Soil Composition and LiDAR Detection (SoCoLD) in Martian Lava Tubes

L'Space Mission Concept Academy, Arizona State University

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Abbreviation and Acronym

Abbreviation / Acronym	Definition
3D	Viewing in Three Dimensions
BU	Body Unit
CDR	Critical Design Review
CERR	Critical Events Readiness Review
ConOps	Concept of Operations
DR	Decommissioning Review
FWHM	Full Width Half Maximum
LIBS	Laser Induced Breakdown Spectroscopy
LIDAR	Light Detection and Ranging
MCA	Mission Concept Academy
MCRR	Mission Concept and Requirements Review
MRR	Mission Readiness Review
MU	Mast Unit
ORR	Operational Readiness Review
PDR	Preliminary Design Review
PLAR	Post-Launch Assessment Review
PPM	Parts Per Million
RMI	Remote-Micro Imager
SoCoLD	Soil Composition and LIDAR Detection
STM	Science Traceability Matrix
UHF	Ultra High Frequency
V&V	Verification and Validation
VISIR	Visible/Near-Infrared Spectroscopy

1. Introduction and Summary

1.1. Team Introduction

Monica Aguilar

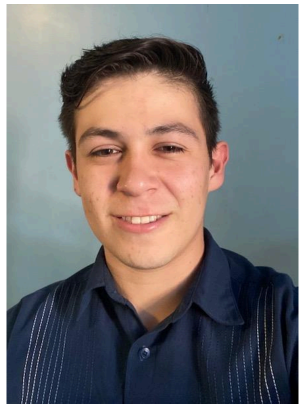
Project Manager, Planetary Geologist / Geochemist, Safety Officer, Outreach Officer, and Business Officer

Monica is a rising senior at California State University, Monterey Bay (CSUMB), in Monterey, CA. Beginning college at Santa Barbara City College (SBCC) as a Film Production major, Monica switched to Computer Science after 3 semesters. Monica has been active in both in-person and virtual leadership roles, including: being President of both the Computer Science Club and Competitive Programming Club at SBCC; organizing projects and recruiting students for local schools' Science Nights; participating virtual in the NASA Community College Aerospace Scholars (NCAS) program; and participating in an apprenticeship program focused on informal science education.

Joseph Christian

Deputy Project Manager, Mechanical Engineer, Electrical Engineer

Joseph is a senior at Embry Riddle Aeronautical University Worldwide studying for a Bachelor's degree in Engineering. After obtaining a Airframe and Powerplant license after high school Joseph began working in the Aviation field as a way to get closer and better understand aircrafts with their related systems. With an increased desire to enter the field of Aerospace Engineering Joseph began pursuing internships and further college education.



Elias Gonzalez

Chief Scientist and Astrobiologist

Elias will be a senior this upcoming fall at California State University, Long Beach (CSULB), in Long Beach, CA. Elias is studying Mechanical Engineering and hopes to enter the space exploration industry after college. Elias has gained various team working skills throughout college courses and group projects.

Pedro S. Rendon

Lead Systems Engineer, Mechanical Engineer, Electrical / Computer Hardware Engineer

Pedro attends California State University, Long Beach (CSULB), in Long Beach, CA. Pedro will be starting his fourth year at CSULB in the fall of 2022. Pedro began at CSULB as an electrical engineering major, but switched to aerospace engineering after three semesters. Pedro has been on the executive board in CSULB's IEEE and AIAA chapters, and actively participates in the university's liquid propellant rocket club (Beach Launch Team) as a member of the propulsion and aerodynamics/structures sub-system.

Justin Pascua

Astrophysicist

Justin is a rising sophomore at Los Angeles City College (LACC) in Los Angeles, CA. Justin is an Applied Mathematics major with an interest in both science and engineering. Justin is also participating in an undergraduate research experience held in partnership with LACC and the California Space Grant Consortium (CaSGC) that focuses on the engineering design process and the use of ESP32 microcontrollers. Justin is currently working on a project involving LiDAR.

Parham Khodadi

Thermal Engineer

This coming fall of 2022, Parham will be a third year with sophomore standing at Santa Monica College, Santa Monica, CA. He is an Aerospace Engineering major planning to transfer to a 4-year institution in fall of 2023. He is also the publicist of the Astronomy Club, as well as an active participant of the engineering club at SMC. Parham has previously finished L'SPACE NPWEE and Virtual NASA Community College Aerospace Scholars programs. He was at NASA AFRC for NCAS Mission 3 in mid-July 2022.

1.2. Mission Overview

1.2.1. Mission Statement

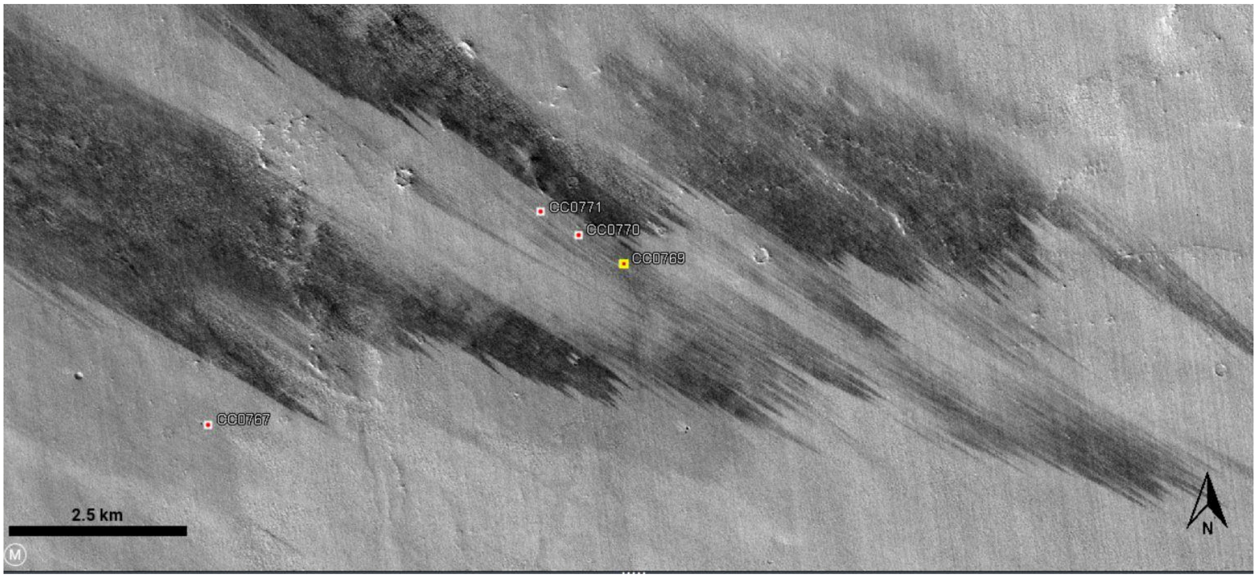


Figure 1: *View of the three sites considered for the mission, per JMARS.*

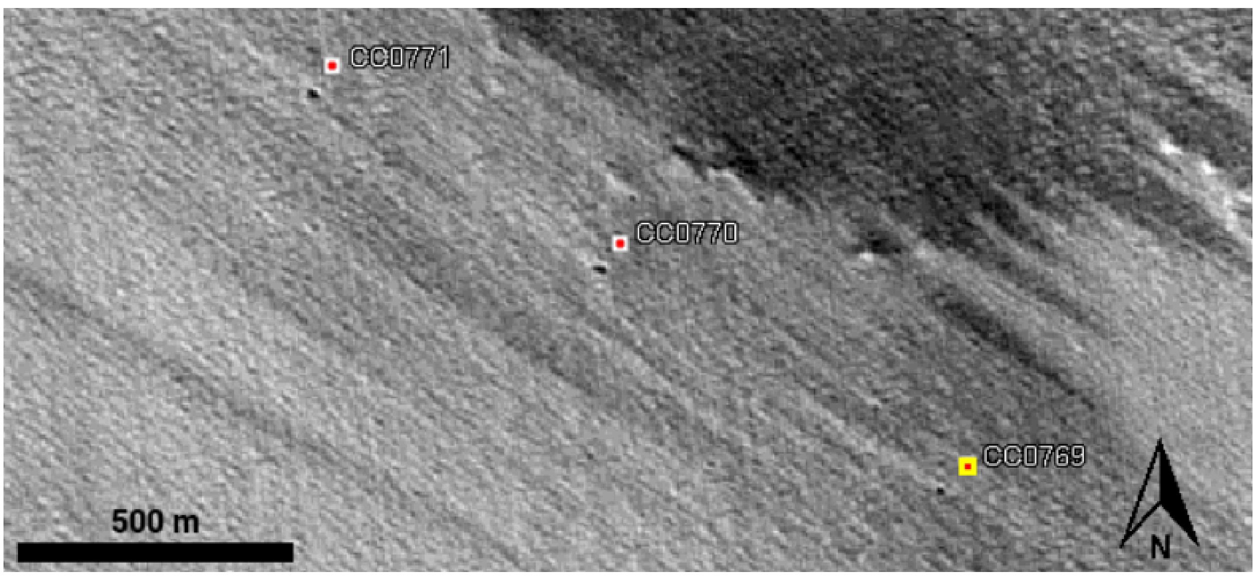


Figure 2: *A closer view of the three sites considered for the mission. The yellow dot is site CC0769. This skylight was chosen as the entrance for this mission.*

This mission will conduct an investigation into the subsurface conditions on Mars by exploring a lava tube, namely site CC0769. There are three science objectives for this mission: to determine the terrain and geography of the lava tubes located at

CC0769; to determine the presence of the mineral olivine within the site; and to determine the mineral composition of the regolith within the Martian lava tube.

