice for TALICO’s rover due to the high level of flight Heritage (Loschiavo et al. 2020). Given its extensive history the actuators have a technology readiness level of 9.

Overall this Sub-assembly has a technology readiness level of 8

Based on all the sub-assemblies under the GNC subsystem the lowest TRL dictates the technology readiness level of the whole subsystem, which at this current stage the GNC subsystem has a TRL of 6.

Environmental challenges faced by the GNC subsystem

Temperature:
The lunar surface experiences drastic temperature variations, from very high temperatures during the lunar day to extremely low temperatures during the lunar night. Use thermal insulation and heating elements to maintain operational temperatures. Components can be housed in a thermally controlled environment within the rover.

Radiation:
The Moon lacks a protective atmosphere, which exposes the lunar surface and in turn the equipment to high levels of cosmic and solar radiation (Aghara and Hu 2012). It is essential that the components are radiation hardened (Campola & Pelish, 2019) and/or have extra shielding to ensure the protection of electronics and that it is monitored for radiation-induced errors (soft-errors) and implement error-correcting algorithms (Baumann 2005).

Lunar Dust:
Also due to this exposure to solar wind and cosmic radiation this has resulted in the dust on the Luna surface being negative electrostatic charge. The fine, abrasive lunar regolith can interfere with many components on TALICOs rover (Choi et al., n.d.), but especially the optical components of the LiDAR system which would significantly impairing the rover’s ability to navigate and traverse the lunar surface safely. It is essential to mitigate this issue that dust shields and protective covers for the LiDAR sensors are implemented, and the use of materials and designs that minimise dust adhesion and use blowers or electrostatic methods to clean the optics regularly. Its charge proved to be an additional challenge for not only interfering with the optical components but also any electrical systems.

Vibration and Shock:
Upon Launch and landing the lunar rover will be subject to significant mechanical stress including the LiDAR system so it is essential that vibration-damping mounts or

some sort of shock absorbers are used to protect potentially sensitive components (Perform extensive pre-launch testing to ensure durability).

Limited Power Supply:

The entire rover has a finite energy budget so effective and efficient power management is necessary. With most power drawn within the GNC subsystem going to the LiDAR sensor it requires software that only activates the equipment when necessary. This too applies for each subsystem and its respective components that they should only run when required to minimise power usage.

Table 25. TALICO Mission GNC Subassembly Specifications

Subsystem	Component	Mass (kg)	Volume (cm^3)	Volume Max Power (Watts)	Notes
Perception	LiDAR	1.5	500	5	LiDAR selected/manufactured will balance weight volume and power consumption
Terrain Monitoring & Analysis	Terrain Monitoring & Analysis	0.80	400	3	Subsystem continuously evaluates the lunar surface, providing real-time data on slopes, barriers, and textures to feed to path planning.
Localisation (Navigation)	IMU	0.50	200	3	IMU is essential for determining the rover's direction and speed. It ensures dependable and accurate navigation by striking a balance between precision, weight, and power efficiency.
	GPS Receiver	0.30	100	2	GPS provides additional localization data
Locomotion/ Manoeuvre Control	Locomotion/ manoeuvre control	1.20	600	5	To optimise mass, volume and power draw to support efficient locomotion while maintaining structural integrity

2.1.5.3 GNC Subsystem Recovery and Redundancy Plans

The redundancy and recovery analysis for the GNC subsystem of the Lunar Ice Investigation mission ensures robustness and resilience in navigating the lunar surface. Dual sets of critical sensors and control units are installed to provide backup in case of primary system failures. Additionally, the system includes fault detection and isolation mechanisms to quickly identify and switch to redundant components, ensuring continuous operation. By implementing redundant components and recovery strategies across key subsystems such as location, perception, path planning, terrain monitoring, and locomotion control, the mission safeguards against potential failures, ensuring continuous operation and mission success.

Table 26. TALICO Mission GNC Recovery and redundancy plans

Subassembly	Recovery	Redundancy
Localisation (Navigation)	Backup plans shall be devised in case the rover's main navigation system encounters any issues. If a GPS loses signal, the rover can switch to using landmarks or environmental features to figure out where it is. Another alternative is for the rover to communicate with the orbiting satellites to get updated information on its location. These "fallback" measures ensure that even if the primary navigation fails, the rover can still find its way around safely.	In the event LiDAR or IMU fail, redundant sensors including Stereo Cameras and RADAR systems are incorporated to provide alternative methods of determining the rover's position allowing for a continued navigation. Corresponding alternative algorithms shall be implemented to ensure that the rover can adapt and recalibrate its position estimation based on the available sensor data.
Perception	If there is a perception subsystem failure, the rover can rely on alternate perception methods, such as IMU-based dead reckoning or remote operator guidance. Diagnostic routines will be activated to isolate the fault, and corrective actions can be implemented through software patches or hardware reconfiguration.	Redundant sensors such as Stereo Cameras or RADAR ensure continuous perception capabilities. Redundant processing units (RPU) shall be deployed to provide alternative data inputs, ensuring the rover's ability to perceive the environment and make informed decisions autonomously.
Path Planning	The rover can switch to pre-defined backup navigation modes, such as waypoint navigation or manual teleoperation. Mission control will assess the situation and provide updated guidance commands based on real-time telemetry data and terrain assessments. Post-mission analysis will be conducted to identify any systemic issues and implement corrective measures for future missions.	Redundant algorithms and decision-making frameworks can be leveraged to generate safe and optimal paths for the rover. Multiple mission scenarios and contingency plans preloaded into the system to accommodate any unforeseen obstacles or deviations from the planned trajectory.
Terrain Monitoring and Analysis	If a failure occurs within the Terrain Monitoring and Analysis Subsystem, the rover can rely on onboard memory and historical terrain data to inform navigation decisions temporarily. Mission control will assess the impact of the subsystem failure on mission objectives and devise recovery strategies, such as adjusting the rover's speed or prioritising safer terrain traversal routes. Thus, the subsystem can fall back on its memory of past terrain data to keep the rover on track and avoid obstacles, even if it can't see them in real-time.	Backup plans are in place to make sure the subsystem can still understand the terrain and identify any dangers, even if something goes wrong with its main methods. This may involve using different ways of looking at the ground and analysing it such that if the main approach i.e., using a camera, has a problem or does not provide clear images, the subsystem can switch to another method such as the use of RADAR to still understand what is going on below.

Locomotion and Manoeuvre	In the event of a subsystem failure, the rover can transition to a reduced mobility mode, conserving power and minimising further damage. Mission control will assess the impact of the failure on mission objectives and devise recovery strategies, such as remote troubleshooting and hardware reconfiguration. Post-mission analysis will be conducted to identify root causes and implement design improvements for future missions.	Redundant actuators and drive systems are incorporated to ensure continued locomotion in the event of primary component failure or mechanical damage. Additionally, associated redundant control algorithms are implemented to facilitate autonomous manoeuvring and obstacle avoidance. These redundant systems provide failover mechanisms to mitigate the impact of hardware failures on the rover's movement capabilities.

2.1.5.4 GNC Subsystem Manufacturing and Procurement Plans

For the lunar rover to have precise navigation, reliable control, and accurate positioning on the lunar surface, it needs the GNC subsystem with guaranteed excellent performance and dependability. To ensure this outcome the components for the GNC subsystem will be sourced from a combination of reputable contractors, and potentially COTS suppliers to ensure high reliability and performance.

Table 27. TALICO Mission GNC Manufacturing and Procurement Plans

Component	Description	Supplier type	Potential Supplier	Reasoning
LiDAR	Electro-optic systems for navigation	Contractor	EOS	EOS specialises in high-precision optical components suitable for space missions.
IMU	Detecting rovers motion and orientation	contractor	Northrop Gruman	High technology readiness (used on Mars rovers)
Actuators	Control movement Orientation adjustments	COTS	Maxon	State-of-the-art navigation and control solutions
GPS (GNSS) system	Provides Geolocation data based on orbiting satellite	COTS	Garmin	Expertise in geolocation technology

The estimated lead time for the development, including procurement, testing, integration, and validation, is approximately 24 months. This time frame ensures that all components are delivered, tested, and integrated in a timely manner.

Testing/Qualification:

All GNC components will undergo extensive testing according to industry standards such as MIL-STD-810 and NASA-STD-7009. These tests will simulate lunar conditions to ensure performance, durability, and reliability. To verify performance of all components they shall undergo environmental testing including extreme temperatures, radiation, and vacuum conditions for testing. They will also undergo functional testing to ensure that each component operates correctly and meets design specifications. And finally to ensure that all components work together seamlessly within the rover's architecture all GNS components and their respective subsystems will undergo integration testing

Verification and Validation (V&V):

The V&V process will focus on ensuring the GNC subsystem meets all mission goals, undergoing compliance testing to ensure all components comply with its mission requirements. Also sensor calibration, this is to ensure accurate data from all sensors, including LiDAR, IMU and star trackers. It will also validate the Navigation Algorithms to be used for Terrain Monitoring & Analysis, Localisation, and especially Path Planning navigation subsystems. Through procurement of premium components from reliable vendors and extensive testing and validation, the GNC subsystem will be suitably equipped to facilitate the lunar rover's functions. Accurate navigation, precise control, and effective mission execution on the lunar surface will be ensured by the integration of these advanced systems.

2.1.5.5 GNC Subsystem Verification Plans

The GNC subsystem is critical for ensuring the rover can accurately determine its location, navigate the lunar surface, and avoid obstacles. The verification plans involve a series of tests, analyses, demonstrations, and inspections to ensure each requirement is met. The verification plans outlined below provide a comprehensive approach to ensuring that the GNC subsystem meets all its requirements. Each requirement will undergo rigorous testing, analysis, and demonstration to confirm that the system performs as expected under various conditions.

Table 28. TALICO Mission Verification plans for GNC

Requirement ID	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan	Expected Outcome
SYS-GNC2-01	System shall determine relative rover location/position on lunar surface	Test	Direct testing provides evidence of accurate localisation capabilities	Conduct localisation tests in simulated lunar environments to verify accuracy and reliability. Test with various landmarks and features.	Localisation
SYS-GNC2-02	System shall use a sensor system, using laser light to measure distances to objects with a detection range of X.	Test	Testing the sensor system ensures it meets the required detection range and accuracy	Test the sensor system in controlled conditions to measure distances accurately. Validate against known distances and obstacles.	Perception
SYS-GNC2-03	System shall extract distinct visual features from sensor/cameras	Test	Testing visual feature extraction confirms system can identify/ utilise the features.	Use test images and real-world scenarios to extract/ validate distinct visual features. Compare extracted features w/ expected outcomes.	Visual Feature Extraction
SYS-GNC2-04	Shall use distinct visual features to provide accurate guidance to the rover.	Test	Direct testing of guidance accuracy ensures reliable navigation	Test guidance system using extracted visual features in a simulated environment to ensure the rover follows the planned path accurately.	Guidance Using Visual Features
SYS-GNC2-05	System shall utilise perception/ terrain monitoring subsystems to identify obstacles.	Analysis	Analytical evaluation ensures system identifies obstacles w/ perception data	Perform analytical simulations using perception data to identify obstacles. Validate with real and simulated terrain data.	Obstacle Identification
SYS-GNC2-06	System shall create 3-dimensional surround mapping.	Test	Testing ensures accurate 3D mapping of the environment	Conduct tests to create 3D maps in controlled and real-world environments. Validate accuracy/ completeness of maps produced.	3D Mapping
SYS-GNC2-07	System shall classify surroundings (rocks, craters slopes)	Test	Testing classification capabilities ensures the system can accurately identify different terrain features	Test the system's ability to classify various types of terrain in both simulated and real-world scenarios. Verify against known classifications.	Terrain Classification
SYS-GNC2-08	System shall use classified surroundings to determine safest route	Analysis	Analytical evaluation ensures the system selects the safest path	Perform path planning simulations using classified terrain data to ensure safest routes chosen. Validate with expected path outcomes.	Safe Route Determination
SYS-GNC2-10	System shall follow determined path trajectory	Test	Direct testing ensures the system can follow a planned path accurately	Conduct trajectory-following tests in controlled environments. Validate ability to adhere to predetermined paths w/o deviation.	Path Trajectory Following
SYS-GNC2-12	Rover shall utilise IMU data to autonomously adjust its velocity.	Demonstration	Demonstrating system's response to IMU data ensures real-time velocity adjustments	Use IMU data in dynamic tests to demonstrate the rover's ability to adjust its velocity autonomously. Validate stability and control.	Velocity Adjustment Using IMU Data
SYS-GNC2	System shall autonomously steer to avoid	Demonstrat	Demonstrating obstacle avoidance	Conduct obstacle avoidance demonstrations in both simulated and	Obstacle

Requirement ID	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan	Expected Outcome
-13	obstacles/ maintain path trajectory	ion	ensures safe and efficient navigation	real-world environments. Validate ability to steer/ maintain trajectory.	Avoidance

2.1.6. Payload Subsystem Overview

TRIDENT:

The TRIDENT (Regolith and Ice Drill for Exploring New Terrains) is the chosen drilling instrument for the VIPER mission, designed to achieve the science goals of exploring and analysing potential ice deposits below the lunar surface. Developed by Honeybee Robotics in Altadena, California, TRIDENT represents a significant advancement in lunar exploration technology, particularly in the realm of drilling. The overall Technology Readiness Level (TRL) of the TRIDENT subsystem is defined at a 7 as it has completed on

Earth tests equivalent to its role on the moon but is yet to be placed on a mission.

1. Drill Depth: TRIDENT is capable of drilling up to one metre below the lunar surface, allowing for the collection of soil cuttings from various depths. This depth range is crucial for accessing potential ice deposits and other valuable materials.

2. Drilling Mechanism: TRIDENT employs a rotary percussive drilling mechanism, combining spinning motion with hammering action to efficiently penetrate the lunar regolith. This innovative approach ensures effective drilling even through hard materials.

3. Drill Bit: The drill bit at the tip of the drill string is equipped with carbide cutting teeth, renowned for their hardness and durability. These teeth maintain sharpness over extended periods of drilling, ensuring optimal performance in the harsh lunar environment.

4. Temperature Sensor: TRIDENT is equipped with a temperature sensor located at the drill tip, allowing for real-time temperature readings below the lunar surface. This feature provides valuable data for understanding the thermal characteristics of the lunar regolith.

5. Drill Cuttings Transport: Along the length of the drill string are spiral shaped flutes, which serve to transport drill cuttings up to the surface as TRIDENT operates. This mechanism ensures efficient removal of excavated material for further analysis.

6. Sample Collection: A rotating brush sweeps the soil sample off the drill bit and into a chute, where it forms a neat pile on the ground. This collected sample can then be analysed by VIPER's suite of instruments to gather valuable scientific data.

7. Size, Mass, and Power: The TRIDENT instrument's size, mass, and power draw have been optimised and broken down in detailed tables, ensuring it fits within mission constraints. The Size, Mass, and Power is outlined in the table below.

BIRCHES:

The BIRCHES (Broadband InfraRed Compact High Resolution Exploration Spectrometer) is the chosen spectrometer on the Lunar IceCube 6U cubesat. The Lunar IceCube mission was led by Morehead State University, while the BIRCHES spectrometer is a miniaturised version of the OVRVIS spectrometer. The Lunar IceCube mission launched as a secondary mission from the Artemis 1 launch, with specific goals aligning with the TALICO mission goals: to categorise and map lunar volatiles. Contact was lost with the satellite shortly after deployment, and further details have not been released on the cause of the error. As such, the BIRCHES spectrometer is at TRL 8.

1. Spectral Resolution: The BIRCHES spectrometer has a spectral resolution of 10 nm, providing high-resolution measurements critical for distinguishing various volatiles and minerals.

2. Focal Plane Array: Equipped with a compact Teledyne H1RG HgCdTe focal plane array, the BIRCHES instrument is capable of measurements in the 1 to 4 micron range, essential for detecting specific lunar volatiles.

3. Filter Technology: The instrument leverages the OSIRIS JDSU Linear Variable Filter to characterise volatiles, allowing it to distinguish H_2O, H_2S, NH_3, CO_2, CH_4, and OH, as well as other mineral bands.

4. Thermal Design: Thermal management is critical for the BIRCHES instrument. It uses an IR detector that can operate below 115K. An on-board radiator is employed to cool the optic equipment alone, maintaining operation below 230K.

5. Adjustable Iris: The adjustable iris allows for variation in the field of view (FOV) and focus of the instrument at varying distances. This feature is key for adapting the instrument from satellite to rover applications.

6. Size, Mass, and Power: The BIRCHES instrument's size, mass, and power draw have been optimised and broken down in detailed tables, ensuring it fits within mission constraints. The Size, Mass, and Power is outlined in the table below.

Neutron Spectrometer System (NSS):

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

The Neutron Spectrometer System (NSS) is a vital component designed to ascertain the presence of hydrogen-bearing materials near the lunar surface, crucial for determining potential water ice and regolith composition. It operates by detecting local thermal and epithermal neutron flux, providing essential insights into hydrogen content within the landing site vicinity. The NSS has been through intermediate testing and has achieved a TRL of 5.

1. Sensor Configuration: The NSS comprises two gas-proportional counter (GPC) sensors filled with helium-3 at 15 atmospheres. One sensor is bare, detecting both thermal and epithermal neutrons, while the other is enveloped in a 0.63 mm cadmium layer, rendering it sensitive solely to epithermal neutrons. By comparing readings from both sensors, the thermal neutron flux can be derived, enhancing the instrument's precision.

2. Integration and Control: These sensors are integrated with a high-voltage power supply and pre-amplifiers within a sensor module, while a separate data processing module controls their operation, ensuring efficient functionality and streamlined data management.

3. Compact and Efficient Design: The NSS exhibits a compact and efficient design, with a total mass of 1.6 kg and power consumption of 1.5 W, suitable for lunar

missions where resource constraints are significant. The sensor module measures 21.3 x 32.1 x 6.8 cm, while the data processing module is 13.9 x 18.0 x 3.0 cm, ensuring minimal space requirements.

4. Detection Capabilities: Each sensor generates a 32-channel spectrum per second, capturing neutron events and background gamma-ray energy, facilitating detailed analysis of the lunar surface composition. The system can detect water-equivalent hydrogen concentrations as low as 0.5 wt% at spatial scales of tens of centimetres, providing high-resolution data critical for scientific investigations.

5. Size, Mass, and Power: The NSS instrument's size, mass, and power draw have been optimised and broken down in detailed tables, ensuring it fits within mission constraints. The Size, Mass, and Power is outlined in the table below.

Tri-band LVMM LIDAR:

https://ttu-ir.tdl.org/server/api/core/bitstreams/39983d26-879e-4a31-a63f-138641fcf651/content

The compact LVMM (Lunar Volatiles Mapping and Monitoring) system is a sophisticated multi-wavelength Chemical Lidar designed for stand-off mapping of lunar ice distribution through active laser illumination. With a net mass of approximately 6.1 kg, the system integrates fibre lasers emitting at 532 nm, 1064 nm, and 1560 nm wavelengths. The LVMM has been through intermediate testing and has achieved a TRL of 5.

1. Laser System: It comprises a 4W 532 nm/8-10W 1064 nm fibre laser and a 4W 1560 nm fibre laser. The laser beam expander/combiner, featuring a dichroic beam combiner and pan/tilt mirror, ensures precise laser beam control and alignment.

2. Fiber Laser Design: The 1560 nm fibre laser employs a stabilised DFB laser seed with an integral Electro-Absorption Modulator, optically amplified to 4W output. It is powered by redundant 11W diode pumps at 980 nm. Similarly, the 532 nm/1064 nm fibre laser utilises two 915 nm pumps, each providing up to 25W output, with redundancy ensured by one pump.