Data collection on the tube's geography and terrain will be performed using a 3D LiDAR sensor. As the Rover travels through the tube, the sensor will collect data in order to produce a three-dimensional image of the environment. This will be used 1) to aid the navigation of the Rover and 2) for further geographical analysis to evaluate the possibility of using this site, or similar environments, in future missions to shelter humans or resources from harsh surface conditions. Along the path, the Rover will also conduct soil analysis to determine the mineral composition of the regolith within the tube. tubes provide protection from cosmic radiation and erosive processes on the surface, so determining the mineral composition of the regolith within may provide insight into the early formation of Mars. This soil analysis will aid in the mission's search for olivine, which is a mineral known to support certain chemolithotrophs on Earth. Finding olivine within the tube could provide insight into the possibility of microscopic life on Mars.

1.2.2. Complete Mission Requirements

Table 1: *System Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem
0.1	The system shall not exceed 50kg	The system must remain within the mass constraint provided by the mission task	NASA L'SPACE Academy	POW-0.1 CDH-0.1 NAV-0.1 COMM-0.1 MEC-0.1 THM-0.1 PAY-0.1	Inspection	All
0.2	System shall have a volume constraint of (1.5 X 1.5 X 1.5)m	System must accommodate into launch vehicle size restriction	NASA L'SPACE Academy		Inspection	All
0.3	The total cost of the mission shall not exceed $300M	Budget constraint	NASA L'SPACE Academy	POW-0.3 CDH-0.3 NAV-0.3 COMM-0.3 MEC-0.3 THM-0.3 PAY-0.2	Inspection	All
0.4	The system shall investigate the Martian cave	The system must have adequate time to gather data within the cave	NASA L'SPACE Academy	SYS-0.1 SYS-0.2 SYS-0.3	Demonstration	All
0.5	The system shall communicate with earth via the primary lander	The data collected from the system must be retrievable and readable	NASA L'SPACE Academy	COMM-0.4	Demonstration	COMM

SYS-0.1	System shall maintain operation within allowable operating temperatures within Martian cave, within [-40C, +40C]	The system must be regulated at operating temperatures to ensure mission operation	0.4	THM-0.4	Demonstration	THM
SYS-0.2	The system shall have the mobility to navigate the Martian cave	Necessary for operation of mission	0.4	CDH-0.4 NAV-0.4, 0.5 MEC-0.5	Test	MEC CDH NAV
SYS-0.3	The system shall provide enough power for operations for ≥3 days	All systems need power to operate and perform tasks	0.4	POW-0.2	Demonstration	POW
SYS-0.4	The system shall provide a method of entering into cave formation from deployment site	The system upon deployment must be able to enter cave formation through Martian cave ceiling	0.4	MEC-0.4	Demonstration	MEC
SYS-0.5	The system shall provide mapping of the cave formation	STM Science Objective	0.4	PAY-0.3	Test	PAY CDH NAV COMM
SYS-0.6	The system shall search for olivine within the Martian cave	STM Science Objective	0.4	PAY-0.4	Demonstration	PAY
SYS-0.7	The system shall analyze soil composition within the Martian cave	STM Science Objective	0.4	PAY-0.5	Test	PAY
SYS-0.8	The system shall provide images of soil/rock samples within the Martian cave	STM Science Objective	0.4	PAY-0.6	Demonstration	PAY

Table 2: *Power Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
POW-0.1	The total mass of the power system shall not exceed 7.0 kg	Allocation of mass constraint	0.1		Inspection
POW-0.2	The power system shall provide energy to each subsystem	Each subsystem requires energy to operate	SYS-0.3	CDH-0.2, NAV-0.2, COMM-0.2, MEC-0.2, THM-0.2, PAY-0.6, POW-0.2.1	Test
POW-0.2.1	The power system shall provide enough energy to sustain the system for a minimum of 3 days	Describes performance requirement of subsystem	POW-0.2	POW-0.2.1.1 POW-0.2.1.2	Test
POW-0.2.1.1	While in active mode, the power system shall provide sufficient energy to each subsystem	Describes performance requirement while vehicle is in active mode	POW-0.2.1		Test
POW-0.2.1.2	While in rest mode, the power system shall provide sufficient energy to maintain the vehicle's operating temperatures	Describes performance requirement while vehicle is in rest mode	POW-0.2.1		Test
POW-0.3	The cost of the power system shall not exceed 10% of the total budget	Allocation of budget	0.3		Inspection

Table 3: *Command & Data Handling Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
CDH-0.1	The Command & Data Handling system shall not exceed 4.0 kg	Allocation of mass constraint	0.1		Inspection
CDH-0.2	The power consumption of the Command & Data Handling system shall not exceed 80 Watts	5% of the power consumption will be allocated to the command & data handling subsystem	POW-0.2		Test
CDH-0.3	The cost of the Command & Data Handling system shall not exceed 8% of the total budget	Allocation of budget	0.3		Inspection
CDH-0.4	The Command & Data Handling system shall allow the vehicle to operate autonomously	Necessary for operating the vehicle in an environment where communication delays and dropouts are frequent	SYS-0.2	CDH-0.4.1 CDH-0.4.2 CDH-0.5	Demonstration
CDH-0.4.1	The Command & Data Handling system shall have the ability to receive and act on teleoperated commands	Necessary for ensuring ground team can make act on system when needed	CDH-0.4		Demonstration
CDH-0.4.2	The Command & Data Handling system shall communicate the navigation plans to the mechanical system	Describes how CDH system interacts with MEC system	CDH-0.4 NAV-0.5		Test
CDH-0.5	The Command & Data Handling system shall be able to send commands to each major subsystem	Necessary for operating each subsystem	CDH-0.4	CDH-0.5.1 CDH-0.5.2	Test
CDH-0.5.1	The Command & Data Handling system shall send commands to the PAY system as needed by operational procedures	CDH system should control the activity/inactivity of the instrumentation to preserve energy and to ensure quality of data samples	CDH-0.5		Demonstration

CDH-0.5.2	The Command & Data Handling system shall send the cave mapping from PAY to NAV system	NAV system requires information on cave geography to determine a planned route	CDH-0.5		Demonstration
CDH-0.6	The Command & Data Handling system shall collect data and other telemetry from each subsystem	Necessary for tracking health of the entire system	CDH-0.4	CDH-0.6.1 CDH-0.6.2 CDH-0.6.3	Test
CDH-0.6.1	The Command & Data Handling system shall gather telemetry from the instrumentation	Necessary for collecting mission data	CDH-0.6		Test
CDH-0.6.2	The Command & Data Handling system shall collect data on the thermal state of each subsystem	Provides information that informs the actions of the THM system	CDH-0.6		Test
CDH-0.6.3	The Command & Data Handling system shall receive navigation plans from the NAV system	Necessary for operating the vehicle autonomously	CDH-0.6		Test
CDH-0.7	The Command & Data Handling system shall have the ability to send telemetry to other subsystems	Necessary for communicating to subsystems that require data, such as COMMS and THM	CDH-0.4	CDH-0.7.1 CDH-0.7.2	Test
CDH-0.7.1	The Command & Data Handling system shall deliver instrument data to the COMM system	Necessary for transmitting mission data to Earth	CDH-0.7	COMM-0.5	Test
CDH-0.7.2	The Command & Data Handling system shall communicate the thermal state of each subsystem to the Thermal system	Provides data that informs the actions of the THM system	CDH-0.7	THM-0.4.4	Test