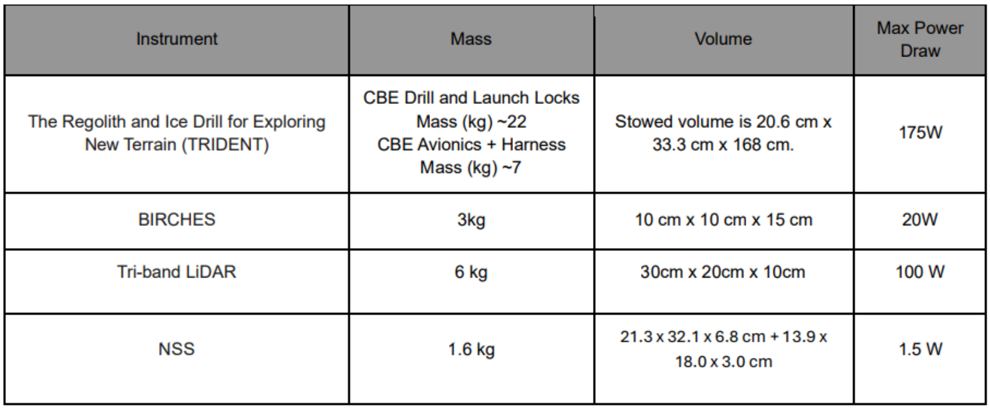
3. Imaging Photoreceiver: The photoreceiver incorporates a stray light-reducing baffle and Acktar black coating for enhanced performance. It utilises a UV/Vis/SWIR optical filter dichroic to direct light to respective imagers: a Prime-95B CMOS imager for UV/Vis with a 1200x1200 pixel array, and a Sensors Unlimited InGaAs imager for SWIR with a 640x512 pixel array.

4. Avionics: LVMM avionics include a microcontroller, data acquisition board, laser driver boards, and a fault-tolerant DC-DC power supply, ensuring reliable operation compatible with spacecraft power systems.

5. Flight Heritage: System components boast extensive flight heritage from previous missions such as ESA's Proba-2 and NASA's LCROSS, demonstrating reliability and performance in space environments.

6. Size, Mass, and Power: The Tri-Band LIDAR instrument's size, mass, and power draw have been optimised and broken down in detailed tables, ensuring it fits within mission constraints. The Size, Mass, and Power is outlined in the table below.

Table 29. Science Instrument Specifications



Instrument	Mass	Volume	Max Power Draw
The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)	CBE Drill and Launch Locks Mass (kg) ~22 CBE Avionics + Harness Mass (kg) ~7	Stowed volume is 20.6 cm x 33.3 cm x 168 cm.	175W
BIRCHES	3kg	10 cm x 10 cm x 15 cm	20W
Tri-band LiDAR	6 kg	30cm x 20cm x 10cm	100 W
NSS	1.6 kg	21.3 x 32.1 x 6.8 cm + 13.9 x 18.0 x 3.0 cm	1.5 W

2.1.6.1 Science Instrumentation Requirements

The scientific instrumentation requirements for the TALICO rover are derived from the scientific requirements and goals as set out by the Science Traceability Matrix (StM). In part, these lower-level requirements are also built from and expand upon the specific requirements of the customer and the constraints imposed. Each instrumentation has requirements derived that allow for a better understanding of the performance and rationale, as well as to better understand the impact and reliance of each instrumentation on the rest of the rover. More importantly, the requirements set out for the payload subsystem drive how the rover will accomplish the mission and how each instrumentation will rely on each respective payload to complete their own task. A summary of the payload system requirements has been provided in the science instrumentation requirements table.

Req #	**Requirement**	**Rationale**	**Parent Req**	**Child Req**	**Verification method**	**Relevant Subsystem**	**Req met?**
Tri-band LiDAR Instrumentation Reqs							
STM-01	The instrument shall capture images with spatial resolution of 0.1 to 0.2% wt of water ice	High-resolution images are necessary for detailed analysis of the lunar surface features.	PAY-02	STM-02, STM-03	Inspection	Blank	Met
STM-02	The imaging system shall provide sufficient illumination over the entire imaging field of view (FOV).	Proper illumination is crucial for capturing clear and detailed images.	STM-01	STM-03	Inspection	Blank	Met
STM-03	The imaging system shall have a field of view wide enough to capture the desired area on the lunar surface	A wide FOV is necessary to image the entire target area effectively.	STM-01, STM-02	.	Inspection	Blank	Met
TRIDENT Instrumentation Reqs							
STM-04	The tool must drill a total of 1m into the lunar	Provided by Mission Document	Customer	STM-04.1	Inspection	Blank	Met

	surface.						
STM-04.1	The tool must take regolith samples in 10 cm increments.	High-resolution depth map of lunar volatiles' properties.	STM-04	STM-05	Demonstration	Blank	Met
STM-05	The TRIDENT instrumentation shall obtain temperature readings every 10cm			STM-04.1	Demonstration	Blank	Met
BIRCHES Instrumentation Reqs							
STM-06	The instrumentation shall have a range of 10nm across 40 bands	To identify volatiles with accuracy			Demonstration	Blank	Met
STM-07	The measurements taken by the spectrometer shall be accurate to 3 microns	To identify volatiles with precision			Demonstration	Blank	Met
STM-08	Detection up to a depth of 3 feet with an accuracy of 0.5% wt of hydrogen	To eliminate time spent mining resource sparse areas			Test	Blank	Met
STM-09	The tool must isolate and identify all the different compositions in the water ice sample	Characterise the properties of water ice.			Test	Blank	Met

2.1.6.2 Payload Subsystem Recovery and Redundancy Plans

Payload equipment and instrumentation are common single point failures, due to their inherent volume and cost of development. Physical backups of payload systems will be excluded from the design and construction of the rover. Due to the nature of the TALICO mission being that of a low-cost, high-risk mission, such risks are acceptable. As such, robust recovery systems will be utilised to mitigate the risks while ensuring feasible continued operation of scientific equipment during the mission lifespan of the rover.

Table 30. TALICO Mission Payload Recovery and Redundancy Plans

Subassembly	**Recovery**	**Redundancy**
Drilling Instrument	In the event of the drill bit getting stuck inside the lunar regolith, TRIDENT activates the percussive feature dislodging the stuck drill bit. However, in the event of system failure though recovery can be difficult for the largest onboard instrument for a low-cost mission like TALICO. The high-cost mission ICEBREAKER on mars implements a scooping arm to take surface samples in the event of a drill failure.	The TRIDENT drill will not incorporate a Redundancy policy, though a failure in the drill would result in the rover losing its ability to collect lunar regolith samples. The cost and size of redundant instruments are prohibitive, making it impractical to include a backup system. However, this decision is justifiable given the low likelihood of a complete drill failure and the high-cost, high-risk nature of the TALICO mission.

Sample Analysis Instrumentation	In the event of system error, the BIRCHES instrument will have the capability to ensure equipment is kept at operating temperatures through the inbuilt thermal management system. Sensors and thermal insulation are in place to ensure that in the event of thermal system error, specific instrumentation thermal temperatures will remain nominal for periods of time until the system error is autonomously resolved. Failure to resolve such thermal errors will result in a single point failure of the system. Returning to safe configurations post error is critical in ensuring the continued operation of the BIRCHES instrumentation.	Due to the small size of the BIRCHES system, it is possible and feasible to employ the use of two spectrometers; this is however reliant on the cost of manufacture and development of such systems on the budget employed. Including a backup physical redundant system for the BIRCHES spectrometer is therefore deemed impractical, as such leaves the subsystem as a single point failure. More practically, redundant thermal systems will be in place to ensure such risks are mitigated within the thermal subsystem of BIRCHES at least.
Imaging Instrument	The tri-band LiDAR does not deploy a recovery system, failure of this will mean lack of supplementary data to the mission. The main science objectives of the mission are not affected. NSS deploys recovery system as described by NASA[1].	The tri-band LiDAR system has redundant optical pumps for the laser. NSS deploys redundancy systems described by NASA[1].

2.1.6.3 Payload Subsystem Manufacturing and Procurement Plans

Trident:

Honeybee Robotics, based in Altadena, California, is a renowned leader in advanced robotic systems for various applications, including space exploration, mining, and defence. With decades of experience, they specialise in designing and manufacturing innovative technologies such as robotic arms, drills, and sampling systems tailored for challenging environments, including extraterrestrial surfaces.

They were commissioned by the VIPER team to design and build the first TRIDENT. To procure a new TRIDENT drill from Honeybee Robotics, we will engage in a direct commissioning process, leveraging their expertise and track record in developing space-grade drilling instruments. Through clear communication of our mission requirements and specifications, we will collaborate closely with their team to ensure the successful fabrication and delivery of a high-quality new TRIDENT drill that meets our precise needs for the TALICO mission.

Honeybee Robotics, Altadena, CA

Birches:

The Goddard Space Flight Center (GSFC), located in Greenbelt, Maryland, is a premier NASA facility specialising in space and Earth sciences research, satellite missions, and technology development. GSFC has a rich history of developing cutting-edge instruments and spacecraft for a wide range of scientific investigations, including lunar exploration.

They were commissioned by the Lunar Icecube team to design and build the BIRCHES spectrometer. To procure a new BIRCHES spectrometer, we will engage with GSFC's Instrument Systems and Technology Division, which has extensive experience in developing compact and high-resolution spectrometers for space missions. Through a procurement process with GSFC, we will work closely with their team to articulate our mission requirements and specifications, ensuring the successful fabrication and delivery of a new BIRCHES spectrometer optimised for the TALICO mission. This collaboration will leverage GSFC's expertise and capabilities to provide a reliable and scientifically impactful instrument for our lunar exploration objectives.

Goddard Space Flight Center

Tri-band LVMM lidar:

MPD, headquartered in Canada, is a leading company specialising in cutting-edge technology solutions, including the design and development of advanced lidar systems. As the head of design for the Tri-band LVMM lidar, MPD brings a wealth of expertise and experience in optical engineering and space instrumentation.

To procure the Tri-band LVMM lidar, we will collaborate directly with MPD to obtain the finalised design. Once the design is complete, we will leverage existing partnerships with Lockheed Martin or Honeybee Robotics, with whom we are already working to obtain the TRIDENT drill and the NSS (Neutron Spectrometer System), respectively. By taking the finalised design to these manufacturers, we ensure seamless integration and consistency across our suite of lunar exploration instruments while benefiting from the manufacturing capabilities and expertise of these established aerospace companies. This collaborative approach streamlines the procurement process and ensures the timely delivery of a high-quality Tri-band LVMM lidar for our mission objectives.

NSS:

Lockheed Martin Advanced Technologies Center (ATC) is a renowned division of Lockheed Martin, a global aerospace and defence company. The ATC specialises in cutting-edge research, development, and manufacturing of advanced technology solutions for various applications, including space exploration.

Lockheed and Martin designed and developed the NSS for both the VIPER mission and the Astrobotic Peregrine-1 mission. Thus, to procure the Neutron Spectrometer System (NSS), we will engage with Lockheed Martin ATC to leverage their expertise in space instrumentation and manufacturing capabilities. Through collaboration with their team, we will communicate our mission requirements and specifications for the NSS. Lockheed Martin ATC will then utilise their resources and expertise to develop and manufacture the NSS according to our needs. This partnership ensures the delivery of a high-quality NSS instrument that meets the rigorous standards of our lunar exploration mission.

Lockheed Martin Advanced Technologies Center

2.1.6.4 Payload Subsystem Verification Plans

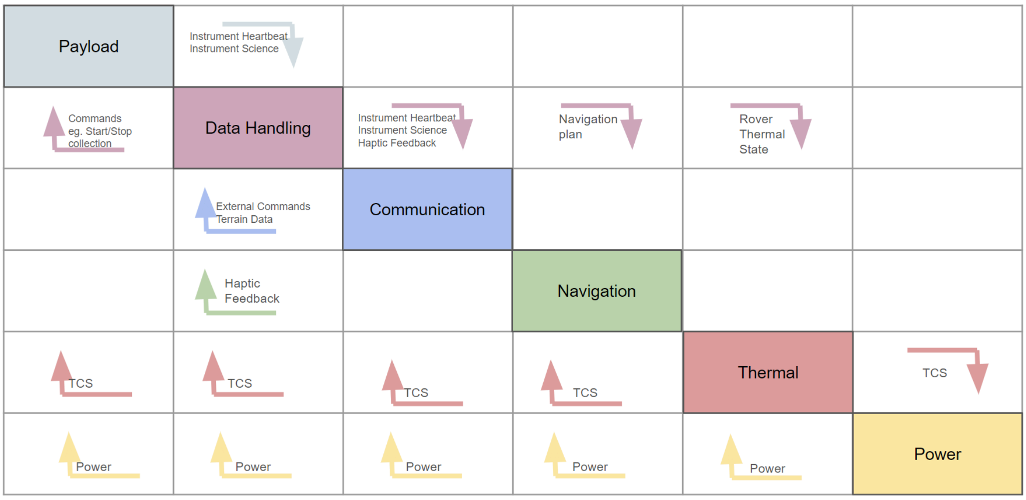
The following table outlines the requirement verification matrix, which is used as a preliminary guide only for the verification of each requirement. The verification method and plan for each requirement is subject to change. Further development of the rover and the scientific instrumentation will evolve the requirement verification methods; however, the following table outlines a brief overview of the expected path to requirement compliance for each requirement outlined above.

Table 31. TALICO Mission Verification plans for Payload/Science Instruments

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
STM-01	The instrument shall capture images with spatial resolution of 0.1 to 0.2% wt of water ice	Inspection	Imaging technologies are proven and robust systems, inspection will qualify system for flight	Equipment will perform to these requirements through inspection of the provided specification manual
STM-02	The imaging system shall provide sufficient illumination over the entire imaging field of view (FOV).	Inspection	Imaging technologies are proven and robust systems, inspection will qualify system for flight	Equipment will perform to these requirements through inspection of the provided specification manual
STM-03	The imaging system shall have a field of view wide enough to capture the desired area on the lunar surface	Inspection	Imaging technologies are proven and robust systems, inspection will qualify system for flight	Equipment will perform to these requirements through inspection of the provided specification manual
STM-04	The tool must drill a total of 1m into the lunar surface.	Inspection	The TRIDENT drill is a proven platform. Inspection only will reduce requirement compliance testing cost	Equipment will perform to these requirements through inspection of the provided specification manual
STM-04.1	The tool must take regolith samples in 10 cm increments.	Demonstration	The TRIDENT drill is a proven platform. Demonstration will reduce requirement compliance testing cost over testing	Equipement will demonstrate the manoeuvre in a replicate environment
STM-05	The TRIDENT instrumentation shall obtain temperature readings every 10cm	Demonstration	The TRIDENT drill is a proven platform. Demonstration will reduce requirement compliance testing cost over testing	Equipement will demonstrate the manoeuvre in a replicate environment
STM-06	The instrumentation shall have a range of 10nm across 40 bands	Demonstration	As an adapted unit, BIRCHES should demonstrate effective compliance with this vital requirement post development	Equipement will demonstrate the data acquisition on a replicate sample
STM-07	The measurements taken by the spectrometer shall be accurate to 3 microns	Demonstration	As an adapted unit, BIRCHES should demonstrate effective compliance with this vital requirement post development	Equipement will demonstrate the data acquisition on a replicate sample
STM-08	Detection up to a depth of 3 feet with an accuracy of 0.5% wt of hydrogen	Test	BIRCHES spectrometer is an adapted unit, as such should be tested independently to ensure technology readiness	During development of the instrument, testing on purpose built rigs will ensure requirement compliance
STM-09	The tool must isolate and identify all the	Test	BIRCHES spectrometer is an adapted unit, as such should	During development of the instrument, testing on

	different compositions in the water ice sample		be tested independently to ensure technology readiness	purpose built rigs will ensure requirement compliance

2.2 Interface Control



Payload	Instrument Heartbeat Instrument Science				
Commands eg. Start/Stop collection	Data Handling	Instrument Heartbeat Instrument Science Haptic Feedback	Navigation plan	Rover Thermal State	
	External Commands Terrain Data	Communication			
	Haptic Feedback		Navigation		
TCS	TCS	TCS	TCS	Thermal	TCS
Power	Power	Power	Power	Power	Power

Figure 10. N^2 Chart

All subsystems rely on Power and TCS to function. Power to the Thermal system is necessary for emergency heaters and the batteries in the Power subsystem require TCS to stay within an operating temperature range. Data handling sends inputs commands into Payload to begin imaging or extraction, returning the status or heartbeat of the instruments, as well as data to be sent through communications. Data handling also inputs the thermal state to the Thermal subsystem through sensors around the rover. Navigation outputs haptic feedback through the Inertial Measurement instrument to Data handling, then is passed on to communication, to confirm pathing to mission control.

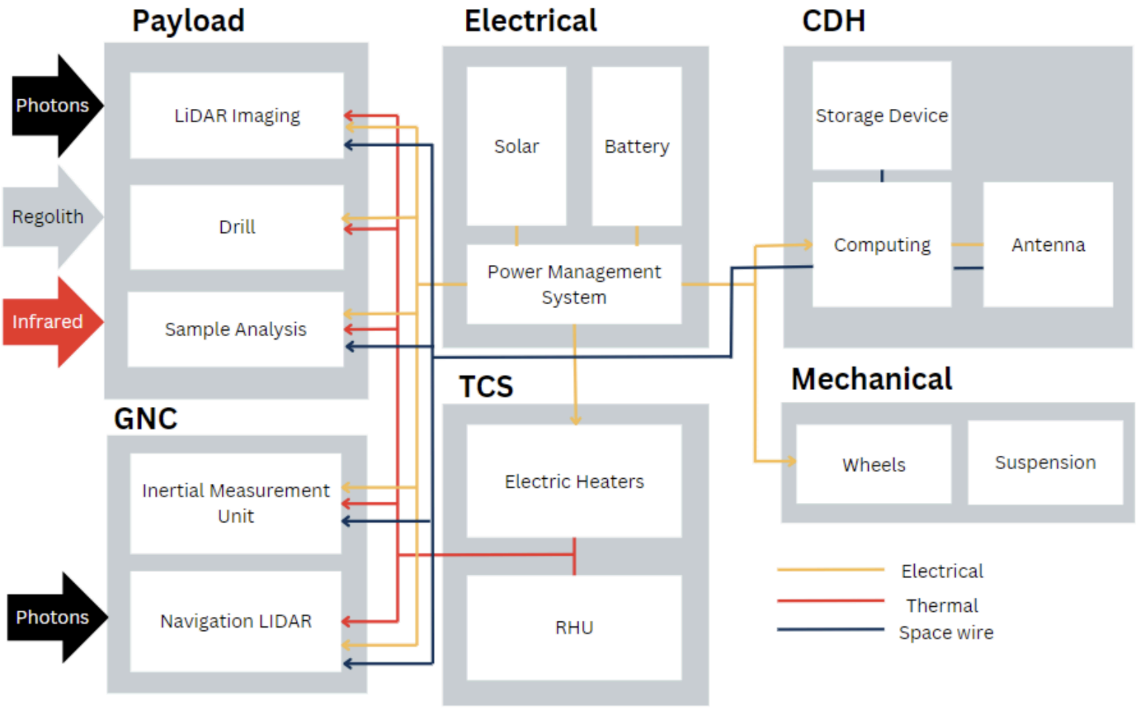


Figure 11. Functional Block Diagram

As previously stated, the temperature of the whole system is regulated through TCS, and power is delivered to all subsystems through the Power Management System. Data is passed from Payload instrumentation and GNC to Computing in CDH which stores and communicates necessary information. Payload consists of LiDAR imaging which relies on photons, Drilling which depends on regolith, and Sample Analysis which depends on utilises infrared. Similarly, GNC uses LiDAR depending on photons, as well as an inertial measurement unit.