Table 4: *Navigation Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
NAV-0.1	The Navigation system shall not exceed 1 kg	Allocation of mass constraint	0.1		Inspection
NAV-0.2	The power consumption of the Navigation system shall not exceed 30 Watts	10% of the power consumption will be allocated to the navigation subsystem.	POW-0.2		Test
NAV-0.3	The cost of the Navigation system shall not exceed < 1% of the total budget	Allocation of budget	0.3		Inspection
NAV-0.4	The Navigation system shall determine a route into the cave	Describes overall purpose of NAV system: to determine safe path for vehicle	SYS-0.2	NAV-0.4.1 NAV-0.4.2	Demonstration
NAV-0.4.1	The Navigation system shall generate a route that is suitable for the traversal methods provided by the MEC system	Planned route should not endanger the system	NAV-0.4 MEC-0.5		Analysis
NAV-0.4.2	The Navigation system shall generate a route using data on the cave terrain given by instrumentation	Planned route will be based on relevant data collected by instrumentation	NAV-0.4 CDH-0.5.2		Demonstration
NAV-0.5	The Navigation system shall send the planned route to the CDH system	Necessary for system to act on planned route	SYS-0.2		Test

Table 5: *Communication Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
COMM-0.1	The Communication system shall not exceed 4 kg	Allocation of mass constraint	0.1		Inspection
COMM-0.2	The power consumption of the Communication system shall not exceed 75 Watts	26% of the power consumption will be allocated to the communication subsystem	POW-0.2		Test
COMM-0.3	The cost of the Communication systems shall not exceed 8% of the total budget	Allocation of budget	0.3		Inspection
COMM-0.4	The Communication system shall maintain contact with the primary lander	Necessary for receiving mission data	0.5	COMM-0.4.1 COMM-0.4.2	Test
COMM-0.4.1	The Communication system shall provide a method of communicating with the primary lander while inside the cave	Comms system must account for likelihood of communication dropouts due to cave environment	COMM-0.4		Test
COMM-0.4.2	The Communication system shall deliver instrument data to the primary lander	Necessary for receiving mission data on Earth	COMM-0.4		Test
COMM-0.5	The Communication system shall receive instrument data from the CDH system	Necessary for collecting and transmitting mission data	0.5 CDH-0.7.1		Test

Table 6: Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
MEC-0.1	The mechanical system shall not exceed a mass of 15 kg	Allocation of mass constraint	0.1		Inspection
MEC-0.2	The power consumption of the mechanical system shall not exceed 100 Watts	40% of the power consumption will be allocated to the mechanical subsystem	POW-0.2		Test
MEC-0.3	The cost of the mechanical system shall not exceed 5% of the total budget	Allocation of budget	0.3		Inspection
MEC-0.4	The mechanical system shall provide a way of entering the cave	Vehicle must enter cave from deployment point	SYS-0.4		Demonstration
MEC-0.5	The mechanical system shall provide a way of traversing the cave's terrain	Necessary for investigating the cave	SYS-0.2	MEC-0.5.1 MEC-0.5.2 NAV-0.4.1	Demonstration
MEC-0.5.1	The mechanical system shall have adequate traction to traverse sandy, rocky, and loose terrain	The method of traversal must account for an array of conditions as the exact conditions of the cave are unknown	MEC-0.5		Demonstration
MEC-0.5.2	The mechanical system shall provide a method to maneuver over and around potential obstructions	It is necessary for the vehicle to be able to navigate around potential obstacles to its path	MEC-0.5		Demonstration

Table 7: *Thermal Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
THM-0.1	The thermal system shall not exceed a mass of 1.5 kg	Allocation of mass constraint	0.1		Inspection
THM-0.2	The power consumption of the thermal system shall not exceed 50 Watts	5% of the power consumption will be allocated to the thermal subsystem	POW-0.2		Test
THM-0.3	The cost of the thermal system shall not exceed 5% of the total budget	Allocation of budget	0.3		Inspection
THM-0.4	The thermal system shall maintain vehicle's operating temperatures throughout the duration of the mission	Thermal system must maintain operating temperatures to protect the functionality of other subsystems	SYS-0.1	THM-0.4.1 THM-0.4.2 THM-0.4.3 THM-0.4.4	Demonstration
THM-0.4.1	The thermal system shall maintain a temperature within the range [-40C, 40C]	Specifying the system's operating temperatures	THM-0.4		Demonstration
THM-0.4.2	The internal temperature of any given subsystem shall not deviate from its operating temperature by more than ± 5C	Outlines margin of error of thermal system	THM-0.4		Demonstration
THM-0.4.3	The thermal system shall generate heat to sustain operating temperatures during operations	Surface temperatures near the chosen site are around 20C. The subterranean environment will be cooler than this, so it is likely that the system will need to generate heat in order to balance heat flux	THM-0.4		Test
THM-0.4.4	The thermal system shall receive telemetry on the thermal state of each subsystem from the CDH system	Necessary for determining course of action to maintain operating temperatures	THM-0.4 CDH-0.6.2		Demonstration

Table 8: *Payload Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
PAY-0.1	The sum of payload components shall not exceed 15 kg	Allocation of mass constraint	0.1		InspectionSTM
PAY-0.2	The cost of the payload components shall not exceed 30% of the total budget	Allocation of budget	0.3		Inspection
PAY-0.3	The system shall map the terrain of the Martian cave	STM Measurement Objective	SYS-0.5	PAY-0.3.1 PAY-0.3.2	Demonstration
PAY-0.3.1	The method used to map the cave shall have a range of at least 30m	The instrument used to map the cave must have adequate range to scan surfaces well out of reach of the vehicle	PAY-0.3		Test
PAY-0.3.2	The mapping of the cave shall be accurate to the nearest 10cm	Specifying the expected resolution	PAY-0.3		Test
PAY-0.4	The system shall search for olivine in the Martian cave	STM Measurement Objective	SYS-0.6	PAY-0.4.1	Test
PAY-0.4.1	The method used to find olivine shall have a range of at least 5m	The instrument must have adequate range to scan surfaces that may be out of reach to the vehicle	PAY-0.4		Test
PAY-0.5	The system shall determine the mineral composition of the regolith within the cave	STM Measurement Objective	SYS-0.7	PAY-0.5.1	Test

PAY-0.5.1	The method used to analyze the soil shall have a range of at least 5m	The instrument must have adequate range to scan surfaces that may be slightly out of reach to the vehicle	PAY-0.5		Test
PAY-0.6	The system shall produce images of soil/rocks within the Martian cave	STM Measurement Objective	SYS-0.8	PAY-0.6.1 PAY-0.6.2	Test
PAY-0.6.1	Close-range images produced by the system shall have a resolution of at least 60 µm	Specifying the expected resolution	PAY-0.6		Demonstration
PAY-0.6.2	Long-range images produced by the system shall have a resolution of within 300-500 µm	Specifying the expected resolution	PAY-0.6		Demonstration
PAY-0.7	The power consumption of the payload system as a whole shall not exceed 45 Watts	18% of the power consumption will be allocated to the payload subsystem.	POW-0.2		Analysis

1.2.3. Mission Success Criteria

1.2.3.a SuperCam

Table 9: *SuperCam Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Investigate and analyze the regolith within the Martian cave using all of SuperCams' instruments: Remote Micro-Imager (RMI), Remote Raman Spectroscopy, Visible/Near-Infrared Spectroscopy (VISIR), Laser Induced Breakdown Spectroscopy (LIBS). Utilize RMI to capture images of selected sample sites Conduct spectroscopy of minerals using Remote Raman Spectroscopy and VISIR Identify elemental composition of regolith using LIBS Utilize VISIR to identify molecular composition of regolith and detect presence of minerals such as olivine, phosphates, carbonates, sulfates, and metal oxides	- RMI spatial resolution of at least 55 μm [1] - Remote Raman Spectroscopy pixel resolution < 4 cm^{-1} and a full width half maximum (FWHM) resolution < 12 cm^{-1} [2] - VISIR instrument should be conducted at an absolute radiometric calibration better than 10% and relative calibration better than 1% [14]. - LIBS instrument should observe and determine the presence of elements to at least 300 parts per million (ppm) [3]
Minimum Success	SuperCam must at least capture images using RMI and identify minerals using VISIR	- VISIR instrument should be conducted at an absolute radiometric calibration better than 10% and relative calibration better than 1% [14]. - RMI spatial resolution of at least 55 μm [1]
Associated Failure Mode	SuperCam is unable to conduct any spectroscopy analysis and only RMI is able to capture images for analysis	- RMI spatial resolution of at least 55 μm [1]