3. Science Mission Plan

3.1. Science Objectives

Lunar water ice (water ice) provides a great resource for sustaining long-term human presence on the moon, as it can be used to produce drinking water, oxygen, and rocket fuel, significantly reducing the need to transport resources from earth. It offers a record of the history of our solar system with insights into the origins of water and geological processes on the moon. To support NASA’s Artemis III mission in establishing a sustainable lunar presence and pave the way for future deep space exploration, TALICO aims to assess the abundance, surface distribution (and its temporal evolution) and characteristics of water ice in PSRs. Using well-researched detection (NSS), imaging (Tri-band lidar), and analysis (BIRCHES) techniques, TALICO shall comprehensively characterise the presence and properties of water ice. The TALICO rover will be equipped with TRIDENT to provide the mechanical aid needed to collect samples and measure the subsurface temperature during this process. The temporal evolution of the surface distribution of water ice shall be used to observe patterns and check for evidence for the hypothesised lunar water cycle. This mission will produce a geo-positioned 3D map with each data point consisting of the concentration of water ice, temperature, important chemical properties and (potentially) variation in surface concentration over time. Additional analysis and post-processing of data (relayed back to earth) will be implemented to assess various use cases and their practical feasibility.

3.2. Experimental Logic, Approach, and Method of Investigation

The experimental logic and data collection methods have been shown in Figure 12. The Tri-band LiDAR shall survey the surroundings (10 m radius, see Figure Yb) of the rover at regular intervals to repeatedly image the surface, collecting information about the surface concentration of water ice and temperature.

At every potential location, i.e., where subsurface investigations are to be carried out, NSS shall first be used to detect the presence (concentration) of OH. If a certain threshold for the concentration is met, then TRIDENT shall be activated to collect subsurface regolith samples and simultaneously measure their temperature, see Figure []a. The regolith samples shall then be subjected to BIRCHES to perform spectral analysis to determine the composition in terms of the chemical components of interest. Finally, the sample shall be subjected to Tri-band LiDAR, which determines the concentration of water ice. The sample is then discarded, and the procedure discussed in this paragraph shall be repeated until either a depth of one meter is reached (with a 10 cm increment in each cycle) or the OH concentration threshold is not met. The collected data is stored at the end of each cycle. If NSS determines that the OH threshold is not met, then the rover shall manoeuvre to the next potential location.

The abundance, i.e., the distribution and concentration of water ice, can be assessed using the data from Tri-band LiDAR (surface survey and subsurface sample) and NSS (positive subsurface detection but TRIDENT not activated). This will generate a 3D water ice distribution map of the surveyed region. Each data point will be supplemented with the temperature details from TRIDENT and Tri-band LiDAR. The surround imaging from Tri-band LiDAR shall add a third depth to the surface data

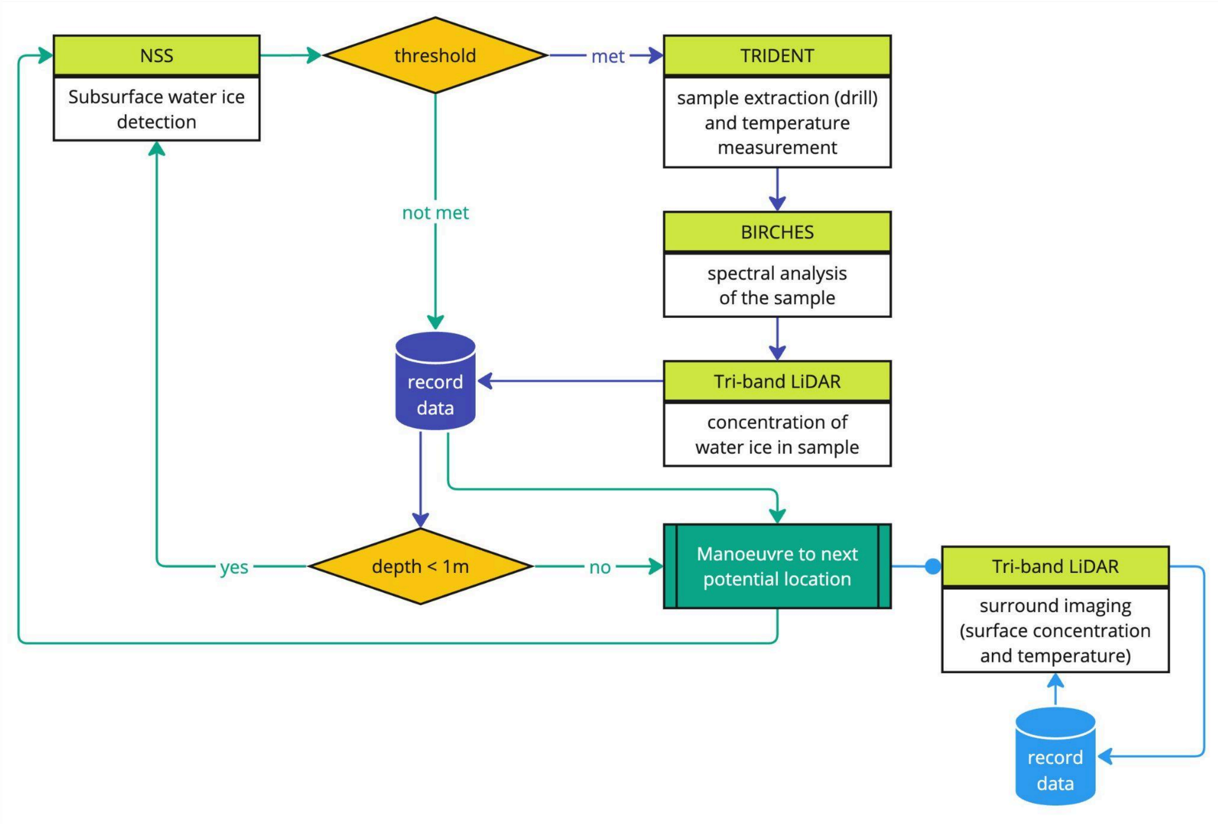


Figure 12. Experimental Logic and Data Collection Flowchart

points, providing information on the temporal evolution of the concentration. Collective information about the change in surface concentration in a region over time shall help understand the factors that contribute to the redistribution of water ice, like the hypothesised lunar water cycle.

This simple yet effective experimental setup allows TALICO to gather all the information necessary to carry out its scientific objectives. The maximum resolution of the map shall be 10 cm x 10 cm x 10 cm per spatial pixel (spaxel). Data processing from instruments shall take place onboard the rover. All data relayed back to Earth may additionally be processed to provide a running assessment of the scientific mission performance and assessed to determine the feasibility of proposed use cases for water ice.

Figure X. Flow diagram showing the scientific data collection scheme for TALICO. Threshold refers to the minimum required concentration of OH to trigger TRIDENT, and depth refers to the subsurface depth drilled by TRIDENT.

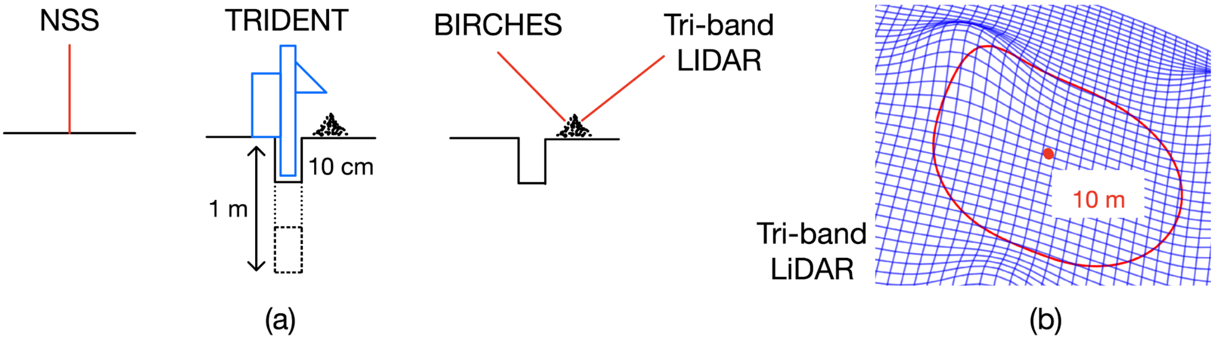


Figure 13. (a) Subsurface data collection scheme. (b) Tri-band LiDAR surround imaging.

3.1.1. Tri-band LiDAR

The Tri-band LiDAR uses high-power, single-mode fibre lasers emitting simultaneously at 532 nm, 1064 nm, and 1560 nm wavelengths. The lasers are specifically chosen for mapping the distribution of water ice by assessing the ratio of reflectance (absorption feature) at these wavelengths. The use of single-mode fibre lasers provides a small beam divergence, allowing high spatial resolution mapping in the range of 10 m at the lunar surface. This approach, validated through prior lab testing (!cite), can determine water at as low as 2% mass fraction in various types of lunar regolith. Thus, assisting TALICO with water ice concentration measurements and surface distribution mapping.

3.1.2. **BIRCHES**

The Broadband InfraRed Compact High-Resolution Exploration Spectrometer (BIRCHES; !cite) is the primary payload on the Lunar IceCube mission. BIRCHES performs high-resolution infrared spectroscopy (1-4 μm range with 10 nm resolution) on samples. Spectral analysis can provide information about volatiles such as H2S, NH3, CO2, CH4, OH and organics. It uses a cryogenically cooled HgCdTe detector array and a Linear Variable Filter to achieve a high signal-to-noise ratio (> 400) required for volatile detection. This allows TALICO to gather information about the composition of water ice and the availability of other volatiles.

3.1.3. TRIDENT

The TRIDENT (The Regolith and Ice Drill for Exploration of New Terrains) is a rotary-percussive drilling system that uses a bite sampling technique where it drills 10 cm at a time, captures the regolith, and then extends the drill string before repeating the process. This incremental approach reduces power requirements, reduces the risk of the drill getting stuck, and allows analysis of different subsurface layers. TRIDENT is also equipped with temperature sensors and a heater to measure thermal properties and determine the physical state and distribution of potential water ice deposits. Therefore, TALICO can collect subsurface samples for further analysis using other instruments and measure the temperature of the sample.

3.1.4. NSS

The Neutron Spectrometer System (NSS; NASA, 2024) measures the count and (loss of) energy of neutrons as they interact with hydrogen atoms up to a depth of three feet below the surface. The measurement is of the local thermal and epithermal neutron flux. A higher concentration of low-energy photons provides evidence for the presence of water ice. This measurement is crucial to TALICO to determine if TRIDENT needs to be activated for collecting deeper subsurface samples. NSS is also an important instrument for NASA’s planned VIPER mission.

3.3. Payload Success Criteria

Imaging Instrumentation:

Success Criteria: The imaging instrumentation's success hinges on capturing high-resolution images of the lunar surface, ensuring proper illumination, and encompassing a wide field of view (FOV). Specifically, the instrument must successfully meet the following criteria:

1. Image Capture (PAYIMG01): The primary success criterion is the ability to capture high-resolution images, which are essential for detailed analysis of the lunar surface features. This criterion is directly linked to the parent requirement PAY-02, emphasizing its critical role in the mission's scientific goals.

Failure Modes: Potential failure modes include malfunctioning camera sensors, loss of data transmission, or software errors leading to corrupted images. Any failure to capture clear and detailed images would severely compromise the mission's objectives.

2.Illumination (PAYIMG02):The system must provide sufficient illumination across the entire imaging field of view. Proper lighting is crucial for the clarity and detail of the captured images, ensuring that lunar features are accurately represented.

Failure Modes: Insufficient or uneven illumination could result in dark or poorly contrasted images, making it difficult to analyze the lunar surface. Malfunctions in the lighting system or power supply issues could lead to inadequate illumination.

3. Field of View (PAYIMG03): The imaging system needs to have a sufficiently wide FOV to capture the entire desired area on the lunar surface effectively. This ensures comprehensive coverage of the target region without missing critical details.

Failure Modes: A narrow FOV could result in incomplete imaging of the target area, necessitating multiple passes and potentially missing important features. Mechanical or optical issues could restrict the FOV, impacting the mission's efficiency and effectiveness.

Drilling Instrumentation

Success Criteria: The success of the drilling instrumentation is defined by its ability to drill 1 meter into the lunar surface and collect regolith samples in 10 cm increments. The accuracy of depth sensors is also crucial for producing quality depth maps.

1. Drilling Depth (PAYDRL01): The drilling tool must successfully penetrate 1 meter into the lunar surface. Achieving this depth is fundamental to the mission’s goal of studying subsurface properties.

Failure Modes:*Possible failures include mechanical failure of the drill, inability to achieve the required depth due to unexpected surface hardness, or breakage of the drill bit. Any failure to reach the 1-meter depth would limit the depth of subsurface analysis.

2. Incremental Sampling (PAYDRL01.1): The tool must take regolith samples in 10 cm increments. This requirement is essential for creating a high-resolution depth map of the lunar volatiles’ properties.

Failure Modes:Failure to collect samples in the specified increments could result in a lack of detailed subsurface data. Issues with the sampling mechanism or data logging errors could compromise the quality and resolution of the depth map.

3. Depth Sensor Accuracy (PAYDRL02): Depth sensors must have an acceptable range of 1 meter and an accuracy within 5% to produce quality depth maps.

Failure Modes: Inaccurate depth measurements could lead to incorrect interpretations of subsurface structures and properties. Sensor calibration issues or hardware malfunctions could result in measurement errors, undermining the mission's scientific goals.

Sample Analysis Instrumentation

Success Criteria: The sample analysis instrumentation must measure samples accurately to 10 microns and identify the composition of water ice. Accurate temperature measurements during extraction are also critical.

1. Measurement Accuracy (PAYSNL01): Sample measurements need to be accurate to within 10 microns. This precision is necessary to assess the subsurface temperature gradient and other physical properties accurately.

Failure Modes: Measurement inaccuracies could lead to erroneous data regarding the subsurface environment. Calibration errors, sensor malfunctions, or environmental contamination could all impact measurement precision.

2. Timing of Measurements (PAYSNL01.1): Measurements must be taken during sample extraction to ensure that the temperature of the sample is accurately recorded. This helps in understanding the thermal properties of the sample in its natural state.

Failure Modes: Delayed or improper timing of measurements could result in inaccurate temperature readings due to the influence of drilling and transport processes. Any failure in synchronizing the measurement process with sample extraction could compromise data integrity.

3. Composition Analysis (PAYSNL02): The tool must isolate and identify all different compositions in the water ice sample. This characterization is crucial for understanding the properties of lunar water ice.

Failure Modes: Failure to accurately isolate and identify the sample's compositions could result in incomplete or incorrect characterization. Issues could arise from contamination, insufficient sensitivity of the analysis tool, or errors in data interpretation.

3.4. Testing and Calibration Measurements

https://ntrs.nasa.gov/api/citations/20210015009/downloads/20210015009%20-%20Colaprete-VIPER%20PIP%20final.pdf

Birches:
Upon landing at the target body, the Birches spectrometer will undergo a series of preliminary tests to ensure all science instrumentation is functioning correctly. These tests are critical for validating the instrument's performance and accuracy before beginning the primary scientific mission.

1. Initial Checkout and Calibration:

Operational Status Verification: Immediately after landing, the Birches spectrometer will perform an initial checkout to verify that all systems and components are operational. This includes checking power levels, communication links, and basic sensor functionality.

Radiometric Calibration: The spectrometer will conduct a radiometric calibration using a reflectance target affixed to the rover/lander interface assembly. This calibration target will remain with the lander, providing a stable reference for calibration. The calibration process involves capturing spectral data from the known reflectance target to adjust the spectrometer's response for accurate reflectance measurements.

2. In-Situ Calibration Methods:

Use of Reflectance Target: The reflectance target serves as a known standard for calibrating the spectrometer’s measurements. This process involves comparing the measured reflectance values against the known values of the target, allowing for the correction of any deviations.

Environmental Monitoring: Sensors will monitor environmental conditions such as temperature, dust levels, and lighting conditions. These factors can influence spectral measurements and will be accounted for during calibration and data analysis.

3. Control Variables for Experiments:

Spectral Data from Reflectance Target: The known properties of the reflectance target will serve as the primary control variable. By comparing the spectrometer's readings to the expected values, we can adjust for any discrepancies.

Ambient Conditions: Monitoring ambient conditions such as temperature and illumination will help control for environmental variations. This information will be used to adjust the spectrometer’s calibration and ensure data accuracy.

TRIDENT:

Upon egress at the target body, the TRIDENT drill will undergo preliminary tests to ensure all components are functioning correctly. This testing plan focuses on operational status verification and system calibration.

1. Operational Status Verification:

Initial System Check: Immediately after egress, the TRIDENT drill will perform an initial system check to verify that all components are operational. This includes checking the power system, communication links, motor functionality, and sensors.

2. System Calibration:

Deploy Drill Footpad: The drill will deploy its footpad and apply sufficient force to ensure proper contact with the lunar surface. This step ensures the drill's stability and readiness for subsequent operations.

Force Application: The drill will apply force to the footpad to simulate drilling conditions without actually drilling. This allows for the calibration of force sensors and the verification of the drill's mechanical system.

No drilling will occur during the calibration process.

3.5. Precision and Accuracy of Instrumentation

Section is blank.

3.6. Expected Data & Analysis

3.6.1. Tri-band LiDAR

The primary analysis for the detection/concentration of water ice will be performed by inspecting the ratio of surface reflectance at the three (532, 1064, and 1560 nm) wavelengths used. Figure 14 shows the ratio of reflectance calculated using the data from the Tri-band LiDAR for various test samples. Assuming that the physical properties of regolith do not change in the PSRs, different ratios can suggest the concentration and roughly the kind of mixture of regolith and water ice. Minimum detectable concentration limits ranging from 2% to 20% wt, depending on the kind of mixture, have been demonstrated. With extensive testing (Parkinson et al., 2023), a robust detection method can be achieved using reflectance at these three wavelengths. The raw data from the CCD contains the intensity of reflectance where each pixel corresponds to the spatial position being imaged. The resolution of the image (area imaged per snapshot) in TALICO can be controlled to better adapt to various environments and improve the SNR.

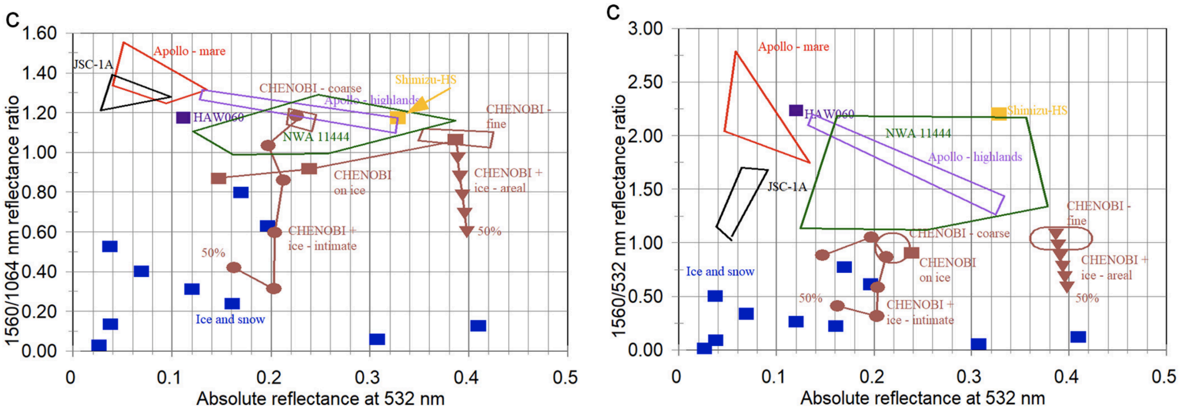
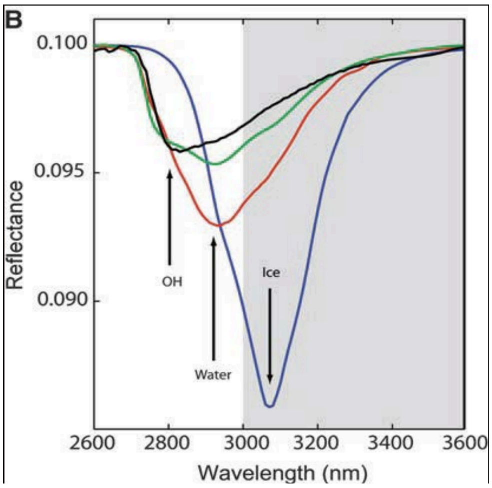
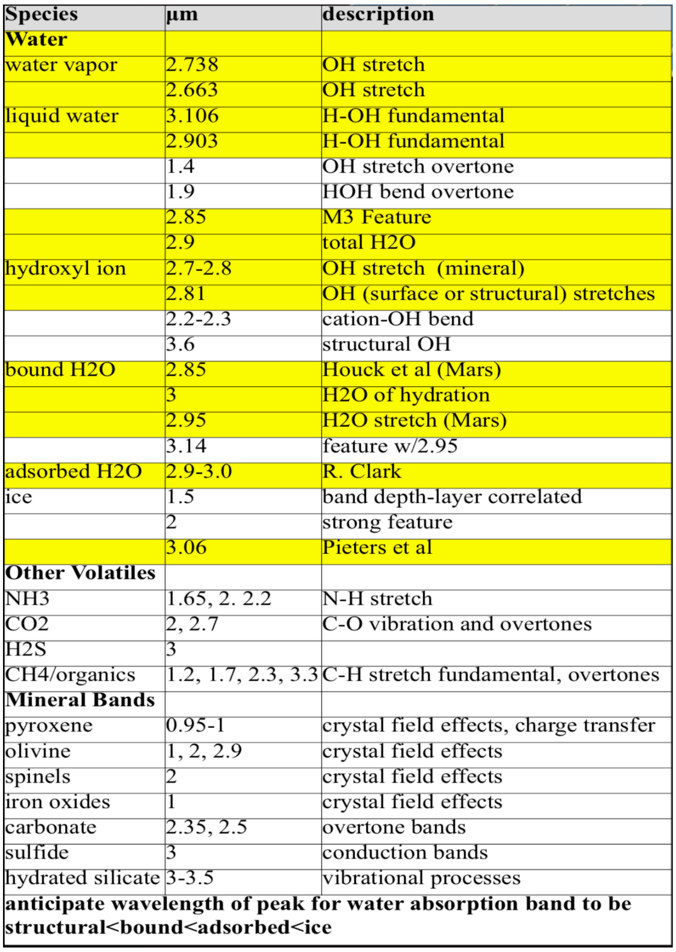


Figure 14. Sample data from Tri-band LiDAR. (left) reflectance ratio of 1560 to 1064 nm (right) reflectance ratio of 1560 to 532 nm for various samples used in laboratory testing; see (!cite) for further details. Each data point corresponds to a certain lunar regolith + water ice mixture and water ice concentration. Taken from the study performed by Parkinson et al. 2023.

3.6.2. BIRCHES

BIRCHES performs spectral analysis; hence the data from the CCD corresponds to the spectrum of the sample over 1-4 μm wavelength range with 10 nm spectral resolution. An example of data obtained from BIRCHES has been provided in Figure X. The obtained spectrum can be analysed to find the absorption features corresponding to various chemical components (see Figure Xb). The intensity of the feature can further be used to assess relative variation in abundance. Similar to astronomical spectral analysis, automated computed programs can be deployed for rapid data processing and classification.





Species	**µm**	**description**
Water		
water vapor	2.738	OH stretch
	2.663	OH stretch
liquid water	3.106	H-OH fundamental
	2.903	H-OH fundamental
	1.4	OH stretch overtone
	1.9	HOH bend overtone
	2.85	M3 Feature
	2.9	total H2O
hydroxyl ion	2.7-2.8	OH stretch (mineral)
	2.81	OH (surface or structural) stretches
	2.2-2.3	cation-OH bend
	3.6	structural OH
bound H2O	2.85	Houck et al (Mars)
	3	H2O of hydration
	2.95	H2O stretch (Mars)
	3.14	feature w/2.95
adsorbed H2O	2.9-3.0	R. Clark
ice	1.5	band depth-layer correlated
	2	strong feature
	3.06	Pieters et al
Other Volatiles		
NH3	1.65, 2. 2.2	N-H stretch
CO2	2, 2.7	C-O vibration and overtones
H2S	3	
CH4/organics	1.2, 1.7, 2.3, 3.3	C-H stretch fundamental, overtones
Mineral Bands		
pyroxene	0.95-1	crystal field effects, charge transfer
olivine	1, 2, 2.9	crystal field effects
spinels	2	crystal field effects
iron oxides	1	crystal field effects
carbonate	2.35, 2.5	overtone bands
sulfide	3	conduction bands
hydrated silicate	3-3.5	vibrational processes
anticipate wavelength of peak for water absorption band to be structural<bound<adsorbed<ice		

Figure X. (left) test spectral data obtained from the BRICES. (right) characteristic absorption feature corresponding to various chemical components. Taken from Clark et al. n.d.

3.6.3. TRIDENT

The TRIDENT provides the temperature data of the extracted sample. Using this, the change in temperature with respect to the spatial position (including depth increments at a point) shall be determined. Figure X shows an example (mock) of data obtained from TRIDENT over the depth increments at a given position.

3.6.4. NSS

The NSS produces data containing the thermal neutron count rate at each position that is to be considered for subsurface investigations. The data from NSS can be visualised using a simple colour map over the lunar surface, see Figure X. Higher concentration of low-energy photons or lower count rate can correspond to the presence/abundance of water ice.

4. Mission Risk Management

4.1. Safety and Hazard Overview

A comprehensive and structured approach is adopted by the team to identify and analyse risks associated with the mission, which includes:

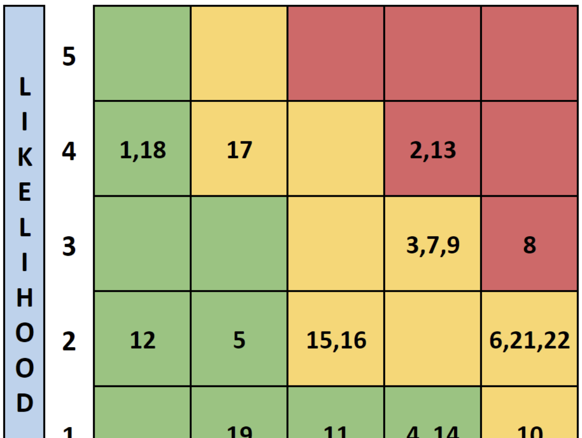
1. Historical data – using information from previous missions and empirical data to identify potential risks.
2. Expert reviews – engaging with subject matter experts to gain insights into possible failure modes and their impacts.
3. Laboratory testing – relying on results from rigorous tests that simulate mission conditions to identify vulnerabilities.
4. Iterative risk assessment – continuously updating risk assessments (see Section 4.1.1) based on running knowledge of the mission to reduce uncertainty over time.
5. Quantitative risk analysis – using statistical techniques to quantify risks and their potential impacts to avoid bias.

The team will maintain a good risk posture by implementing and updating risk mitigation strategies using up-to-date information as the mission progresses. Failure Mode and Effects Analysis (FMEA; see Section 4.1.2) provides a systematic approach to identifying potential failure modes within various systems, thus improving their reliability, safety and quality through proactive identification and addressing of problems. Risk and cost are well-balanced to allow safe demonstration of new technologies while ensuring critical mission components are robust to failure. Personnel hazards and their mitigation strategies are discussed in Section 4.1.3. This ensures the safety of all personnel during various phases of mission development and deployment.

4.1.1. Risk Analysis

<u>Changes in Likelihood and Consequence</u>

Risk statements have been revised from the System Requirements Review to follow the specified format and provide greater depth into the context of the risk. The aforementioned format is Condition, Departure, Asset, Consequence.



LIKELIHOOD	5					
	4	1,18	17		2,13	
	3				3,7,9	8
	2	12	5	15,16		6,21,22
	1		19	11	4, 14	10

Figure 15. Risk Matrix

Risk 1 was found to have a lower likelihood than initially thought as it can be mitigated through the use of Power Management and Distribution Systems (PMAD). Risk 4 was lowered in likelihood due to the existence of shielding materials that could be used. RHUs are also currently under review for whether or not these are necessary, with research on low-power low-temperature power electronics at NASA Glenn Research Center (Hammoud, 2003).

Risks 2, 3, 5, 7, 8, 9, 10, 11, and 12 have remained unchanged in likelihood and consequence, current strategies are being researched regarding implementation and design. 9 new risks have been identified and are currently being reviewed. New risks relate to workmanship (14, 21, 22), adaptation issues (15, 16, 17), or terrain interactions (13, 18, 20).

Mitigation Strategies

Risk 3 can be mitigated using the use of an active thermal system in the form of louvres, as the passive VCHP cannot quickly dissipate heat. Risks 5, 8, and 18 are inherent to the desired mission environment and can be mitigated through careful planning of the mission path using existing data regarding the PSR, namely the Digital Elevation Models (DEM) of the mission location.

Risks 14 and 16 are accepted risks that relate to the reliability of specific components regarding their manufacturing or adaptation. Alternatives to BIRCHES will be considered during the project.

Risks regarding adaptation and workmanship (14, 15, 16, 17, 21, 22) can be mitigated through a thorough test campaign consisting of thermal vacuum testing, shock and vibration testing, and a day-in-the-life simulation.

Risks regarding budget (15) are under research. Currently at this stage, the project cannot access normally private quotes for accurate estimates of costs. Current numbers are ballpark or rough estimates.

Risks relating to regolith (2, 7, 9, 20) can be mitigated using materials or ablation patterns with low regolith adherence characteristics. This is a field of study currently escalating in research and under review (Das, 2024).

Table 32. TALICO Mission Risk Analysis

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Power	1	4	↓	M	Given the possibility of individual battery cells failing, it is possible for a single failure to have a cascading effect on all cells causing inoperability of the entire power subsystem.	Active
2	Power	4	4	→	M	Given the possibility of regolith scattering and levitating (condition), it is possible that solar panels get covered with regolith (departure) causing a decreased power output (Asset) potentially causing insufficient power for spacecraft systems (Consequence)	Active
3	Thermal	3	4	→	M	Due to the highly variable temperatures of the PSR it is possible that the rover can become unexpectedly warm with the thermal link unable to dissipate heat quick enough causing electronic components to overheat potentially damaging especially sensitive instruments such as the CPU or sensors	Active
4	Thermal	1	4	↓	R	Radiation from RHU affects onboard electronics causing digital latchups and causing permanent damage to integrated circuits or affecting memory of digital components	Active
5	Mechanical	2	2	→	A	Due to the rough terrain of the surface of the Moon (condition) the wheels of the rover will deteriorate over time (asset) resulting in mechanical failure of the wheels (asset) and affecting the maneuvarability of the rover (consequence)	Active
6	Mechanical	2	5	↓	M	Due to the lower gravity of the Moon and uneven terrain (condition), there is a possibility that the spacecraft can lose balance (departure) causing damage to the wheels or suspension (asset) rendering the rover immobile (consequence)	Active
7	GNC	3	4	→	M	Given the presence of regolith on the Moon, it is possible for navigational LiDAR instruments to be obstructed compromising navigation accuracy and endangering the rover by increasing the risk of collision or tipover	Active
8	GNC	3	5	→	R	Given limitations in the modelling on terrain, software algorithms and integration within the GNC subsystem may cause navigation errors and obstacle poor avoidance strategies endangering the survival of the spacecraft given solar constraints	Active
9	Payload	3	4	→	R	Due to the presence of regolith dust, obstructions from build up may occur causing interference with the optics of the spectrometer and therefore affecting the accuracy of scientific measurements	Active
10	Payload	1	5	→	A	Due to the sensitive nature of the BIRCHES instrument, it is possible that the component is used beyond its operating temperatures causing the BIRCHES instrument fail	Active
11	Payload	1	3	→	M	Due to poor chip flow it is possible for the drill bit to jam inside the lunar regolith thereby rendering the drill unusable and the rover immobile and unable to extract regolith	Active
12	Budget	2	1	→	W	BIRCHES instrumentation adaptation to rover use (from satellite) balloons in cost of development causing an overrun of budget	Active
13	Power	4	4	NEW	W	Given the radioactive nature of the mission environment (condition), radioactive exposure may degrade solar panel materials (departure), reducing their efficiency and power output (asset) thus increasing the required time in sunlit areas to charge batteries (Consequence).	Active
14	GNC	3	4	NEW	A	Due to a small chance of manufacturing error it is possible the IMU malfunctions impacting the rovers ability to correctly determine velocity and orientation causing difficulty in determining if the rover is correctly navigating the predetermined path	Active
15	Budget	2	3	NEW	R	Due to the high uncertainty with costs of certain materials due to a lack of publicly available pricing, it is possible for the current rover design to run over budget thereby causing financial issues to the mission	Active
16	Schedule	2	3	NEW	A	Due to in-house adaptation of scientific instruments it is possible for delays in production to occur causing the project to be delayed by significant margins	Active
17	Schedule	4	2	NEW	M	Due to some components being commercially off the shelf it is possible for components to be discontinued or out of stock due to supply chain issues or unprofitability causing delays in rover production due to component replacement or system redesign	Active
18	Schedul	4	1	NEW	R	Due to the variable patterns and seasons of the PSR it is possible for the	Active

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
	e					unusually long periods of darkness to occur in Connecting Ridge 1 (recharge point) causing mission delays	
19	CDH	1	2	NEW	R	Due to the lack of an electromagnetic field protecting the Moon from space radiation, it is possible that data storage corruption may occur causing loss in scientific measurements causing a delay in the mission	Active
20	CDH	2	5	NEW	M	Due to the presence of regolith dust, obstructions from build up may occur causing interference in the use of antenna affecting the ability of the rover to communicate	Active
21	CDH	2	5	NEW	M	Due to workmanship error, vibration from drilling may cause spacewiring to become compromised, potentially affecting the operability and connectivity of internal circuitry	Active
22	CDH	2	5	NEW	M	Due to workmanship error, it is possible for outgassing to occur from some materials in reaction to the vacuum of space, creating debris around electronic components that may cause malfunction, possibly to the extent of mission failure	Active

4.1.2. Failure Mode and Effect Analysis (FMEA)

The table below outlines a detailed Failure Mode and Effects Analysis (FMEA) of Potential Risks for the mission that were identified. The table focuses on analyzing and tracing the impact of these risks and their effect on the mission. Each failure mode is analyzed for its potential effects, severity, causes, occurrence, prevention, detection, and the resulting Risk Priority Number (RPN). The Table also includes actions that need to be undertaken to mitigate the risk and include implementation of cleaning systems and incorporating redundancies among others. This structured table allows to assess all risks connected with the mission and contribute to their identification and mitigation, enhancing the overall reliability of the rover and significantly contributing to the success of the mission.

Table 33. TALICO Mission Failure Mode and Effect Analysis

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Power Generation	Solar panels get covered with dust	The covering of solar panels with dust can significantly decrease their energy generation, as there is less are od solar cells that generate the energy this could significantly influence the movability of the rover.	8	Dust on solar panels due to: - While moving the rover will kicks up the dust - micrometeorite impact that ejects dust - drilling in the moon's surface also ejects dust	8	Adding a cleaning mechanism that would wipe the dust of without damaging the solar panels	7	448	Add a redundancy system that would allow the rover to function to its full capabilities even though the solar panels generate less power, decrease the needed power by adjusting the equipment that the rover uses

	Decrease in energy storage of the battery	The decreased capacity to store energy of the battery can influence the rover mobility. With not sufficient power delivered generated certain function of the rover might not work	8	Extreme temperatures , frequent charging and discharging, and aging can reduce the capacity of a battery	7	Adding additional thermal insulation, changing the insulation material, selecting a more robust battery capable of surviving lower temperatures for longer,	7	392	Improve the thermal insulation, select component that are more temperature resistant, adjust the power management system to the battery so that the battery is charged the leas amount of times
	Degradation of solar panels	Decreased energy generation, Decrease in rovers' range and functionality	8	Radiation can lead to the degradation of solar panels, reducing their efficiency and overall lifespan	6	XXXXX	7	336	Use radiation-resistant materials, decrease the needed power by adjusting the equipment that the rover uses
Thermal	Heat not properly distributed	Overheating or freezing I worst case total failure of components	8	Improper distribution of heat, inadequate insulation	6	Adding an advanced thermal management system might help with the heat distribution	8	384	Optimize thermal design, improve thermal insulation
	Influence of radiation from RHU on other components	Radiation can create electronic interferences leading to data corruption and component degradation	7	Primary cause is the radiation from RHU	5	Shielding, covers can be used to absorb the radiation. Additionally the RHU should be strategically placed as to cause the least possible issues(far from	5	175	Improve shielding materials, Relocate the RHU to other position, select electrical components less sensitive to interferences, adjust systems to take int account the interferences

						sensitive components)			
Payload	Optics covered with dust	Can lead to reduced sensor accuracy, impaired imaging, worsened data collection and decrease in overall performance of optical systems	7	Lunar dust from - While moving the rover will kicks up the dust - micrometeorite impact that ejects dust - drilling in the moon's surface also ejects dust	8	Cleaning mechanism which would clean the optics, dust resistant covers would protect the optics from dust and open when needed	8	448	
	Fail of the thermal management system	Overheating or freezing I worst case total failure of components	9	Improper distribution of heat, inadequate insulation	4	Built in redundancies, more sensors if one breaks the next ne takes over	6	216	Add more insulation, change insulation, select different sensors more resistant to the extreme temperatures

	Drill gets stuck in lunar regolith or gets broken	The loss of the drill can lead operational delay, inability to collect samples in the future	9	The possible causes of the drill getting stuck include - Drill from wrong material - Large vibrations, - Systems not working together (ex. Rover start driving while drilling causing the drill to break or get szuck)	5	Decrease vibration while drilling using a control system that drills while checking the vibrations Adding the possibility to change drills	10	450	- Add more spare drills, - Check the material of the drill if it is fit to drill in the regolith, - Add system that with small vibrations gets the drill unstuck
CDH	Data Storage corruption	Can lead to loss of data and communication failure impacting the reliability of the measurements,	7	Radiation, system error, power outage, software issue, coding bug	6	Add back ups	4	168	Utilize error-checking algorithms
	Damage of the Antenna	Damage to the antenna can lead to communication failure, delayed data transmission,	9	- Physical damage from lunar environment micromet	5	- protective casing, - replacement antenna - Better insulation	5	225	- Add redundancies - Add dust repellent coatings - Improve insulation

		loss of contact with base		eorite impact - Lunar dust collecting on the antenna - Thermal stress - Radiation		-			
	Compromise of wiring	power failure, system malfunction	9		7	- Add protective casings - Better insulation - Select different wiring more temperature resistant	3	189	Add protective casing, better material selection
	Low level bit error	Data integrity issues	9	Electrical fault, radiation interference	5	Error-correcting codes	9	405	Utilize error-checking algorithms
GNC	LiDAR Obstruction by Regolith	Navigation failure, loss of orientation, inaccurate navigation,	9	Moon dust interferes with the LiDAR sensors	8	Dust removal systems	7	504	As long as the issue is known and measurable we can adjust the navigation through software patches
	Navigation Software Errors	Inaccurate navigation, incorrect path planning, interruptions	8	Software bugs, coding errors	6	Software patches, Error-correcting codes	6	288	Utilize error-checking algorithms

	IMU Sensor Failure	reduced performance, inaccurate results	7	Sensor malfunction, degradation through radiation and thermal stress	5	Redundant sensors Protective casing	8	280	Sensor redundancy
	Sensor Impairment by Dust Accumulation	Inaccurate results, whole mission can be compromised	7	Dust covering sensors due to: - While moving the rover will kicks up the dust - micrometeorite impact that ejects dust drilling in the moon’s surface also ejects dust	9	Protective covers, mechanisms that cleans the sensors without damaging	5	315	Adjusting the measurements by the inaccuracies due to sensor impairment,
Mechanical	Mechanical Component Degradation	Shorter lifespan of rover	8	Wear and tear from lunar environment	7	Use high-durability materials	5	280	Use stronger materials and design

4.1.3. Personnel Hazards and Mitigations

Table 34. TALICO Mission Personnel Hazards and Mitigations

Hazard Category	***Specific Hazard***	***Potential Risks***	***Mitigations***
Manufacturing Hazards	*Noise Exposure*	*Hearing loss*	*Use ear protection, monitor noise level, use Noise canceling headphones*
	Welding and Cutting Hazards	*Burns, Cuts, eye damage, fume inhalation blindness*	*Usage of welding helmet, protective clothing, training, adequate ventilation,*
	Machine operation	*Cuts, crush injuries*	*proper training, usage of protective equipment, emergency stop buttons*
Integration Hazards	*Electrical*	*Electric shock, burns death*	*Wear protective equipment, follow the five rules of electrical safety, install emergency stop buttons*
	Heavy components	*Injuries caused by dropping heavy components*	*Use of lifting equipment*
Testing Hazards	*high pressure systems*	*explosion*	*safety protocols, pressure relief system*
	Thermal testing hazards	*burns*	*Use of protective equipment*
Research Facility and Lab Safety	*Spills of chemicals*	*burns, poisoning*	*safety protocols, proper storage, training, shower,*
General Safety Measures	*Slips Trips, Falls etc*	*Injuries from falling*	*Organizing all the equipment, good housekeeping practices, signage*

	Fire hazards	*Burns, smoke inhalation, death*	*fire drills, fire safety equipment,*

5. Activity Plan

5.1. Project Management Approach

The TALICO structure will evolve as the mission progresses through the NASA mission lifecycle. Following approval past KDP C post PDR, TALICO proposes a mission structure (Figure X) to ensure smooth operation based on the NASA Space Flight Program and Project Management: Requirements (NPR 7120.5F - Main, n.d.) documentation and project plan template. Four centres will be established, which expands upon the teaming structure of TALICO thus far.