1.2.3.b LiDAR

Table 10: *LiDAR Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Utilize Innoviz360 LiDAR to provide detailed 3D mapping of the terrain and geography inside the Martian cave. The 3D mapping should be accurate enough to allow for the Rover to safely traverse the cave and for adequate analysis of the cave's macroscopic features.	- LiDAR should be able to map up to a range of 200 meters
Minimum Success	LiDAR is not accurate enough for analysis of macroscopic features but it is still able to aid in mapping a route for the Rover	- LiDAR should be able to map up to a range of 200 meters
Associated Failure Mode	LiDAR is very limited in mapping and only large objects can be identified. SuperCam's RMI would then have to be used to aid in navigation	- N/A

1.2.3.c Communications and Data Handling

Table 11: *Communications and Data Handling Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Utilizing the UHF Transceiver C/TT-510 Electra Lite, communication between the primary lander and mission Rover must be maintained during times of data downloading. RAD750 3U Compact PCI must be able to process all data collected and allow for systems such as thermal management to make adjustments as data is collected	- Data sent to the primary lander should be clear and without data corruption below 5% of total data sent.
Minimum Success	It is necessary that Communications and Data Handling still performs all actions in above section for Minimum Success	- Data sent to the primary lander should be clear and without data corruption below 10% of total data sent.
Associated Failure Mode	If the RAD750 fails there is a second controller that would be able to take over.	- N/A

1.2.3.d Mechanical

Table 12: *Mechanical Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Rovers body must be able to withstand environmental conditions and protect all contents within the body. Anchoring component of egress system must firmy attach itself to Martian surface and allow for safe descent into the cave. Tether must be able to support Rover during descent into the cave. The tether must also be long enough to allow for the Rover to reach the bottom of the cave. Wheels and suspension must allow Rover to traverse over obstacles within lava tube	- Rover's body must give a yield and tensile strength of 2500 MPA and 4000 MPA respectively - Tether must withstand up to 750N of force [27] - Spool component of egress system must be able to deploy all 60 meters of tether if needed - Wheels and suspension must allow Rover to travel at least 20 meters inside cave
Minimum Success	Rovers body protects majority of inner contents and there is no major damage to any internal systems Anchoring component of egress system must firmy attach itself to Martian surface and allow for safe descent into the cave. Tether is able to support Rover and allow for partial descent into Martian cave	- Rover's body must give a yield and tensile strength of 2500 MPA and 4000 MPA respectively - Tether must withstand up to 750N of force [27]
Associated Failure Mode	Rover cannot complete full descent into Martian cave and science instruments will be deployed to collect whatever data it can	- Rover's body must give a yield and tensile strength of 2500 MPA and 4000 MPA respectively - Tether must withstand up to 750N of force [27]

1.2.3.e Thermal

Table 13: *Thermal Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Thermal system must keep Rover within operating temperatures for at least 3 days Silicone heating patches must be able to produce required amount of heat	- Rover must stay within -40C and 40C - Silicone heating pads must produce up to 200C if needed
Minimum Success	Thermal system must keep Rover within operating temperatures for at least one round of data collection Silicone heating patches must be able to produce required amount of heat	- Rover must stay within -40C and 40C - Silicone heating pads must produce up to 200C if needed
Associated Failure Mode	Thermal system is unable to function and will collect data until temperature begins to reach limits of operating temperatures	- N/A

1.2.3.f Power

Table 14: *Power Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Enough power is provided and Rover is able to function for at least 3 days Solar panel is able to recharge Rover	- 165.9 Watts is consumed during data collection mode - 77 Watts is consumed while the Rover is sending data - 27 Watts is consumed during full rest mode
Minimum Success	Enough power is provided and Rover is able to function for at least 1 day Solar panel is able to recharge Rover	- 165.9 Watts is consumed during data collection mode - 77 Watts is consumed while the Rover is sending data - 27 Watts is consumed during full rest mode
Associated Failure Mode	Not enough energy is able to be produced and Rover will operate until it reaches a critically low power level	- N/A

1.2.4. Concept of Operations

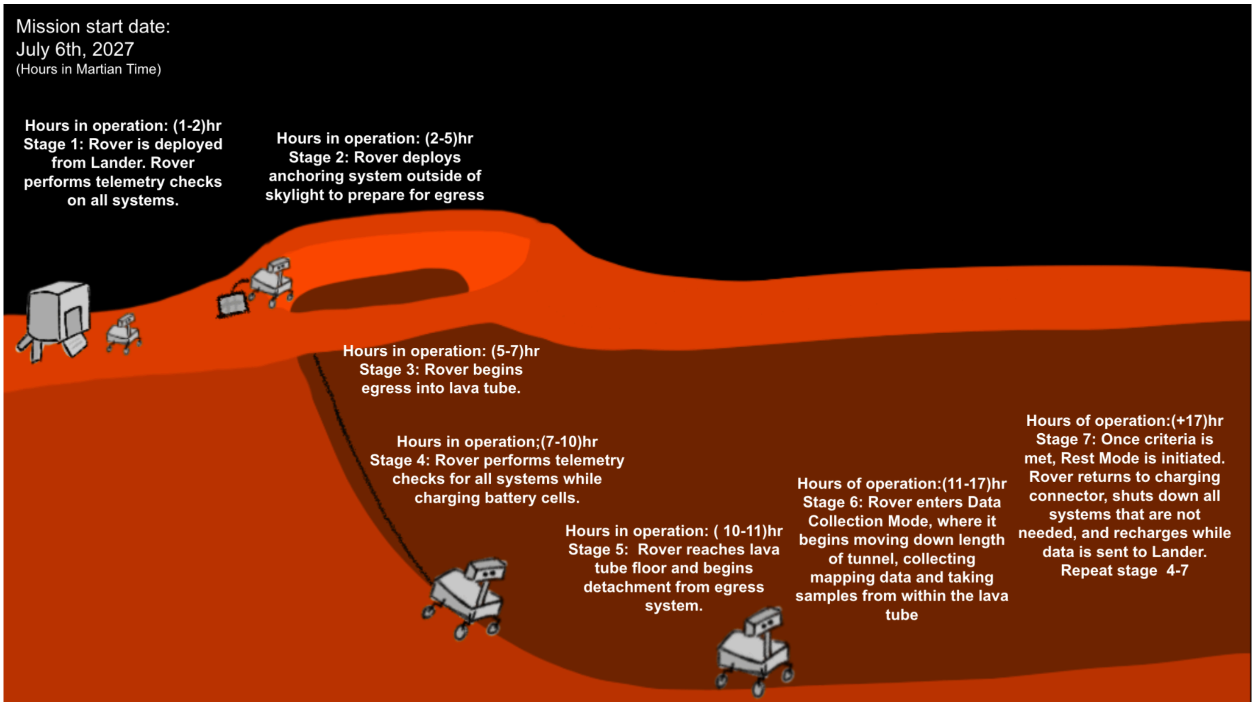


Figure 3: *Concept of Rover Operations.*

The mission begins with the Rover being deployed from the primary lander near the entrance of the lava tube. Once deployed, the Rover performs telemetry checks on all systems to verify no incidents have occuring during travel. It will then move to the skylight opening and prepare for egress into the lava tube. After deploying the anchoring system to egress into the skylight, the Rover descends to the lava tube floor. Once in a stable location, the Rover will once again complete a telemetry check to verify no damage has occurred during the descent from the skylight. Once completed the Rover will begin to detach from the egress system. The Rover then initiates its instruments to begin data collection, verifying systems are operational, and communication to the lander is achieved. The Rover begins moving down the length of tunnel and enters Data Collection Mode.

During Data Collection Mode, the Rover takes LiDAR scans and generates a map of the scanned environment. With an environment sampled the data can be processed and areas of interest can be detected and elevated to next level sampling using SuperCam. Soil analysis using SuperCam can be done either at a range or up close quickly identifying the chemical and mineral composition. Within this process the Rover is scanning for the presence of olivine along with any other abundant chemicals and minerals. Once the priority area has been analyzed, the Rover takes a new LiDAR scan to generate a new map of a previously unscanned environment to determine a future path. The Rover follows the newly determined path and repeats Data Collection Mode until the criteria is met for Rest Mode. This criteria would include a variable percentage of power remaining in the system for safely return to the charging station for data return.

During Rest Mode, the Rover returns to the egress location and will dock itself to the charger connector. The Rover then shuts off all instruments except for systems needed to send data back to the primary lander to conserve energy and to focus on sending data and replenishing battery power. Once all data has been sent back and the batteries have been fully charged, the Rover will undock from the charger connector and enter Data Collection Mode to repeat the process in a new area within the cave.

1.2.5. Major Milestones Schedule

Phase A (Concept and Tech Development):

During the Concept and Tech Development, teams will rigorously define science goals and objectives, and develop mission requirements on the subsystem level. Teams will also define mission risks and develop mitigation plans. This phase culminated in the finalization of a Mission Concept Readiness Review (MCRR) on 6/20/22.