Each team will have its own team lead, who will oversee all operations within the subteams under their command. Decisions at a subteam level will be made at the team leads discretion. Communication between branches will be handled internally between teams, but should consult through team leads who will be in constant communication with one another and have knowledge and breadth on the entire scope of the TALICO project. All teams will have direct access to Mission Enabling channels, to ensure effective structure, discipline, and individual employee satisfaction.

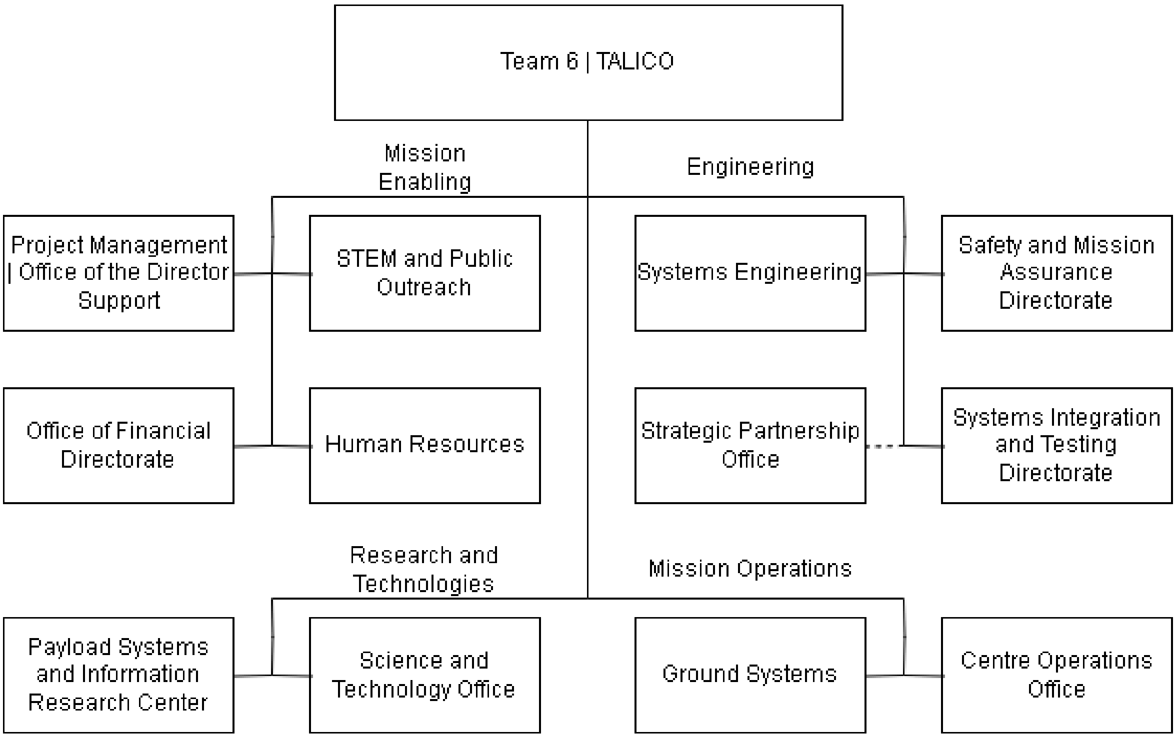


Figure 16. Proposed TALICO Team organisation flow chart

Mission Enabling extends from the Programmatics team, being an administrative body that will handle management, financial allocations, hiring and personnel, and public outreach. All other teams under the TALICO mission are required to operate within the scope and bounds set by the Mission Enabling centre.

Engineering will be expanded to provide greater structure going into heavy periods of manufacturing and design, verification, and validation, through Phases C and D. Systems engineering will still operate at a rover subsystem level, while safety and mission assurance and systems integration and testing will be outsourced to new teams, respectively. The strategic partnership office, which will be housed under the engineering umbrella, will collaborate with outside contractors who will be required to build equipment and systems for the rover, if necessary.

The science team will be expanded into the Research and Technologies team, which consists of payload systems and information research centre, responsible for the data the rover collects and the instrumentation associated with that, and the science and technology office, which will handle the data on a broader scope of international collaboration, distribution, and sharing of data.

Finally, a Mission Operations team will be established to handle rover life operations in a ground mission control centre. All systems relating to rover communications will be handled and managed by this centre, as well as ongoing operations during Phases E and F.

Personnel allocations for each branch have been set out as a guide only. Allocations have been set to conform to the TALICO project management structure laid out above, but are flexible and able to change subject to branch management recommendations and needs. During Phase D, the most personnel heavy stage, TALICO will employ the following number of professional personnel:Upper management personnel refers to the TALICO project manager, and the respective branch leads which will be established going forward. This structure of the five upper managers will be consistent through the project lifecycle, to ensure consistent and smooth progress on the rover through different phase milestones, KDP's, and goals.

Table 35. Personnel Allocations of TALICO Team

Profession	# People on Team
Science Personnel:	8
Engineering Personnel:	20
Technicians:	12
Administration Personnel:	8
Management Personnel:	5
Upper Management Personnel	5

TALICO requires a multidisciplinary team comprising engineers, scientists, business professionals and support staff to accomplish its objectives. A brief overview of the roles and responsibilities required is provided in Table 5.

Table 36. Overview of Team Roles

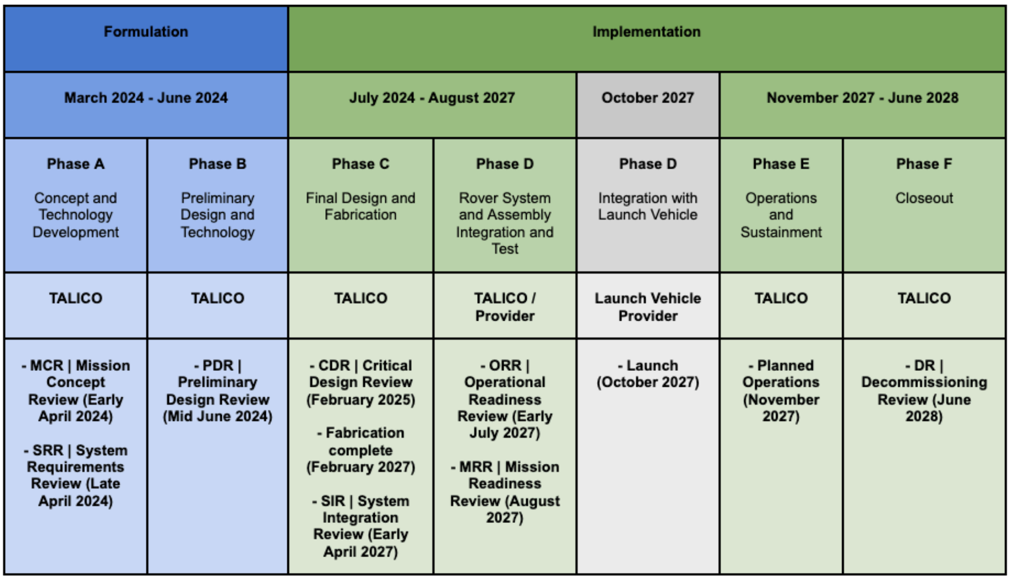
Category	Role	Responsibility
Engineers	Hardware Engineers	Responsible for designing, testing, and implementing hardware components, including mechanical systems and electronic hardware.
	Software Engineers	Develop and maintain software systems for navigation, data handling, and communication.
	Systems Engineers	Ensure integration and compatibility of subsystems, manage requirements, and conduct system-level testing.
	Instrumentation Engineers	Design and oversee the implementation of scientific instruments, ensuring accuracy and reliability in data collection.
Scientists	Planetary Scientists	Provide expertise in interpreting lunar data and guiding scientific objectives.
	Instrument Scientists	Work closely with engineers to optimise instrument performance and data analysis techniques.
Business Professionals	Project Managers	Coordinate project activities, manage schedules and budgets, and ensure overall project success.
	Finance and Budgeting Experts	Manage project finances, allocate resources, and ensure adherence to budget constraints.
Support Staff	Administrative Assistants	Provide logistical and administrative support to the project team.
	Communications Specialists	Handle internal and external communications, including media relations and public outreach.

5.2. Mission Schedule

5.2.1. Schedule Basis of Estimate

TALICO determined a project schedule of roughly 4 years after close analysis of similar missions (i.e VIPER, IM-1). This schedule has been selected as a reasonable and achievable goal given the financial restrictions presented. As seen through the IM-1 mission, 3 years is not enough to produce a product capable of surviving the lunar environment for a long time. The VIPER mission's schedule of 5 years leads the TALICO to believe that a project schedule of roughly 4 years should be sufficient to produce a functional rover due to the accelerated phase A (Concept and Technology Development) and B (Preliminary Design and Technology).

Table 37.Schedule Basis of Estimate

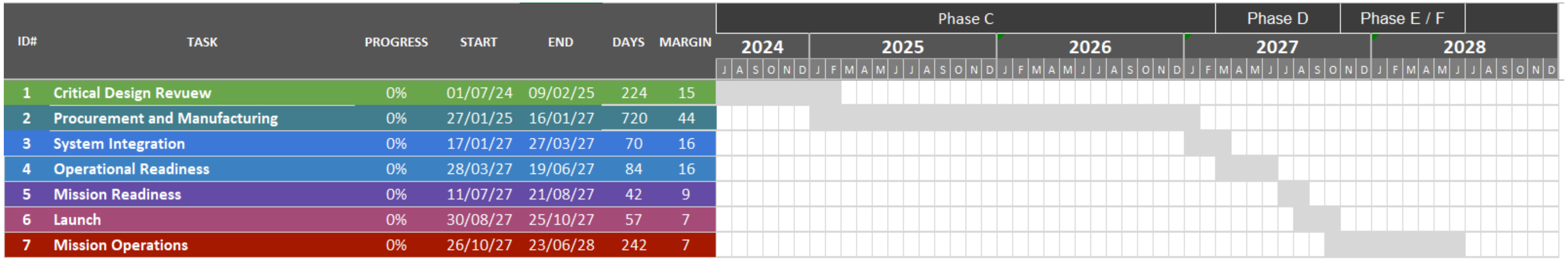


Formulation		Implementation				
March 2024 - June 2024		July 2024 - August 2027		October 2027	November 2027 - June 2028	
Phase A Concept and Technology Development	**Phase B** Preliminary Design and Technology	**Phase C** Final Design and Fabrication	**Phase D** Rover System and Assembly Integration and Test	**Phase D** Integration with Launch Vehicle	**Phase E** Operations and Sustainment	**Phase F** Closeout
TALICO	**TALICO**	**TALICO**	**TALICO / Provider**	**Launch Vehicle Provider**	**TALICO**	**TALICO**
- MCR | Mission Concept Review (Early April 2024) **- SRR | System Requirements Review (Late April 2024)**	**- PDR | Preliminary Design Review (Mid June 2024)**	**- CDR | Critical Design Review (February 2025)** **- Fabrication complete (February 2027)** **- SIR | System Integration Review (Early April 2027)**	**- ORR | Operational Readiness Review (Early July 2027)** **- MRR | Mission Readiness Review (August 2027)**	**- Launch (October 2027)**	**- Planned Operations (November 2027)**	**- DR | Decommissioning Review (June 2028)**

The constraint of the accelerated phase A and B in the mission task document allows TALICO to slow down during the manufacturing and testing phases, increasing mission assurance and reducing errors which may result in failure to meet deadlines. TALICO is aware that the launch vehicle window is dependent on external factors and the team will remain flexible to the possibility of change. Despite all these constraints, TALICO will have approximately 37 months to design, manufacture, purchase, assemble and test all components which provides the team with sufficient time to ensure all components work together seamlessly.

5.2.2. Mission Schedule

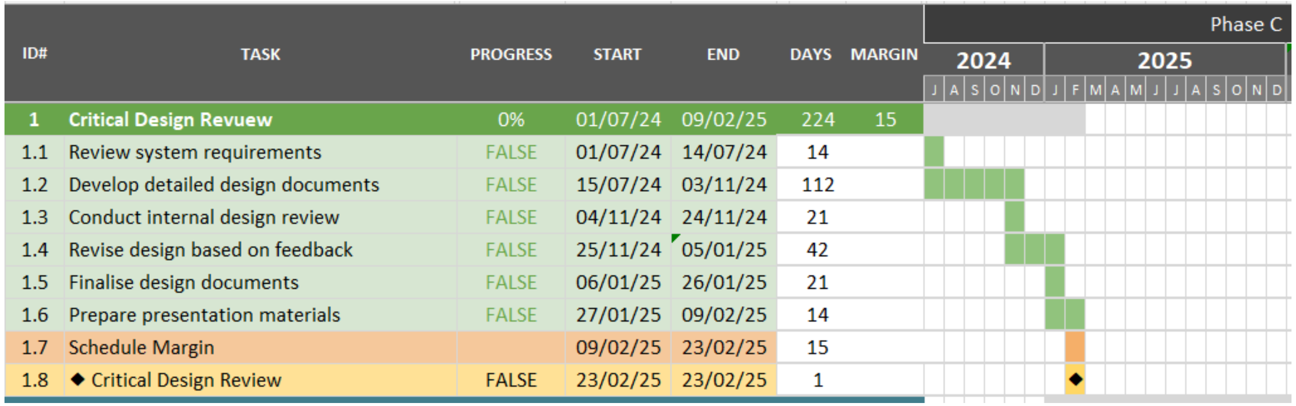
The schedule was meticulously planned to align with the NASA Mission Life Cycle, commencing from Phase C (Final Design and Fabrication) through Phase F (Mission Operations and Closeout). The estimates were derived based on historical data from similar missions, collective judgement, and best practices outlined in the NASA Systems Engineering Handbook and the NASA Space Flight Program and PMI's PMBOK. Each phase includes built-in schedule margins to mitigate any potential delays and risks. The critical path tasks amount to a total of 1439 days (approximately 48 months), ensuring that each phase transitions smoothly into the next, adhering to NASA's rigorous standards and guidelines. In summary, the mission schedule is designed to meet all critical milestones (Figure 17) within the estimated timeframe, with built-in schedule margins to mitigate potential delays and ensure mission success.



ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
1	Critical Design Revuew	0%	01/07/24	09/02/25	224	15
2	Procurement and Manufacturing	0%	27/01/25	16/01/27	720	44
3	System Integration	0%	17/01/27	27/03/27	70	16
4	Operational Readiness	0%	28/03/27	19/06/27	84	16
5	Mission Readiness	0%	11/07/27	21/08/27	42	9
6	Launch	0%	30/08/27	25/10/27	57	7
7	Mission Operations	0%	26/10/27	23/06/28	242	7

Figure 17.

Schedule Estimates

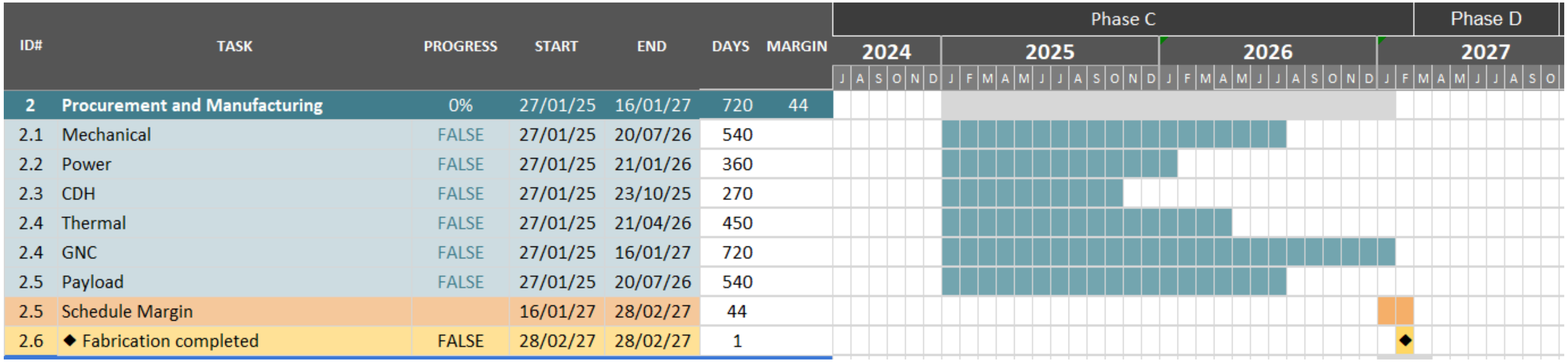


ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
1	Critical Design Revuew	0%	01/07/24	09/02/25	224	15
1.1	Review system requirements	FALSE	01/07/24	14/07/24	14	
1.2	Develop detailed design documents	FALSE	15/07/24	03/11/24	112	
1.3	Conduct internal design review	FALSE	04/11/24	24/11/24	21	
1.4	Revise design based on feedback	FALSE	25/11/24	05/01/25	42	
1.5	Finalise design documents	FALSE	06/01/25	26/01/25	21	
1.6	Prepare presentation materials	FALSE	27/01/25	09/02/25	14	
1.7	Schedule Margin		09/02/25	23/02/25	15	
1.8	◆ Critical Design Review	FALSE	23/02/25	23/02/25	1	

Figure 18.

Critical Design Review (Figure 18): estimated based on historical data from similar missions, taking into account the complexity of design and the iterative process required to meet stringent review standards. The timeline includes ample time for internal reviews and revisions based on feedback, ensuring thorough preparation for the final review.

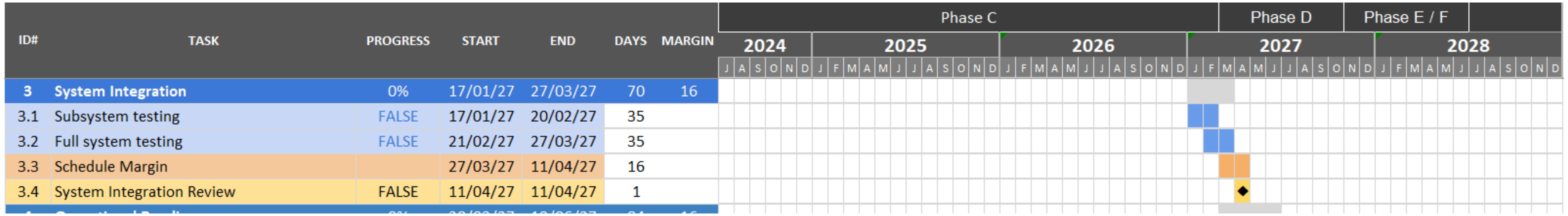
Procurement and Manufacturing (Figure 18): estimated from expert judgement and best practices. The duration allows for concurrent engineering efforts across subsystems, optimising resource use and ensuring timely completion of fabrication.



ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
2	**Procurement and Manufacturing**	0%	27/01/25	16/01/27	720	44
2.1	Mechanical	FALSE	27/01/25	20/07/26	540	
2.2	Power	FALSE	27/01/25	21/01/26	360	
2.3	CDH	FALSE	27/01/25	23/10/25	270	
2.4	Thermal	FALSE	27/01/25	21/04/26	450	
2.4	GNC	FALSE	27/01/25	16/01/27	720	
2.5	Payload	FALSE	27/01/25	20/07/26	540	
2.5	Schedule Margin		16/01/27	28/02/27	44	
2.6	◆ Fabrication completed	FALSE	28/02/27	28/02/27	1	

Figure 19.

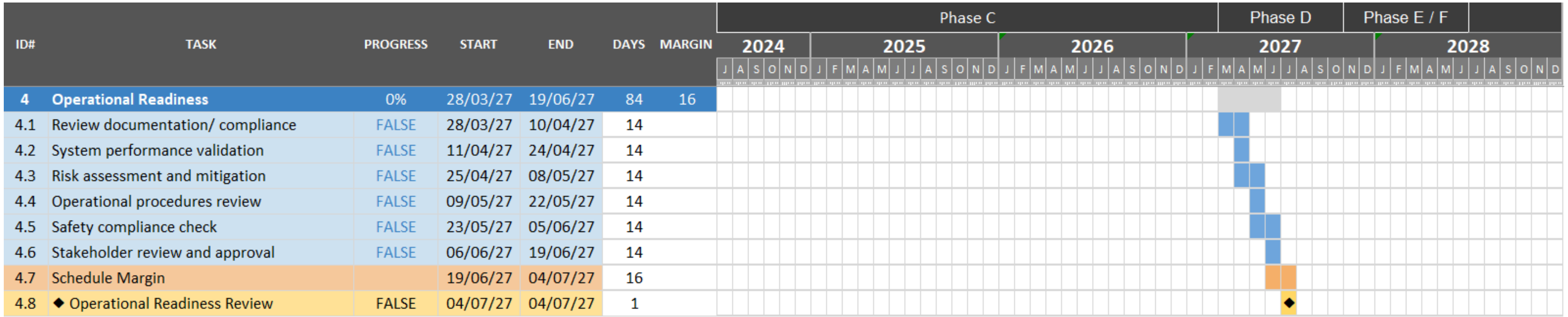
System Integration (Figure 19): estimated based on subsystems complexity and historical data. It includes detailed testing to validate the performance and compatibility of the integrated system, ensuring no delays in transitioning to operational readiness.



ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
3	**System Integration**	0%	17/01/27	27/03/27	70	16
3.1	Subsystem testing	FALSE	17/01/27	20/02/27	35	
3.2	Full system testing	FALSE	21/02/27	27/03/27	35	
3.3	Schedule Margin		27/03/27	11/04/27	16	
3.4	System Integration Review	FALSE	11/04/27	11/04/27	1	

Figure 20.

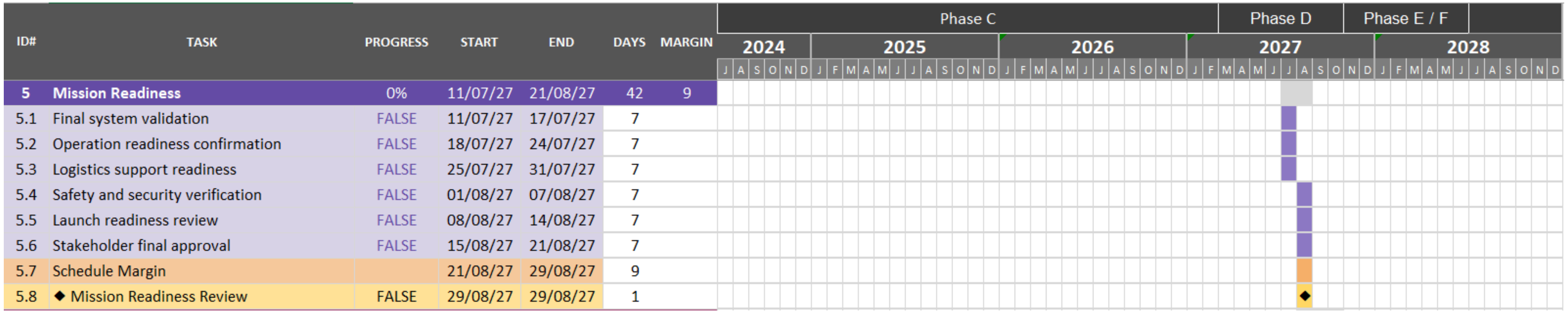
Operational Readiness Review (Figure 20): includes a comprehensive review of all operational procedures, safety checks, and compliance requirements. The schedule allows for detailed validation and risk assessments, ensuring that all aspects of operational readiness are thoroughly reviewed and approved.



ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
4	**Operational Readiness**	0%	28/03/27	19/06/27	84	16
4.1	Review documentation/ compliance	FALSE	28/03/27	10/04/27	14	
4.2	System performance validation	FALSE	11/04/27	24/04/27	14	
4.3	Risk assessment and mitigation	FALSE	25/04/27	08/05/27	14	
4.4	Operational procedures review	FALSE	09/05/27	22/05/27	14	
4.5	Safety compliance check	FALSE	23/05/27	05/06/27	14	
4.6	Stakeholder review and approval	FALSE	06/06/27	19/06/27	14	
4.7	Schedule Margin		19/06/27	04/07/27	16	
4.8	◆ Operational Readiness Review	FALSE	04/07/27	04/07/27	1	

Figure 21.

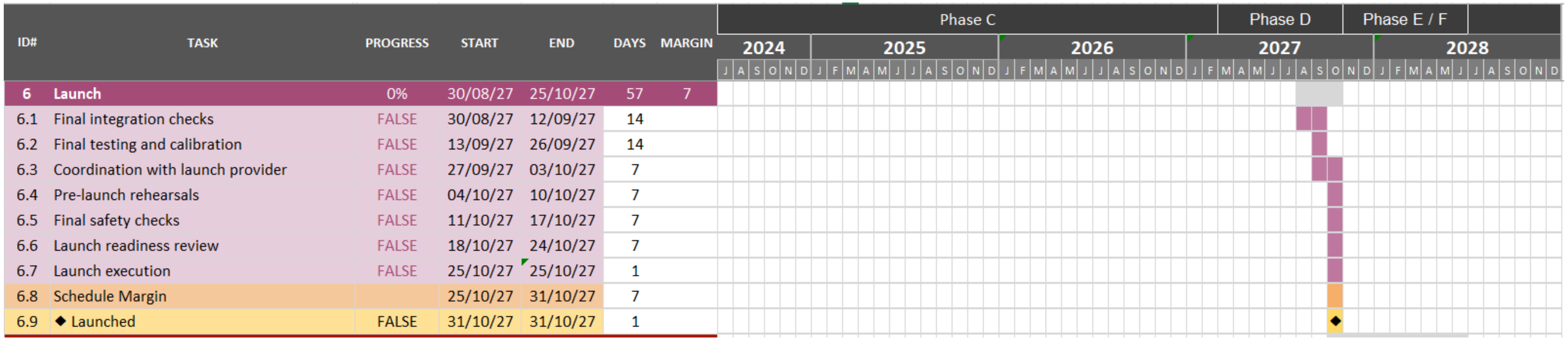
Mission Readiness Review (Figure 20): based on final validation and confirmation activities, logistical support readiness, and safety and security checks. The timeline ensures fully-operational systems ready for launch, with stakeholder approvals secured.



ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
5	**Mission Readiness**	0%	11/07/27	21/08/27	42	9
5.1	Final system validation	FALSE	11/07/27	17/07/27	7	
5.2	Operation readiness confirmation	FALSE	18/07/27	24/07/27	7	
5.3	Logistics support readiness	FALSE	25/07/27	31/07/27	7	
5.4	Safety and security verification	FALSE	01/08/27	07/08/27	7	
5.5	Launch readiness review	FALSE	08/08/27	14/08/27	7	
5.6	Stakeholder final approval	FALSE	15/08/27	21/08/27	7	
5.7	Schedule Margin		21/08/27	29/08/27	9	
5.8	◆ Mission Readiness Review	FALSE	29/08/27	29/08/27	1	

Figure 22.

Launch (Figure 20): accounts for final integration, testing, rehearsals, and safety checks, ensuring a smooth and successful launch. The estimates were based on coordination with the launch provider and historical data from similar missions.

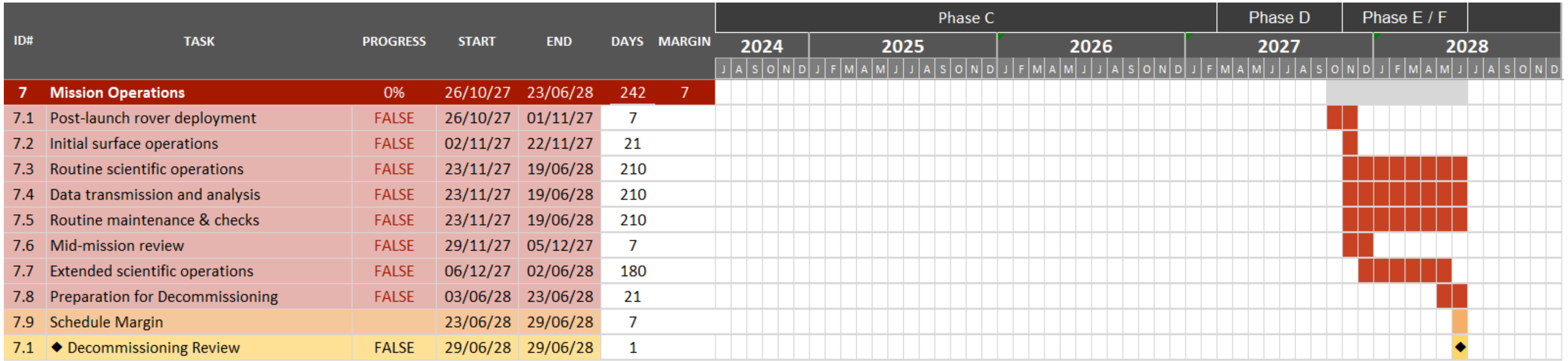


ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
6	**Launch**	0%	30/08/27	25/10/27	57	7
6.1	Final integration checks	FALSE	30/08/27	12/09/27	14	
6.2	Final testing and calibration	FALSE	13/09/27	26/09/27	14	
6.3	Coordination with launch provider	FALSE	27/09/27	03/10/27	7	
6.4	Pre-launch rehearsals	FALSE	04/10/27	10/10/27	7	
6.5	Final safety checks	FALSE	11/10/27	17/10/27	7	
6.6	Launch readiness review	FALSE	18/10/27	24/10/27	7	
6.7	Launch execution	FALSE	25/10/27	25/10/27	1	
6.8	Schedule Margin		25/10/27	31/10/27	7	
6.9	◆ Launched	FALSE	31/10/27	31/10/27	1	

Figure 23.

Mission Operations (Figure 20): The operations phase was scheduled to maximise scientific return, including post-launch deployment, initial surface operations, routine scientific activities, and extended operations. The estimates were based on mission objectives and expected operational challenges, allowing for routine maintenance and mid-mission reviews.

Decommissioning (Figure 20): The final phase includes preparation for mission closeout, ensuring all operations are concluded systematically and data is archived appropriately. The schedule was based on best practices for mission decommissioning.



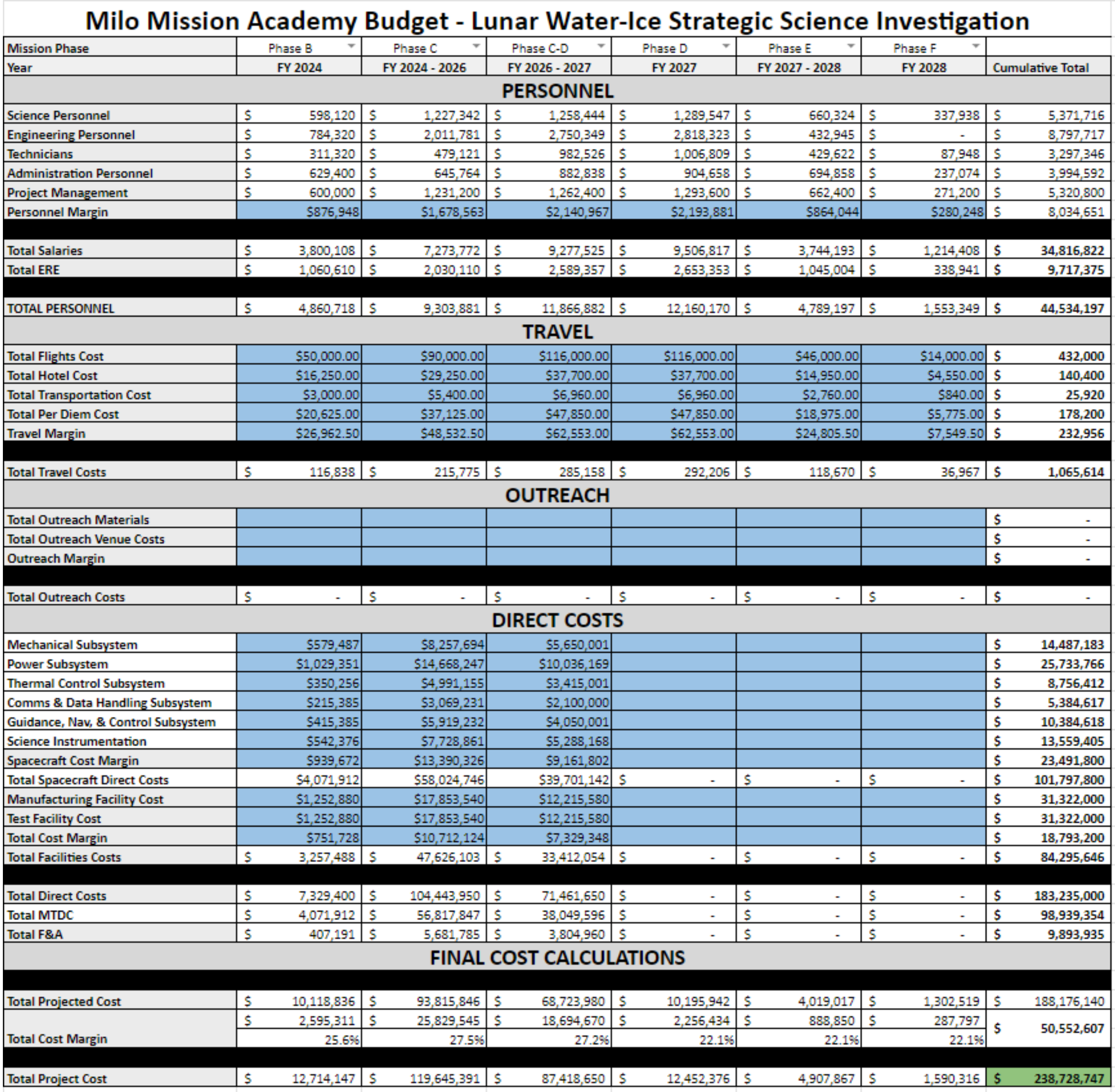
ID#	TASK	PROGRESS	START	END	DAYS	MARGIN
7	**Mission Operations**	0%	26/10/27	23/06/28	242	7
7.1	Post-launch rover deployment	FALSE	26/10/27	01/11/27	7	
7.2	Initial surface operations	FALSE	02/11/27	22/11/27	21	
7.3	Routine scientific operations	FALSE	23/11/27	19/06/28	210	
7.4	Data transmission and analysis	FALSE	23/11/27	19/06/28	210	
7.5	Routine maintenance & checks	FALSE	23/11/27	19/06/28	210	
7.6	Mid-mission review	FALSE	29/11/27	05/12/27	7	
7.7	Extended scientific operations	FALSE	06/12/27	02/06/28	180	
7.8	Preparation for Decommissioning	FALSE	03/06/28	23/06/28	21	
7.9	Schedule Margin		23/06/28	29/06/28	7	
7.1	◆ Decommissioning Review	FALSE	29/06/28	29/06/28	1	

Figure 24.

5.3. Budget

The budget for the TALICO mission is designed to ensure the efficient allocation of resources while achieving all mission objectives. The budget cap is set at $225 million, with the total estimated costs meticulously calculated to stay within this limit. This section provides a concise summary of the financial planning and considerations involved in the budgeting process, highlighting the major cost categories.

Figure 25. Budget. Overview



Milo Mission Academy Budget - Lunar Water-Ice Strategic Science Investigation

Mission Phase	Phase B	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	FY 2024	FY 2024 - 2026	FY 2026 - 2027	FY 2027	FY 2027 - 2028	FY 2028	Cumulative Total
PERSONNEL							
Science Personnel	$ 598,120	$ 1,227,342	$ 1,258,444	$ 1,289,547	$ 660,324	$ 337,938	$ 5,371,716
Engineering Personnel	$ 784,320	$ 2,011,781	$ 2,750,349	$ 2,818,323	$ 432,945	$ -	$ 8,797,717
Technicians	$ 311,320	$ 479,121	$ 982,526	$ 1,006,809	$ 429,622	$ 87,948	$ 3,297,346
Administration Personnel	$ 629,400	$ 645,764	$ 882,838	$ 904,658	$ 694,858	$ 237,074	$ 3,994,592
Project Management	$ 600,000	$ 1,231,200	$ 1,262,400	$ 1,293,600	$ 662,400	$ 271,200	$ 5,320,800
Personnel Margin	$876,948	$1,678,563	$2,140,967	$2,193,881	$864,044	$280,248	$ 8,034,651
Total Salaries	$ 3,800,108	$ 7,273,772	$ 9,277,525	$ 9,506,817	$ 3,744,193	$ 1,214,408	**$ 34,816,822**
Total ERE	$ 1,060,610	$ 2,030,110	$ 2,589,357	$ 2,653,353	$ 1,045,004	$ 338,941	**$ 9,717,375**
TOTAL PERSONNEL	$ 4,860,718	$ 9,303,881	$ 11,866,882	$ 12,160,170	$ 4,789,197	$ 1,553,349	**$ 44,534,197**
TRAVEL							
Total Flights Cost	$50,000.00	$90,000.00	$116,000.00	$116,000.00	$46,000.00	$14,000.00	**$ 432,000**
Total Hotel Cost	$16,250.00	$29,250.00	$37,700.00	$37,700.00	$14,950.00	$4,550.00	**$ 140,400**
Total Transportation Cost	$3,000.00	$5,400.00	$6,960.00	$6,960.00	$2,760.00	$840.00	**$ 25,920**
Total Per Diem Cost	$20,625.00	$37,125.00	$47,850.00	$47,850.00	$18,975.00	$5,775.00	**$ 178,200**
Travel Margin	$26,962.50	$48,532.50	$62,553.00	$62,553.00	$24,805.50	$7,549.50	**$ 232,956**
Total Travel Costs	$ 116,838	$ 215,775	$ 285,158	$ 292,206	$ 118,670	$ 36,967	**$ 1,065,614**
OUTREACH							
Total Outreach Materials							$ -
Total Outreach Venue Costs							$ -
Outreach Margin							$ -
Total Outreach Costs	$ -	$ -	$ -	$ -	$ -	$ -	$ -
DIRECT COSTS							
Mechanical Subsystem	$579,487	$8,257,694	$5,650,001				**$ 14,487,183**
Power Subsystem	$1,029,351	$14,668,247	$10,036,169				**$ 25,733,766**
Thermal Control Subsystem	$350,256	$4,991,155	$3,415,001				**$ 8,756,412**
Comms & Data Handling Subsystem	$215,385	$3,069,231	$2,100,000				**$ 5,384,617**
Guidance, Nav, & Control Subsystem	$415,385	$5,919,232	$4,050,001				**$ 10,384,618**
Science Instrumentation	$542,376	$7,728,861	$5,288,168				**$ 13,559,405**
Spacecraft Cost Margin	$939,672	$13,390,326	$9,161,802				**$ 23,491,800**
Total Spacecraft Direct Costs	$4,071,912	$58,024,746	$39,701,142	$ -	$ -	$ -	**$ 101,797,800**
Manufacturing Facility Cost	$1,252,880	$17,853,540	$12,215,580				**$ 31,322,000**
Test Facility Cost	$1,252,880	$17,853,540	$12,215,580				**$ 31,322,000**
Total Cost Margin	$751,728	$10,712,124	$7,329,348				**$ 18,793,200**
Total Facilities Costs	$ 3,257,488	$ 47,626,103	$ 33,412,054	$ -	$ -	$ -	**$ 84,295,646**
Total Direct Costs	$ 7,329,400	$ 104,443,950	$ 71,461,650	$ -	$ -	$ -	**$ 183,235,000**
Total MTDC	$ 4,071,912	$ 56,817,847	$ 38,049,596	$ -	$ -	$ -	**$ 98,939,354**
Total F&A	$ 407,191	$ 5,681,785	$ 3,804,960	$ -	$ -	$ -	**$ 9,893,935**
FINAL COST CALCULATIONS							
Total Projected Cost	$ 10,118,836	$ 93,815,846	$ 68,723,980	$ 10,195,942	$ 4,019,017	$ 1,302,519	$ 188,176,140
Total Cost Margin	$ 2,595,311	$ 25,829,545	$ 18,694,670	$ 2,256,434	$ 888,850	$ 287,797	$ 50,552,607
	25.6%	27.5%	27.2%	22.1%	22.1%	22.1%	
Total Project Cost	$ 12,714,147	$ 119,645,391	$ 87,418,650	$ 12,452,376	$ 4,907,867	$ 1,590,316	**$ 238,728,747**

5.3.1. Budget Basis of Estimate

Ground rules, assumptions and drivers (Table 13) were used in making estimates and developing the budget that is realistic and comprehensive, allowing for effective financial management throughout the mission's lifecycle. The budget is periodically reviewed and adjusted to reflect any changes in assumptions or project scope, ensuring continued alignment with mission goals and constraints.