Phase B (Preliminary Design and Tech Completion):

During the Preliminary Design and Tech Completion, teams will begin work on the vehicle design by researching instrumentation and subsystem hardware in order to develop a preliminary design. Previous documentation, such as V&V (Verification and Validation) and risk mitigation, will be refined. A ConOps will be developed as well as a mission schedule. This phase will culminate in the finalization of a Preliminary Design Review (PDR) by 9/2/22.

Phase C (Final Design and Fabrication):

The Final Design portion of Phase C will concentrate on finalizing the established design. Teams will conduct further research into instrumentation and hardware in order to finalize a design. Previous documentation will again be updated. This phase will conclude with the finalization of the Critical Design Review (CDR) by 9/8/23.

The Final Fabrication portion of Phase C will commence following the CDR. The manufacturing and outsourcing of components will begin, allowing teams to initiate V&V tests as outlined by the CDR. Previous documentation will be updated. This phase will conclude with the finalization of the System Integration Review (SIR) by 10/7/23.

Phase D (System Assembly, Integration & Test, Launch & Checkout):

The System Assembly, Integration & Test, Launch & Checkout will focus on assembling subsystems and the final system. Multiple rounds of V&V procedures will be conducted while teams develop the Mission Readiness Review (MRR) and Operational Readiness Review (ORR). Following the final round of V&V, teams will prepare for launch. This mission will launch on 11/24/26. This phase will culminate with the Post-Launch Assessment Review (PLAR) by 1/30/27.

Phase E (Mission Operations):

Mission Operations will be conducted by all teams following the PLAR. During flight operations, the team will complete a Critical Events Readiness Review (CERR). The primary lander will reach Mars on 7/6/27. The system will then be deployed near the skylight and conduct its investigation for at least 3 days. Towards the end of the data collection period, teams will work on the Decommissioning Review (DR). The data will then be collected and analyzed. Active operations will conclude on 9/20/27.

1.3. Vehicle Design Summary

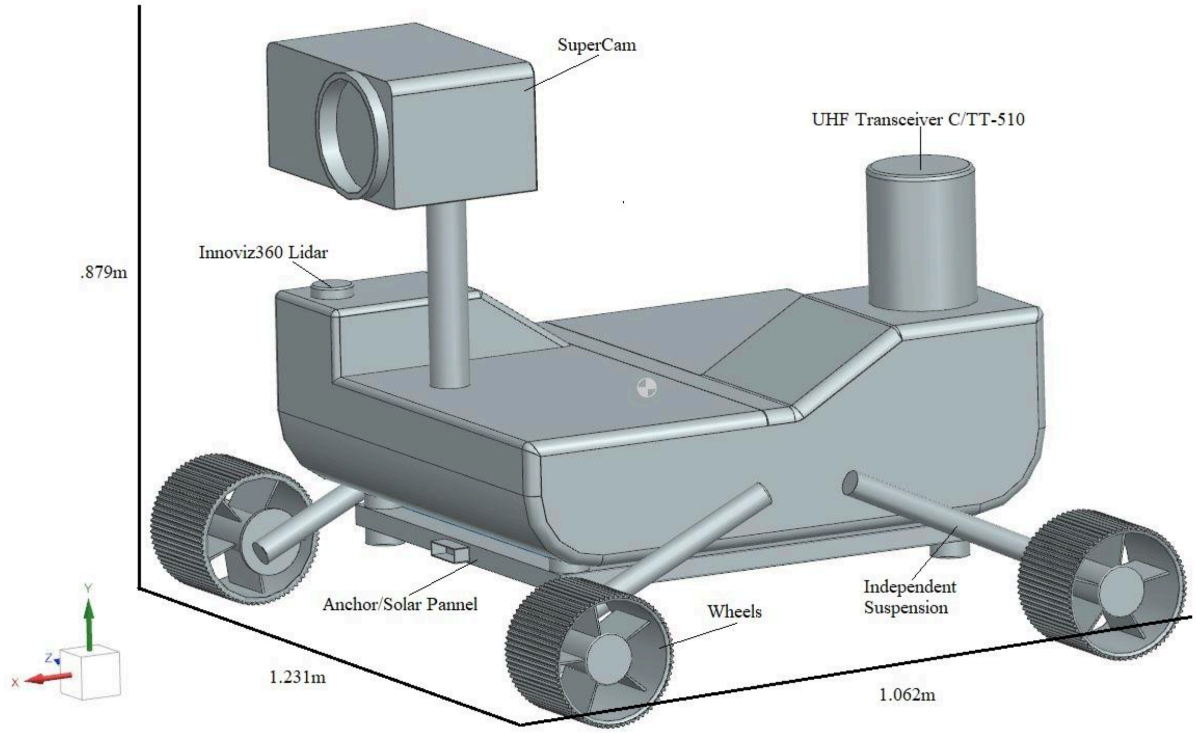


Figure 4: *Rover Assembly Design (Operating Configuration)*

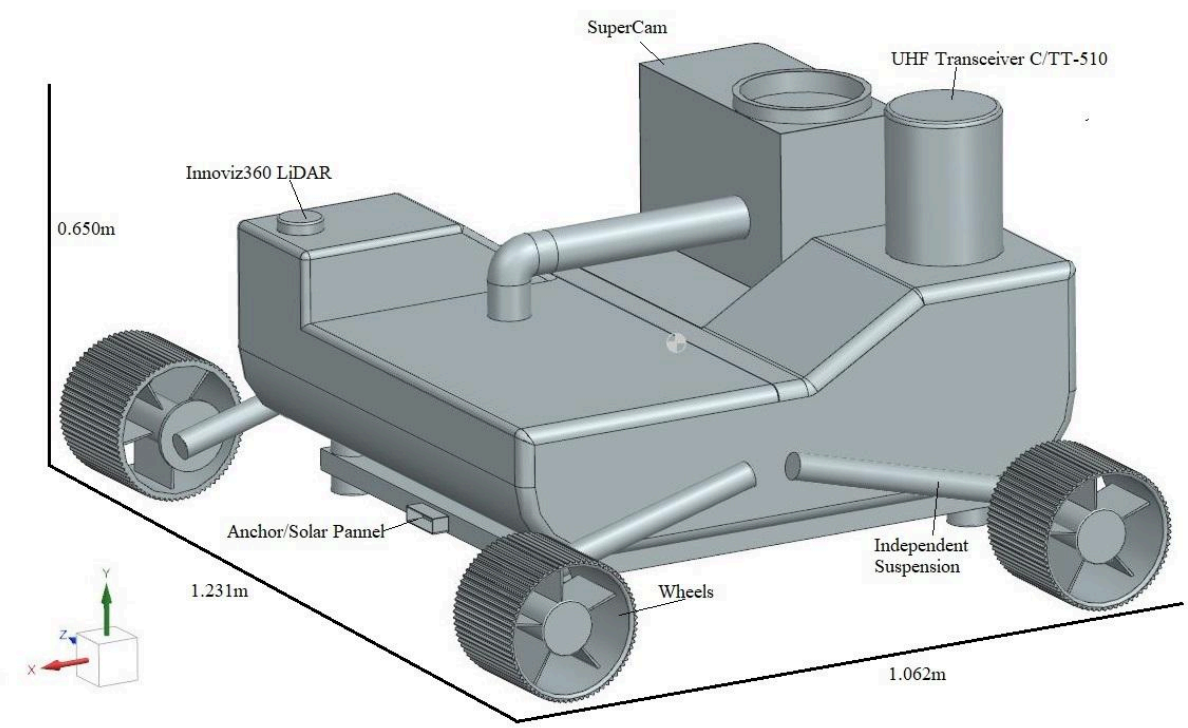
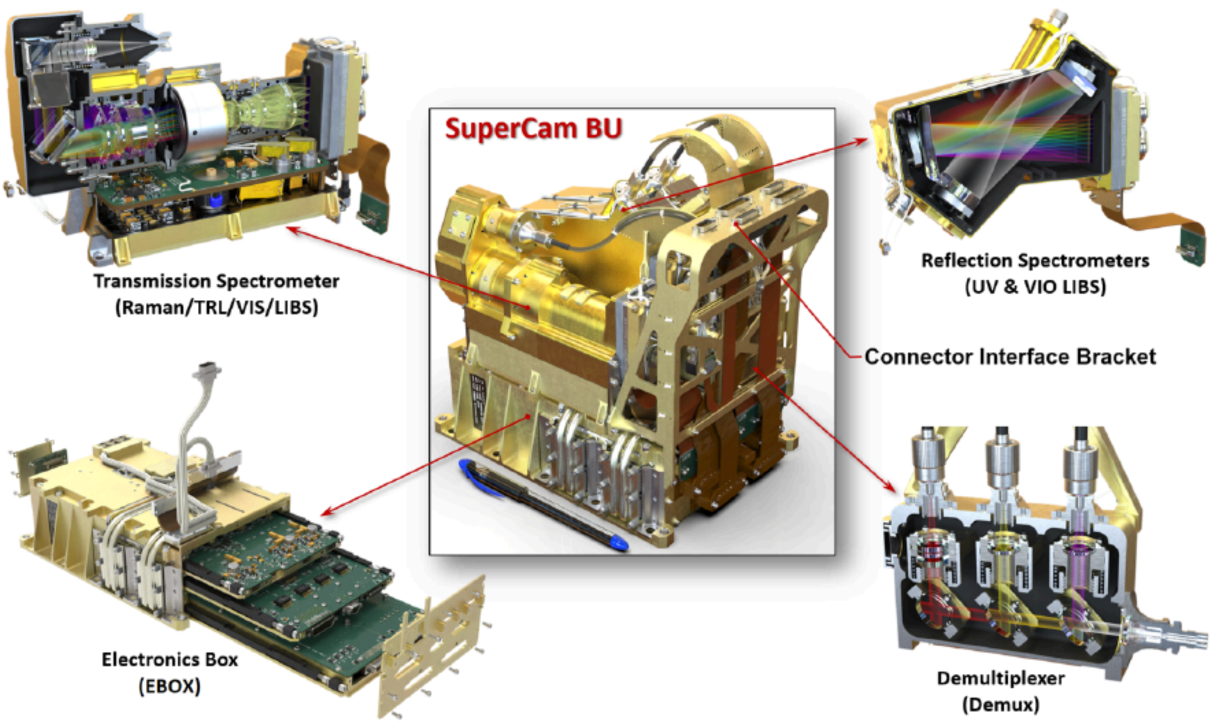


Figure 5: *Rover Assembly Design (Storage Configuration)*

The Rover designed for the mission of observing lava tubes on Mars at cite location CC0769 was built to traverse hard terrain in an unknown environment. The Rover itself has a mass of 46.517kg so as to be kept within mission requirements and to maximize the efficiency of power to mass ratio extending the mission. The lithium-ion battery cells, manufactured by EaglePitcher, are used within the Rover and are proven batteries used on Mars Lander missions with a high power vs low mass benefit [7]. The Rover takes a traditional design with wheels and independent suspension that will provide maximum maneuvering and control over unknown terrain. The independent suspension will allow the Rover to raise and lower its body to adjust for potential hazards and to assist in operation. A matching set of four wheels will be located on each side to allow for an even distribution of mass and place the center of gravity low and in the center of the Rover. With a max clearance of 0.23m from floor to bottom of the Rover, large rocks will be avoided and passed over for safe operation. The Rover will have two main configurations, one being the storage configuration and the other the operational configuration. In its storage configuration, the Rover will measure out to be (1.231 x 1.062 x 0.650)m for compliance of mission requirements and will unfold into its final operating configuration of (1.231 x 1.062 x 0.879)m. Once ready for deployment, the Rover will hoist its main camera and chemical analyzer instrument called SuperCam into operating configuration as well as its anchor base for the egress system.

1.4. Payload and Science Instrumentation Summary

1.4.1. SuperCam



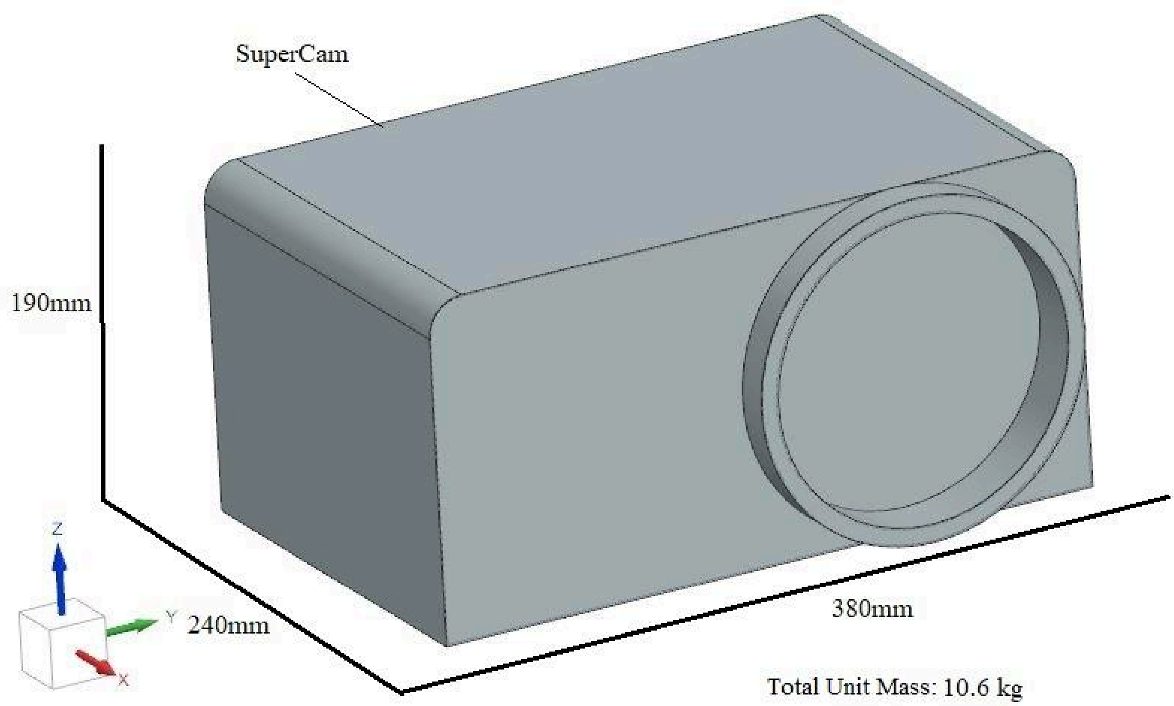


Figure 6: *NX CAD Model: SuperCam Mast Unit*

Figure 7: *Model: SuperCam Body Unit* [3]

The SuperCam suite is a legacy instrument used on the Perseverance Rover with the ability to take pictures and laser sample rocks and soils from up to 7m away. With a total mass of 10.4kg [4], the sensor will be mounted .95m above the Rover's body to give an unobstructed view. SuperCams sensor holds two objectives in which it will search for olivine and observe what other minerals and chemicals are within the soil.

The suite is split into two units: the Body Unit (BU) and the Mast Unit (MU). The BU has a mass of 5.6kg while the MU has a mass of 4.8kg. The system as a whole has a power consumption of 17.9W [4]. The MU holds an Infrared (IR) Spectrometer, the Remote-Micro Imager (RMI), the 1064-nm laser, and a telescope to collect light. The BU contains three spectrometers (UV, Violet, and Transmission) [3]. Light is collected through the MU's telescope. That light is then distributed to instruments within the MU and the BU. Optical fibers within the mast carry the light from the MU to the BU. SuperCam makes use of various methods of spectroscopy, making it an ideal choice for both detecting olivine and conducting thorough analysis of the regolith within the Martian cave.