Table 38. Estimation Criteria Used for the Mission Budget

Ground Rules/ Assumptions/ Drivers	Justification	Benefits	Reference
Currency and Inflation: It is assumed that the rate of inflation will remain constant at 2.6% per year.	Historical data from the U.S. Bureau of Labor Statistics indicates a stable average inflation rate.	Ensures consistent cost projections over the mission timeline, allowing for accurate financial planning.	(“SIB Publications - NASA,” n.d.)
Cost Estimation: Costs for procurement, testing, and integration are based on industry standards and historical data from similar missions.	Derived from past NASA missions and industry benchmarks, adjusted for current market prices.	Provides a reliable basis for estimating costs, reducing the risk of budget overruns.	Historical data from NASA Centres including JPL, JSC, GSFC
Labour Costs: Salaries and wages for the project team are estimated using current aerospace engineering salary data.	Utilises current salary data from the American Institute of Aeronautics and Astronautics (AIAA) and Australia Space Agency Career in Space Booklet (if applicable) salary survey.	Ensures competitive compensation, aiding in attracting and retaining skilled personnel.	US Bureau of Labor Statistics, Australia Space Agency (“Wage Price Index, Australia, March 2024” 2024)
Component Costs: Prices for COTS components are based on quotes from suppliers and historical purchase data.	Reflects current market prices and supplier quotes, ensuring accurate cost estimates for components.	Enhances budget accuracy and ensures procurement cost-effectiveness.	To cite any official quote from potential suppliers
Testing and Integration: Costs associated with testing and integration are derived from standard rates in the aerospace industry.	Considers specialised facilities and expertise required, based on data from NASA JPL and industry reports.	Ensures comprehensive coverage of testing and integration costs, preventing budget shortfalls.	Shreck, Sharratt, and Smith (2008)
Contingency: A contingency of 10% is added to the total estimated costs to account for unforeseen expenses and risks.	Follows best practices in project management to mitigate risks and cover unexpected costs.	Increases the robustness of the budget, ensuring funds are available for unplanned expenses.	(“A model to develop and use risk contingency reserve,” n.d.)

5.3.2. Personnel Budget

For the first fiscal year, the team consists of the current members. However, an increase in members in engineering, administration and management is expected in the second year as the construction and complexities of the rover develop. The numbers of staff ultimately drop back down before the launch date.

The personnel costs are simply a function of the set salaries detailed below multiplied by the number of staff in each respective category. The engineering team is expected to make up the most of the personnel costs, exceeding 12 million whilst administration and management make up 13 million. Scientists and technicians cost 3 million each. Travel is based on a 5 day trip and costs are equivalent to those in section 1.9.3.

Table 39. Schedule of Staff Salaries

Staff Category	Salary
Science Personnel	$ 149,530
Engineering Personnel	$ 130,720
Technicians	$ 77,830
Administration Personnel	$ 104,900
Project Management	$ 120,000

5.3.3. Travel Budget

As a baseline, the requirements outlined in the Milo Mission Task are taken into account. For the mission launch, a stay of 5 days is required in Cape Canaveral, Florida. The cost of a compact car and meals are also accounted for. As most of the team members are from Australia or New Zealand, an additional five days is planned to allow for visiting NASA facilities and rover manufacturing plants. Other costs such as insurance, visas and miscellaneous expenses are arranged. A Per Diem is offered to federal employees which include 70 USD for food and 165 USD for accommodation. As per guidelines, only 70% of this is allocated to team members which totals to 165 USD a day.

In descending order of cost, the largest expense is flights from Sydney, Australia to Cape Canaveral Florida. The corresponding airports are Sydney Kingsford Smith and Orlando Airport which are relevant for rental car pickups. As per Google, the average cost of this route over the year is around 1323 USD round trip. It should be noted that an additional cost of 300 USD is necessary for members from New Zealand, flying to sydney.

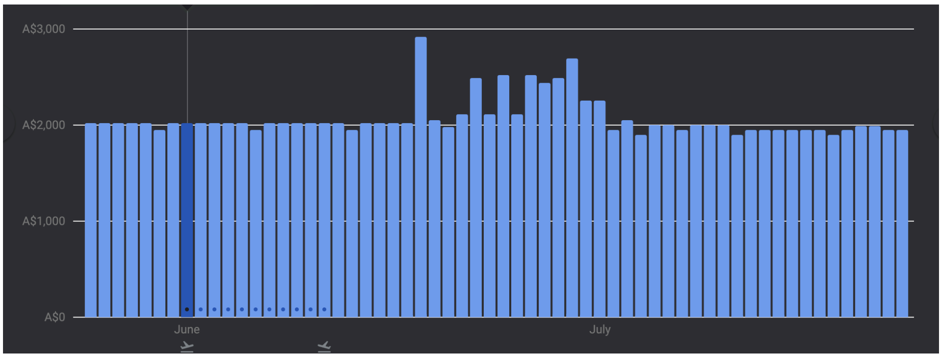
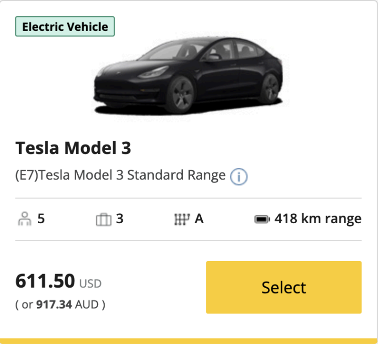


Figure 40. Travel Cost

Next, accommodation will cost an average of 130 USD per night at the launch location which equates to 1300 USD over the ten nights. Miscellaneous costs such as shopping, tipping, group entertainment, communications, currency conversion fees or unexpected costs are expected to cost 1000 USD. Meals, three per day, are cost at the Per Diem allowance which adds up to 500 USD over the 10 days.

Transportation is expected to include public transport in cities, car rentals to launch or testing sites, bus or train tickets for medium length travel, additional flights for longer journeys. Without knowing specifics, the above is simplified into a rental car which is cost as follows.

Hertz car for 611 USD + 200 USD Hertz Add ons, + 150 USD Gas



Electric Vehicle

Tesla Model 3

(E7)Tesla Model 3 Standard Range

5 3 A 418 km range

611.50 USD
(or **917.34** AUD)

Visa application costs 185 USD on the government website and insurance from the Australian company Allianz costs 130 USD.

Your **Comprehensive** plan quote **$194.93**

The total cost of the trip per individual is then, 1878 (Costs not covered by Per Diem) + 1645 (Per Diem) = 3523 USD

5.3.4. Outreach Budget

Table 41. Summary of Outreach Costs

Expense	Cost
Airfares	$15 000
Influencer	$6 000
Interactive Medium	$20 000
Research Sponsorships	$8 000
Research Competitions	$4 000
Total	$53 000

The outreach budget is fairly small in order to allow for more of the budget to be allocated to the project however with targeted advertising towards groups of interest, as outlined by the summary. We can develop research relationships with universities and garner interest at the undergraduate level which would translate into post graduate research once our data become available.

5.3.5. Direct Costs

Direct costs include the associated costs for each subsystem. The total direct cost (Table []) had been estimated to be **USD$183.236M**, which includes a 30-50% buffer to account for any future changes in associated costs since the mission design is only in phase B. It is inclusive of manufacturing testing and assembly of each of the relevant components. The estimate accounts for approximately 81.5% of TALICOs mission budget of $225 million.

All cost estimating relationships calculated using the Mission Concept Cost Estimation Tool (MCCET) are from the NASA Instrument cost model (NICM), providing cost estimates at a dollar rate from 2004. Hence these estimates have been adjusted to the current year (2024). All estimates are not precise and have been rounded up to account for this error, estimates made with the MCCET/NCIM tool, also contain a 50% total estimate buffer, components with known costs have a 30% cost margin added.

We are no longer applying a 50% manufacturing cost margin plus the 30% overall margin as the MCCET/NCIM tool already accounts for some cost margin as it is a parametric of previous missions, which allows us to avoid excessive cost over-estimation.

Table 42. Summary of Direct Costs of Subsystems

Subsystem:	Estimated Cost (M):
Mechanical	33.9
Power	60.217
Thermal Control	20.49
Communication and Data Handling	12.6
Guidance, navigation, and control	24.3
Science Instrumentation	31.729
30-50% margin (included in estimated costs)	55.275
Total Direct costs	183.236

Mechanical System

The mechanical subsystem cost includes the overall structural framework, components within the suspension subsystem that allow mobility and stability, the subsystem that allows for sample collection, mitigating the elements of the lunar surface such as lunar dust (seals) and finally any integration hardware. The subsystem and its associated costs have been calculated using the MCCET tool, specifically the mechanical/structures subsystem CER, which is based on the weight and power draw of components within the subsystem. As the rover is only in the initial stages of design to account for potential variations in cost a buffer margin of 50 % has been included, we have only accounted for a 50% overall cost margin and not also a separate manufacturing cost margin as the MCCET and the CER equations already account for some margin of error as they are based on previous missions. This subsystem will also utilise Titanium R54620 which is accounted for within the buffer. The weight of the mechanical system had been reduced from 60kg to 47kg and has now been further reduced to 35kg to reduce total estimated costs.

Table 43. Direct Cost Calculation of Mechanical Subsystem

Subsystem	Estimated Weight	Estimated Power draw	MCCET CER	Final Mfg Cost (M)	Final testing facility cost (M)	50% cost margin	Total subsystem estimate (M)
Mechanical	35kg	60W	7909.529	17.4	5.2	11.3	33.9

Power System

The Power subsystem set to be implemented into the rover covers the capturing energy through solar panels acting as the power generation responsibility. The battery system acts as the storage for the energy captured by the solar panels, being lithium-ion or lithium-polymer, the battery will have a high energy density. This makes it one of the heaviest components aboard the rover, being approximately 15kg. TALICO's initial weight estimate of the power system being 60 kg was previously reduced to 47kg and again has been reduced further 40kg total (15kg allocated to the solar panels and 25kg for other components like the battery) due to cost estimates being too high.

The solar panel costs however were not estimated based on the MCCET and saw an estimated manufacturing cost of USD\$0.05 million for photovoltaic cells based on a total panel area of 3m^2. This is based on NASA documentation of cost estimates ("Cost-Saving Method Yields Solar Cells for Exploration, Gadgets | NASA Spinoff," n.d.), additionally we have added an additional buffer 30% margin to this found cost to bring the total component estimate up to USD\$0.067M.

Table 44. Direct Cost Calculation of Power Subsystem

Component	Cost (M)	Integration and testing (M)	30% margin	Total component estimate (M)
solar panel	0.05	0.001	0.0153	0.067

Subsystem	Estimated Weight	Estimated Power draw	MCCET CER	Final Mfg Cost (M)	Final testing facility cost (M)	50% margin	Total subsystem estimate (M)
Power	25kg	Generate	13914.301	30.8	9.3	20.05	60.15
Solar panel (component)(15kg)							0.067
							60.217

The total estimated cost for the power subsystem includes a 30% margin 30% cost margin on the solar panels plus a 50% cost Margie on the rest of the power subsystem bringing the total to $60.217 million.

Thermal Control System

The Thermal Control system regulates the temperature of critical components to ensure optimal performance and longevity in the extreme lunar environment. Components include; Variable Conductance Heat Pipe (VCHP) as the chosen thermal link, insulation (aerogel), and heat generation (thermoelectric) are integral to this subsystem.

The LWRHU dissipates excess heat generated by onboard electronics, preventing overheating and thermal damage. The previous mission profiles (Zillmer and Gates 2022) indicate that TALICO will require 9 of these LWRHUs and a unit price of USD1.34M (Werner and Johnson 2016), this cost has been adjusted for inflation to more accurately represent current costs.

The cost of this unit already accounts for the total subsystem estimate determined by NASA Instrument cost model which inherently already applies some margin of error with an additional 50% cost margin included, the subsystem estimate can be brought up to $20.49M (subsystem estimate $8.4M + known cost for 9 LWRHU $12.09M).

Table 45. Direct Cost Calculation of Thermal Subsystem

Unit	Cost (M)	Cost for 9 Units (M)
LWRHU	1.34	12.09

Subsystem	Estimated Weight	Estimated Power draw	MCCET CER	Final Mfg Cost (M)	Final testing facility cost (M)	50% margin	Total subsystem estimate (M)
Thermal	6kg	None if RHU	1949.794	4.3	1.3	2.8	8.4
LWRHU (component, 0.5kg)							12.09
							20.49

Comms & Data Handling (CDH) System

The CDH system manages communication and data processing functions, enabling the transmission of commands and the reception of telemetry data. Key components include RAD750 microcontrollers, RH3480 solid-state drive (SSD), phased array antennas, and relevant software. Microprocessors serve as the computational brain of the rover, executing command sequences and data processing algorithms. SSDs provide high-speed data storage and retrieval capabilities, facilitating rapid access to mission-critical information. Phased array antennas enable high-bandwidth communication with Earth-based ground stations, ensuring reliable data transmission over long distances.

As this subsystem is very heavy on the electronics and software components both have been calculated to determine the total estimated cost of $12.6M. Software algorithms govern data handling processes, including error correction, data compression, and telemetry formatting. This software estimate does not include the GNCs autonomous navigation and hazard avoidance strategies software.

Table 46. Direct Cost Calculation of CDH Subsystem

Subsystem	Estimated Weight	Estimated Power draw	MCCET CER	Final Mfag Cost (M)	Final testing facility cost (M)	50% margin	Total subsystem estimate (M)
CDH	3kg	100W	Electronics: 2531.987	5.5	1.7	3.6	10.8
			Software: 380.735	0.9	0.3	0.6	1.8
Total							12.6

Guidance, Navigation & Control (GNC) System

The GNC system enables precise navigation and control of the rover's movements, ensuring safe traversal across the lunar surface. GNCs main components include LiDAR, IMU, and software algorithms. The estimate of $24.3M was calculated using the NICM for both electronic and software systems as they both are significant elements behind GNC alongside the optical planetary instruments CER for the LiDAR cost. Electronic sensors such as IMUs and LiDAR determine the rover's velocity and orientation, facilitating precise navigation and manoeuvring. So we have used a combination of the electronic subsystem and software subsystem CERs to produce the cost for the necessary software algorithms designed to process sensor data from the LiDAR and IMU to implement autonomous navigation and hazard avoidance strategies, the estimate below, includes a 50% cost margin.

Table 47. Direct Cost Calculation of GNC Subsystem

Subsystem	Estimated Weight	Estimated Power draw	MCCET CER	Final Mfg Cost (M)	Final testing facility cost (M)	50% margin	Total subsystem estimate (M)
GNC	2.8kg	13W	Electronic: 3247.851	7.1	2.1	4.6	13.8
			Software: 480.231	1.1	0.3	0.7	2.1
LiDAR	1kg	13W	1957.401	4.3	1.3	2.8	8.4
Total							24.3

Payload/Science Instrumentation

The Science Instrumentation subsystem comprises instruments used for scientific data collection and analysis, enabling the rover to fulfill its exploration objectives. Components such as the TRIDENT drill and BIRCHES are included in this subsystem. The TRIDENT drill enables the collection of subsurface samples, providing insights into the lunar geology and composition and is estimated to cost 5.02M, this estimate cost found (including manufacturing and testing) was sourced through publicly available federal grant approval documentation ("PRIME-1 TRIDENT Drill Fabrication and Testing" n.d.) at USD5.1 million.

BIRCHES instruments may include various scientific payloads such as cameras, spectrometers, and radiation detectors, to conduct scientific investigations of the lunar surface and has an estimated cost of 7.8M using the NCIM tool. These components are included within the total subsystem estimation of 31.729M using the NCIM tool, As the NCIM/MCCET tool already accounts for some margin we have accounted for an additional 30%.

The additional table accounts for other instruments including the LiDAR, the neutron spectrometer system (NSS) and potentially any other components again using a CER. Including a 50% cost margin, its total is $14.7M in addition to the BIRCHES and TRIDENT DRILL component estimate brings the subsystems total up to $31.729M

Table 48. Direct Cost Calculation of Payload Subsystem

Component	Cost (M)	Integration and testing (M)	30% margin	Total component estimate (M)
BIRCHES	7.8	0.2	2.4	10.4
TRIDENT DRILL	5.02	0.1	1.509	6.629
Total				17.029

Subsystem	Estimated Weight	Estimated Power draw	MCCET CER	Manufacturing Cost (M)	Final testing facility cost (M)	50% margin	Total subsystem estimate (M)
Payload/Inst	3kg	160W	3417.975 (not	7.5	2.3	4.9	14.7

ruments			inclusive of known components)				
Component costs (9kg)							17.029
							31.729

5.4. Scope Change Management

Section is blank.

5.4.1. Change Control Management

Introduction to Change Control Management:

Change control management is a systematic approach to managing alterations to a project's scope, schedule, or resources, ensuring that all changes are carefully considered, approved, documented, and communicated. In the context of the TALICO lunar rover, change control management is vital due to the complex and high-stakes nature of space missions. Every modification, whether it involves design adjustments, component replacements, or procedural updates, can have significant implications for the project's success. A structured process for handling changes is crucial as it ensures that all potential impacts on cost, timeline, and technical performance are thoroughly evaluated before implementation. This approach helps maintain the integrity of the project by preventing unapproved or poorly managed changes that could lead to delays, increased costs, or technical failures. Moreover, clear documentation and communication of changes keep all team members and stakeholders informed, fostering transparency and a coordinated effort towards the common goal of a successful lunar mission.