1.4.2. LiDAR

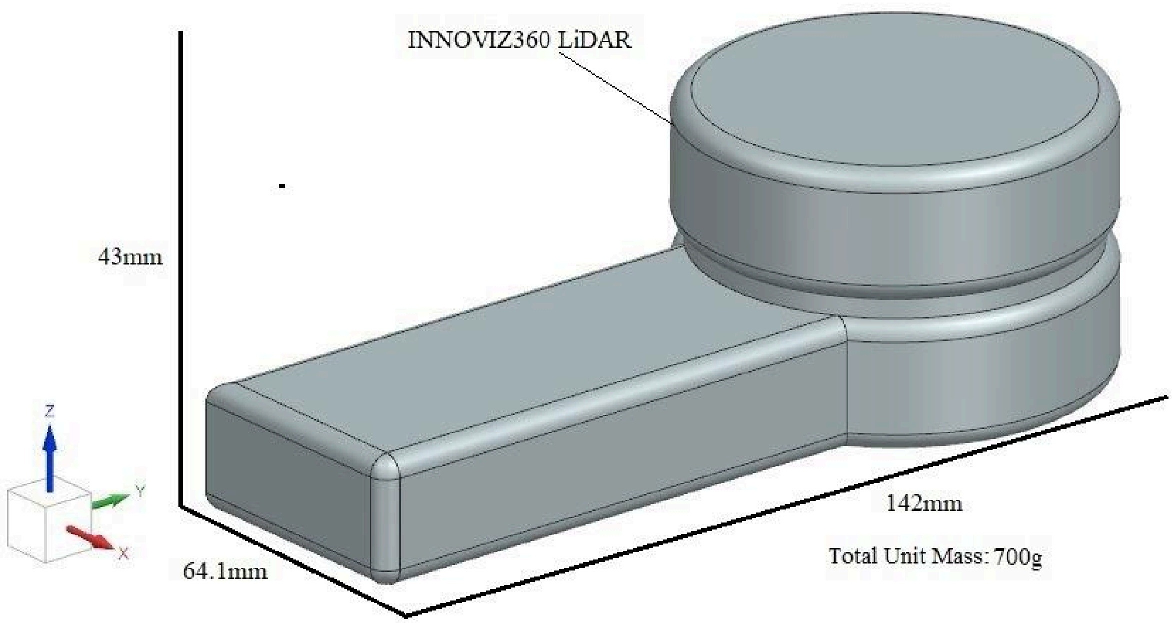


Figure 8: *NX CAD Model: Innoviz360 LiDAR*

With a mission objective being to map out the inner formations within the lava tube, a sensor that could scan and data log environments was needed. The sensor chosen is the Innoviz360 LiDAR sensor with a field view of 360° x 64°. This small (70x200x60)mm and lightmass 700g sensor can scan from 0.3m to 300m and can operate between [-40°C, 85°C] with a power consumption of 25W [5]. Its ability to scan within a large window and range makes this sensor ideal as the Rover can reach further into the lava tube without having to drive as far. This saves power while still prioritizing data collection.

1.4.3. UHF

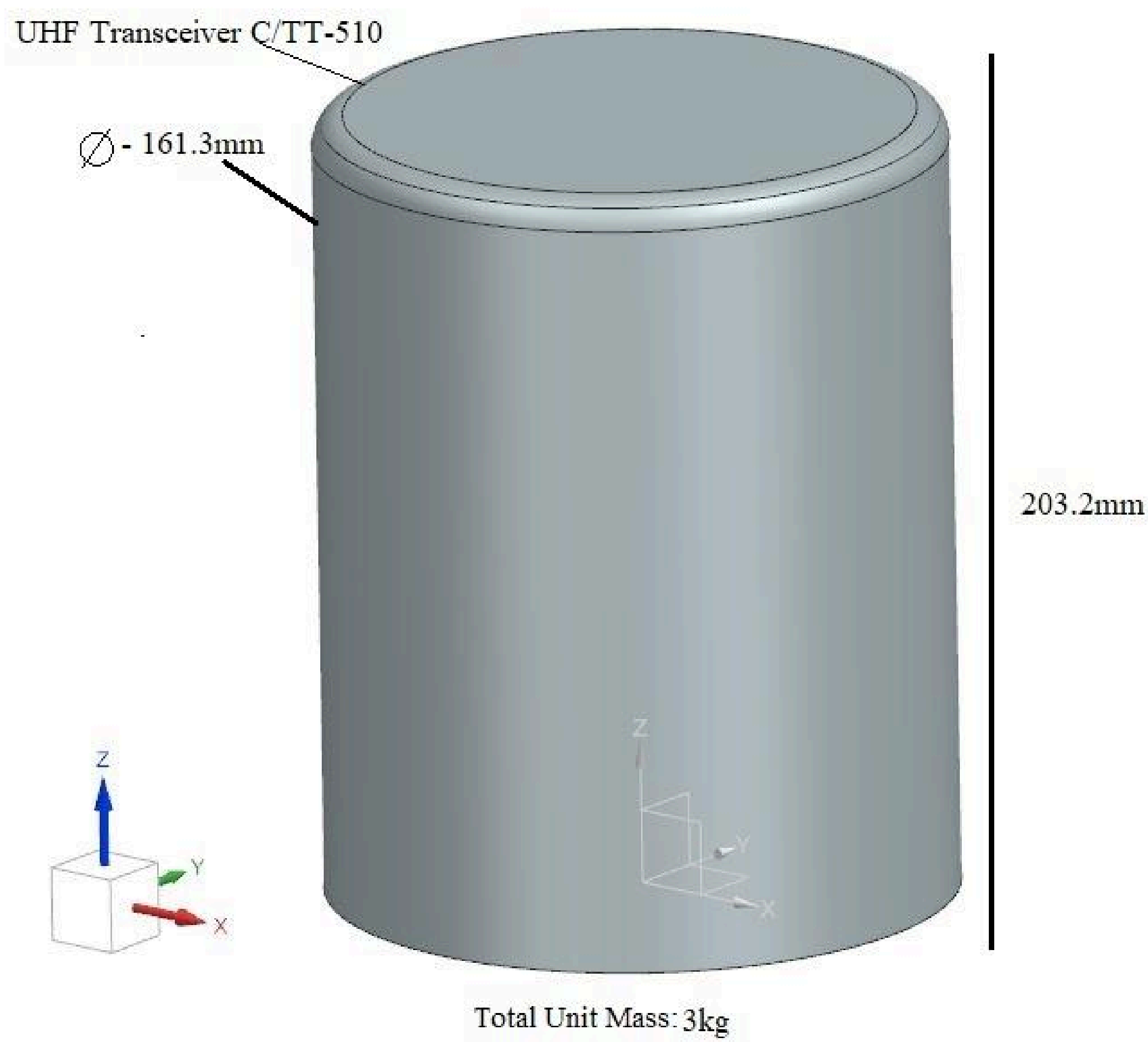


Figure 9: *NX CAD Model: UHF Transceiver C/TT-510*

For communication back to the primary lander the task is given to the UHF transceiver model C/TT-510. This transceiver is also a legacy instrument used on the Perseverance Rover but will be placed in a new environment where the signal will be maintained within a lava tube rather on the surface with no obstructions. The transceiver has a volume of (Dia 161.3 x 203.2)mm and a mass of 3kg [6]. The transceiver is able to send out RF frequency in a range of 435 to 450MHz allowing for a strong signal to reach from within the tube onto the surface where the lander will be located. The Transceiver has a power consumption of 65W when active and 15W in standby mode [6].