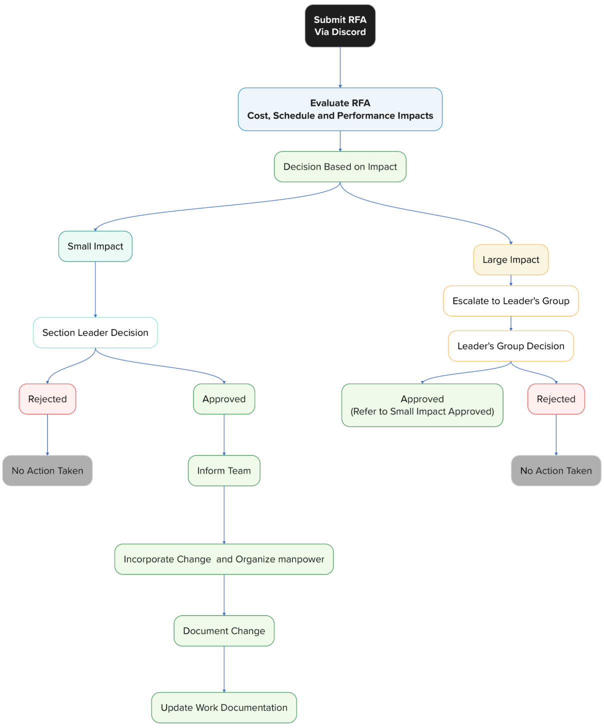
Change Control Process:

In the TALICO team, changes are requested through Requests for Action (RFAs), which can be submitted by anyone in the TALICO team via the shared Discord chat. Before submitting an RFA, the applicant evaluates the request in terms of cost, schedule, and performance impacts. For changes that have small to negligible effects on the project, the leader of the applicant’s section has the authority to make a decision. However, if the change has larger implications, such as design modifications, large cost adjustments, or impacts the agreed schedule, the request is escalated to the leaders' group, which includes the project manager, engineering leader, science leader, and programmatic leader. This group conducts a thorough evaluation using the applicant’s analysis before approving or rejecting the change. Once a change is approved, the applicant is responsible for incorporating the change into the larger scope of the project, organizing the necessary manpower, and informing the rest of the TALICO team, ensuring seamless integration and communication throughout the project.

Tracking and Communication:

In TALICO, changes are documented within the TALICO team's main information-sharing platform, Discord. This ensures that all team members have real-time access to updates. Additionally, work documentation is altered as required, with the most recent version always maintained as the working document is saved in the cloud storage system, Google Drive. All users have access to these documents, ensuring everyone is working with the latest information.

Communication of changes is handled through Discord, and significant changes are discussed in our weekly general meeting. The leader of the section including the change typically covers the details, while the project manager conveys information for broader impacts. Initially, Trello was trialed during the completion of the SRR, but it was discontinued in the MDR phase as many team members were not actively updating their progress. Currently, Google Drive is used for all project work, allowing all members access to the most up-to-date documentation. Documents are organized into "to do", "in progress", and "completed" folders, ensuring a clear and efficient workflow for managing TALICO’s project's documentation and progress.



5.4.2. Scope Change Management

Introduction

Scope change management is the process of understanding where the project is and managing any deviations from initial team objectives, timelines, budget constraints, technical issues, etc. This section will address TALICO's approach and procedures in the event that these situations arise. In order for effective scope change management, the importance of communication within the team must be emphasised, as all changes are managed by a change control board (CCB). In some instances scope changes can be proactively managed with ongoing project monitoring and effective team communication. This section will discuss processes in the event of downscoping, overrun costs, schedule crash, increasing scopes, and rebaselining.

Scope Change Identification and Documentation

In order to address a scope change it must first be identified. This can come from any project team member who believes there is sufficient need to review the current scope. This should be done formally with a request form and given to the CCB to review, which can be shared on discord. The request form should also be accompanied by an impact analysis, so that if the scope change is accepted it will ensure that all aspects have been considered. The CCB can take this request and compare it against the baseline to get an idea of what needs to be done and either approve or disapprove of the scope change request.

Downscoping

There are several possible scenarios that may arise that would result in the downscoping of the project. Firstly, TALICO has proactively put aside a budget margin of 15% ($32.25 million USD) to account for current cost estimations that may not be accurate, which will reduce strain on the budget in this event. Secondly, TALICO is roughly $10 million USD under budget, giving a total of ~$42.25 million USD to cover any unexpected costs. If costs manage to rise above this margin then extra steps must be taken to ensure the completion of the mission. In the event of a schedule crash, there should be enough funds remaining from the $42.25 million USD to support the required personnel to assist the mission. This will allow TALICO to continue to maintain the project's timeline without compromising the quality of the mission. If costs spill over the budget margin then there are several options to swap high cost components and instruments on the rover to cheaper alternatives. This can be done without changing the wider scope of the mission. Several components or instruments can also be changed from in-house manufacturing to purchasing commercial-off-the-shelf products (COTS). Communication with all stakeholders and the customer is essential to ensure that any change is acceptable and approved by all parties.

Table 49. A table of which instruments can be swapped for cheaper components, what kind of instrument it can be swapped to, and its impact on the mission and scope.

Subsystem	Instrument	Impact	Change to	Change in Scope
CDH	Phased Array Antenna	New antenna design needed	Lower cost patched array antenna.	No change in scope
CDH	RAD750	Lower performance	Cheaper CPU	No change in scope
Power	Solar Panels	Lower performance	Cheaper COTS product	No change in scope
Power	Batteries	Lower performance	Cheaper COTS product	No change in scope
Thermal	RHU	Less efficient heat generation. Higher power consumption	Remove completely	No change in sope
Thermal	Aerogel	Less efficient insulation	Reduction of aerogel used	No change in scope
GNU	LiDAR	Lower grade sensor	Stereo cams + light	No change in scope

Increasing Scope

As mentioned previously, TALICO has around $42.25 million USD of potentially unused funds. Firstly communication with stakeholders would be essential to ensure the extra funds are managed responsibly as scope creep would be undesirable, one way to do that would be to focus entirely on improvements to instruments, adding redundancies, and slight adjustments rather than large upgrades that may bring unwanted additions and changes to the project, adding time and potentially affecting deliverable deadlines.

Table 50. This table shows the possibilities for increasing scope on the mission.

Subsystem	Instrument	Improvement	Impact
CDH	RAD750	Install a second microcontroller	Adding redundancy
GNU	LiDAR	Install extra stereo cams + lights	Adding redundancy + software efficiency for non-PSR environments
Power	Solar Panels	Higher grade components	Better power production
Power	Batteries	Higher grade components	Better and more efficient battery
Rover	General improvements	Higher grade components	Stability

Rebaselining

This section has outlined several scenarios in which the scope may need to be adjusted, whether through downscoping or increasing scope due to various factors. Effective communication among project members, team leaders, stakeholders, and customers is crucial to ensure everyone is up to date and changes are implemented proactively and efficiently. TALICO has outlined specific options for both downscoping and increasing scope, emphasising the importance of following this approach to avoid scope creep. Once decisions are finalised, rebaselining should be performed and communicated to all involved parties to maintain project efficiency.

5.5. Outreach Summary

The team will be reaching out to higher levels of education. In an attempt to specifically promote the lunar exploration of the south pole. The research garnered by this is relevant to current undergraduates and future Phd students at universities. As a result a series of talks across the major universities in Australia will be held by the science team to discuss the research opportunities over the next decade as a result of the data collected by the mission.

The team will target Geologists and Biologists due to the mission concerning water and rock samples. This builds into the potential of a lunar base. As for lower levels of education, in order to build an interest from a young age a focus on a broader picture would be ideal. Promoting this as the start to a lunar base is an exciting prospect for the younger generation.

The method of outreach should be diverse. Utilising social media influencers is a must as it penetrates all markets. Space and Science enthusiasts such as Mark Rober should be brought onboard as ambassadors for this mission. Tik Tok and Youtube will be the main avenues for reaching middle school to undergraduates. Beyond that the aim is to have a presence at conferences which are home to world class engineers and scientists to stimulate new questions to be answered and new solutions from the data.

Interactive mediums such as small mobile games simulating a rover collecting data in PSR’s and developing a base at which science is performed could be an innovative way to promote the mission. The game can base its function on something like Blues Clues but for a more mature audience. By repeatable digestible tasks we allow for the science prevalent to the mission to become realised as an avenue for future research.

6. Conclusion

The TALICO mission will seek to comprehensively explore and understand the distribution, composition, and origin of water ice deposits within the Lunar South Pole Region through the methods as set out in the above documentation. All subsystems necessary to the mission requirements are well developed and provide reasonable grounds to ensure the success of the mission within a PSR environment. Scientific instrumentation aboard the lunar rover includes surface mapping, photogrammetry, geolocation, LiDAR, temperature, and mass spectrometry.

The TALICO team will now work towards presenting this preliminary design review to an independent board to gain the resources and approvals required to progress to the next phase (Phase C).

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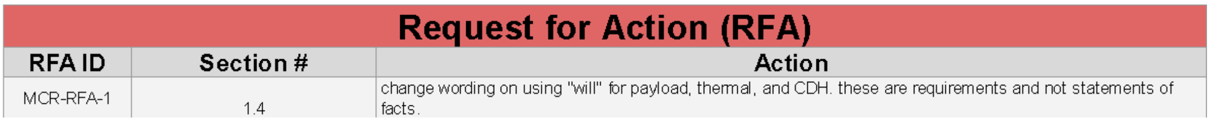
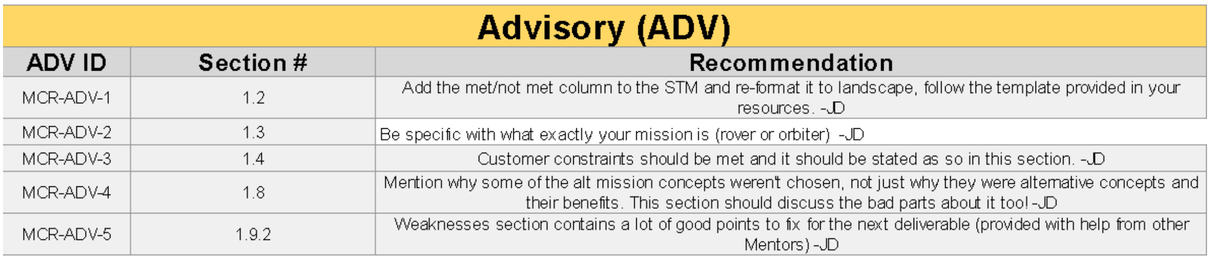
Appendix A

Changes since MCR

*Note - section # refers to the MCR section number



Request for Action (RFA)		
RFA ID	**Section #**	**Action**
MCR-RFA-1	1.4	change wording on using "will" for payload, thermal, and CDH. these are requirements and not statements of facts.

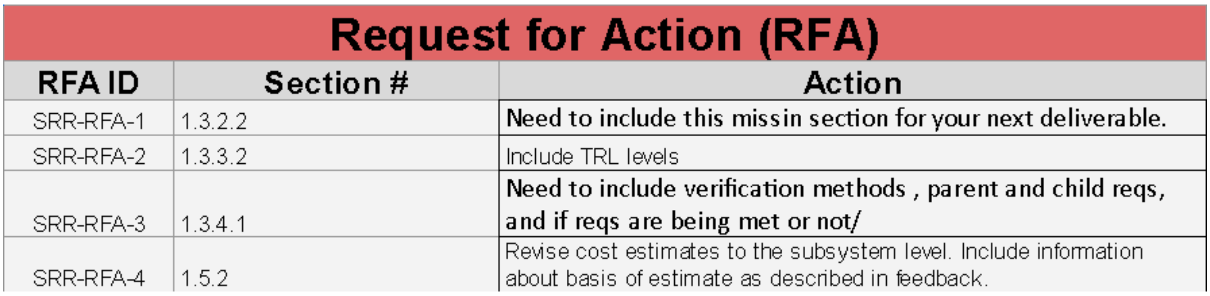


Advisory (ADV)		
ADV ID	**Section #**	**Recommendation**
MCR-ADV-1	1.2	Add the met/not met column to the STM and re-format it to landscape, follow the template provided in your resources. -JD
MCR-ADV-2	1.3	Be specific with what exactly your mission is (rover or orbiter) -JD
MCR-ADV-3	1.4	Customer constraints should be met and it should be stated as so in this section. -JD
MCR-ADV-4	1.8	Mention why some of the alt mission concepts weren't chosen, not just why they were alternative concepts and their benefits. This section should discuss the bad parts about it too! -JD
MCR-ADV-5	1.9.2	Weaknesses section contains a lot of good points to fix for the next deliverable (provided with help from other Mentors) -JD

Appendix B

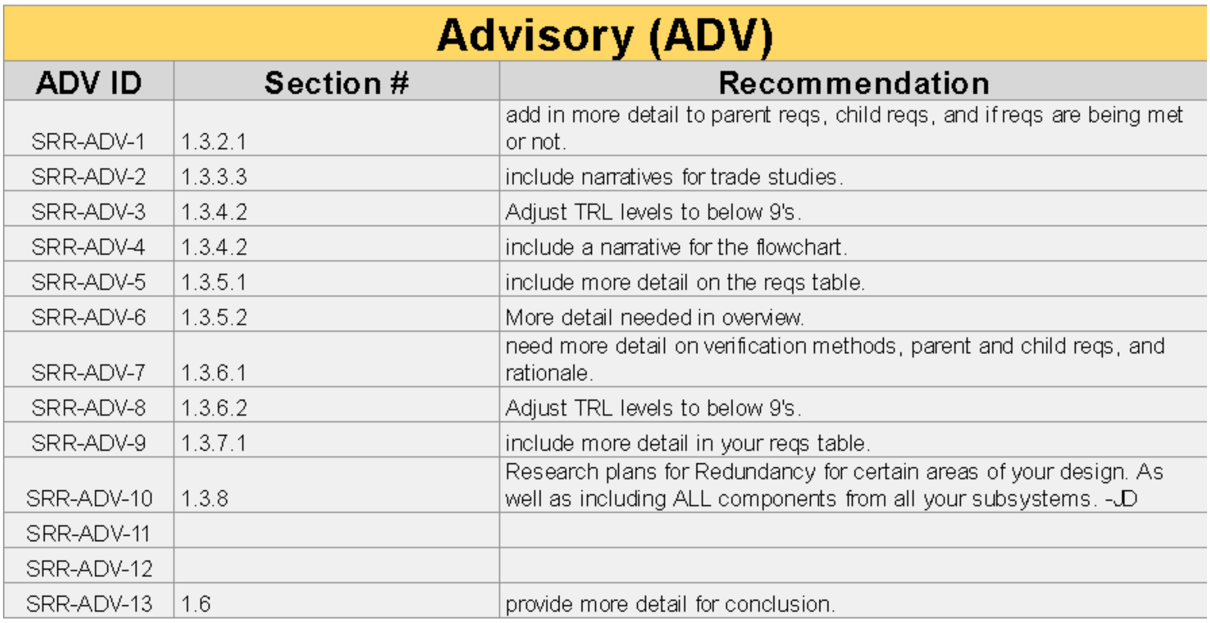
Changes since SRR

*Note - section # refers to the SRR section number



Request for Action (RFA)

RFA ID	Section #	Action
SRR-RFA-1	1.3.2.2	Need to include this missin section for your next deliverable.
SRR-RFA-2	1.3.3.2	Include TRL levels
SRR-RFA-3	1.3.4.1	Need to include verification methods , parent and child reqs, and if reqs are being met or not/
SRR-RFA-4	1.5.2	Revise cost estimates to the subsystem level. Include information about basis of estimate as described in feedback.



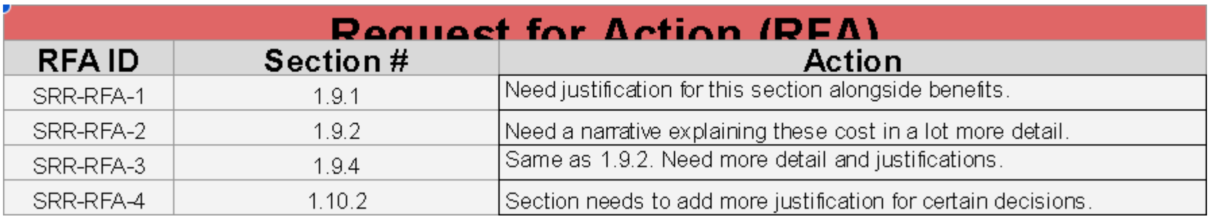
Advisory (ADV)

ADV ID	Section #	Recommendation
SRR-ADV-1	1.3.2.1	add in more detail to parent reqs, child reqs, and if reqs are being met or not.
SRR-ADV-2	1.3.3.3	include narratives for trade studies.
SRR-ADV-3	1.3.4.2	Adjust TRL levels to below 9's.
SRR-ADV-4	1.3.4.2	include a narrative for the flowchart.
SRR-ADV-5	1.3.5.1	include more detail on the reqs table.
SRR-ADV-6	1.3.5.2	More detail needed in overview.
SRR-ADV-7	1.3.6.1	need more detail on verification methods, parent and child reqs, and rationale.
SRR-ADV-8	1.3.6.2	Adjust TRL levels to below 9's.
SRR-ADV-9	1.3.7.1	include more detail in your reqs table.
SRR-ADV-10	1.3.8	Research plans for Redundancy for certain areas of your design. As well as including ALL components from all your subsystems. -JD
SRR-ADV-11		
SRR-ADV-12		
SRR-ADV-13	1.6	provide more detail for conclusion.

Appendix C

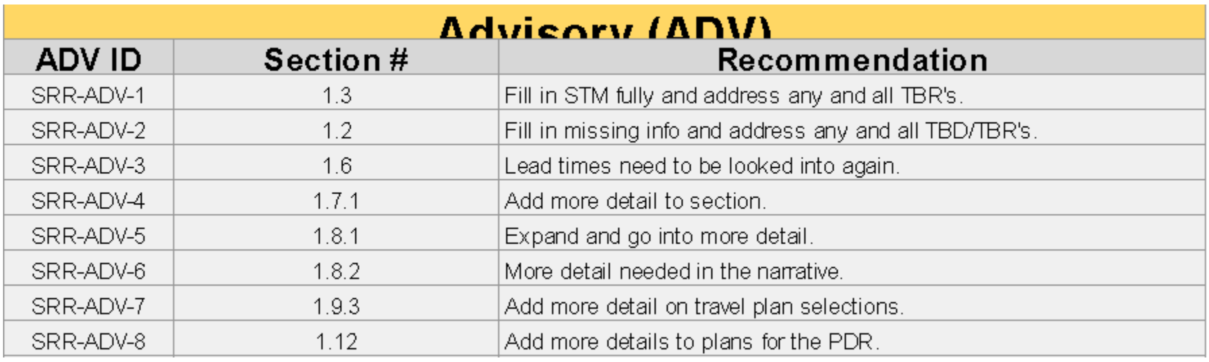
Changes since MDR

*Note - section # refers to the MDR section number



Request for Action (RFA)

RFA ID	Section #	Action
SRR-RFA-1	1.9.1	Need justification for this section alongside benefits.
SRR-RFA-2	1.9.2	Need a narrative explaining these cost in a lot more detail.
SRR-RFA-3	1.9.4	Same as 1.9.2. Need more detail and justifications.
SRR-RFA-4	1.10.2	Section needs to add more justification for certain decisions.



Advisory (ADV)

ADV ID	Section #	Recommendation
SRR-ADV-1	1.3	Fill in STM fully and address any and all TBR's.
SRR-ADV-2	1.2	Fill in missing info and address any and all TBD/TBR's.
SRR-ADV-3	1.6	Lead times need to be looked into again.
SRR-ADV-4	1.7.1	Add more detail to section.
SRR-ADV-5	1.8.1	Expand and go into more detail.
SRR-ADV-6	1.8.2	More detail needed in the narrative.
SRR-ADV-7	1.9.3	Add more detail on travel plan selections.
SRR-ADV-8	1.12	Add more details to plans for the PDR.