1.4.4. Egress System

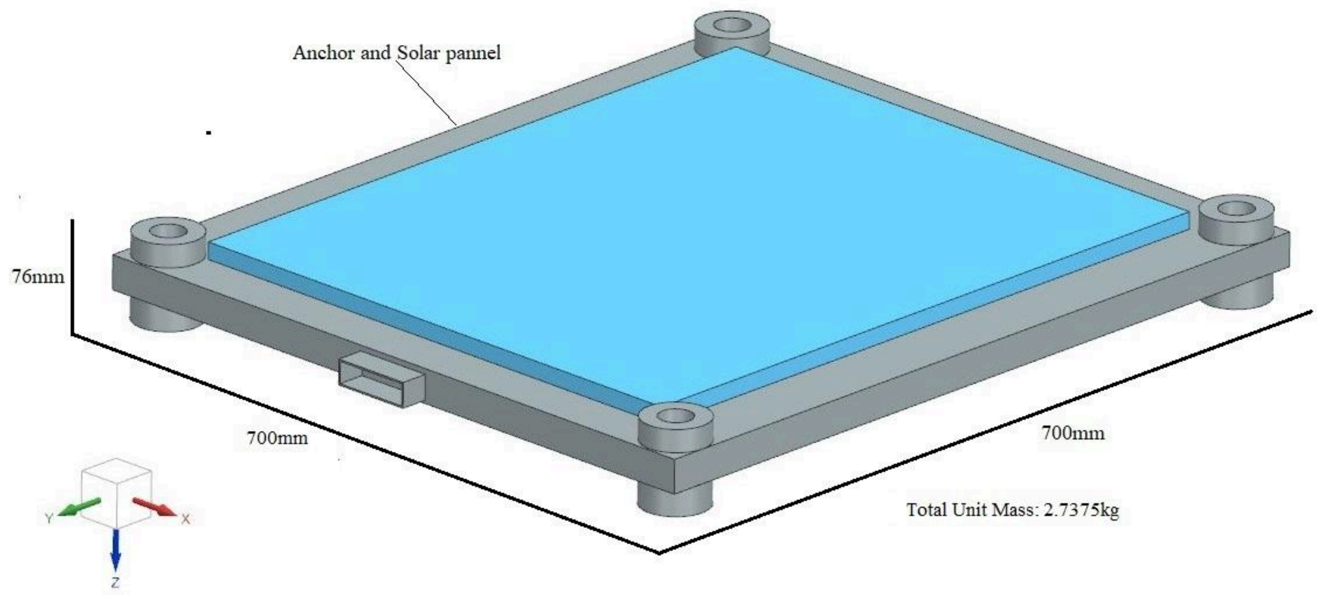


Figure 10: *NX CAD Model: Anchor/Solar System*

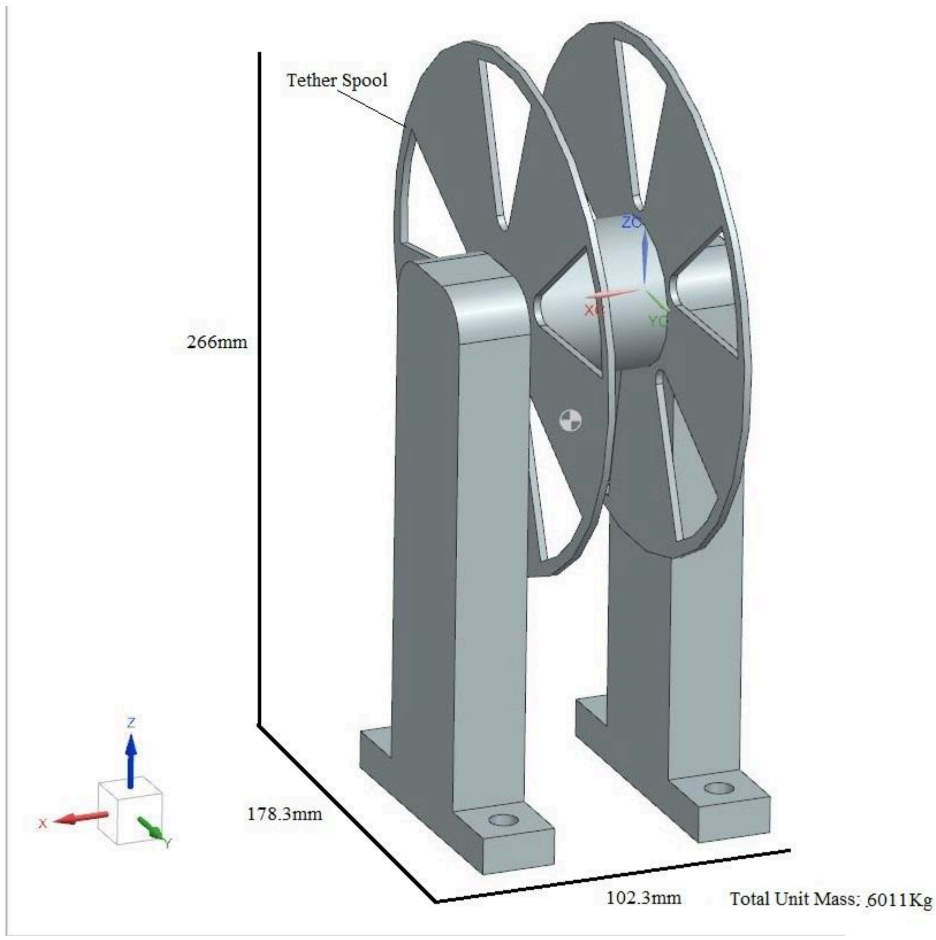


Figure 11: *NX CAD Model: Tether Spool*

For the Rover to enter within the Lava tube it must accessend down into the skylight. To do this the Rover has an integrated anchor and tether system to allow for the Rover to safely descend to the tube floor. The base anchor and solar panel shown in Figure 10 are a two part unit that allows for an anchor spot as well as a power supply for the Rover. The dimensions of the anchor is (700 x 700 x 76)mm with a total mass of 2.7375kg. The solar panel has dimensions (580 x 600.7 x 15)mm and is capable of generating 144.7W for every hour in direct sunlight. The tether and spool mechanism are stored within the Rover and are connected to the anchor. [24]

2. Evolution of Project

2.1. Evolution of Mission Experiment Plan

At the beginning of the mission, different concepts for the mission were suggested. Before the final three mission objectives were selected, the team had gone over other ideas for mission goals that the system would be designed to achieve. For the first iteration, the team had discussed the objective of 3D mapping the interior of the lava tube and measuring moisture/water formation present within. The two objectives would give an indication of the environment of the lava tube and give insight to previously unknown underground conditions on MARS.

Upon further review, the objective for measuring moisture and water levels was decided against and changed to the observation of minerals and chemicals within the soil. Along with these changes in objective, the design of the system was also switched from a possible drone type design to a Rover type which would be able to scan and observe minerals and chemicals within the lava tube leading to the second iteration for the mission.

Lastly, the third iteration was decided upon when the team decided to further define a mineral to observe within the lava tube. The mineral of interest was determined to be olivine to observe the formation of this mineral in an isolated and protected environment. With this change, the three current mission objectives were defined: to produce a 3D map of the tube, to analyze the composition of the soil within the tube, and to determine the percentage of olivine present within the tube.

2.2. Evolution of Vehicle Design

Table 15: *Mobility Trade Study*

Mobility Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**Track System**	**Independent Wheel System**	**Legs**
Mobility	The mobility of the system determines how well the Rover will be able to turn and maneuver over potential obstacles.	5 = high 3 = medium 1 = low	20%	3	5	3
Traction	Due to unknown conditions it is possible for sandy or rocky terrain to exist.	5 = high 3 = medium 1 = low	30%	5	4	2
Power Watt/Hr	Due to limitations in weight and power capacity a low power option is optimal for power consumption.	5 = high 3 = medium 1 = low	20%	1	4	3
Weight	Entire design is limited to 50kg, so the lower the weight possible is favored.	5 = high 3 = medium 1 = low	20%	1	4	5
Durability	The rugged landscape of Mars is likely to cause damage to our choice of mobility. We should consider the likelihood of these options getting damaged.	5 = high 3 = medium 1 = low	10%	2	5	4
		TOTAL	**100.00%**	**54.00%**	**86.00%**	**64.00%**

With the discussion of possible methods of mobility, three main concepts of movement were suggested. Each of the suggestions could be used however each method had its own advantages and disadvantages. When focusing on what would fit best for the mission in terms of tractions, mobility, mass and power consumption it became clear that the independent wheel system would work best. Issues with high power and mass consumption limited tracks to be used and the instability and complexity of legs would exceed cost. With this the team decided on the use of wheels and independent suspension as the primary method of movement. The benefit being that the Rover would adjust its ground height to safely pass over larger rocks. The independent suspension also allows for the four wheels to always maintain contact with the ground while still keeping the body level. These benefits along with the lower power and weight made it clear in the choice of mobility to be used for the mission. The criteria in which each of these systems was evaluated can be seen in Table 15.

2.3. Evolution of Payload and Science Instrumentation

2.3.1. Payload

Table 16: *3D LiDAR Trade Study*

LiDAR Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**Innoviz360 LiDAR**	**Velodyne Puck LiDAR (VLP-16)**	**LW20/C LiDAR**
Range	It would be beneficial for the lidar instrument to have a far range of view, so it could map out the cave ahead.	5 = high 3 = medium 1 = low	40%	5	3	1
Operating Temperature	The lowest temperature the Rover will experience is -123C and the LiDAR instrument must be able to operate in that temperature. (thermal solutions to expand that range are expected)	5 = high 3 = medium 1 = low	40%	3	2	1
Power Watt/Hr	Due to limitations in weight and power capacity a low power option is optimal for power consumption.	5 = high 3 = medium 1 = low	10%	3	4	5
Weight	Entire design is limited to 50kg, so the lower the weight possible is favored.	5 = high 3 = medium 1 = low	10%	3	3	5
		TOTAL	**100.00%**	**95.00%**	**67.50%**	**45.00%**

When deciding upon the mapping and navigation system the mission required a sensor that could 3D map terrain and all features present within the lava tube. It was decided that a LiDAR sensor would be the best option for this task and three possible sensors were suggested for use within the mission. The ability of each sensor was the same but key differences were found between range and operation ability. Sensors that could map in a full 360 degree window with a wider field of view were preferred. Looking at the datasheets for each component the Innoviz360 LiDAR sensor stood out as the most promising sensor that could also handle the extreme environment and provide large amounts of data. With this in mind the Innoviz360 was further examined to also compare its power consumption and weight to the sensors systems requirements. While the Innoviz360 had the highest power consumption it gave the farthest reaching sensing capabilities compared to the other two options. The ability to reach further into the tube without having to physically move the Rover closer was deemed a greater benefit overcoming the sensor's higher power consumption. The criteria in which each of the 3D sensors were evaluated can be seen in Table 16.

2.3.2. Science Instrumentation

Table 17: *Science Instrument Trade Study*

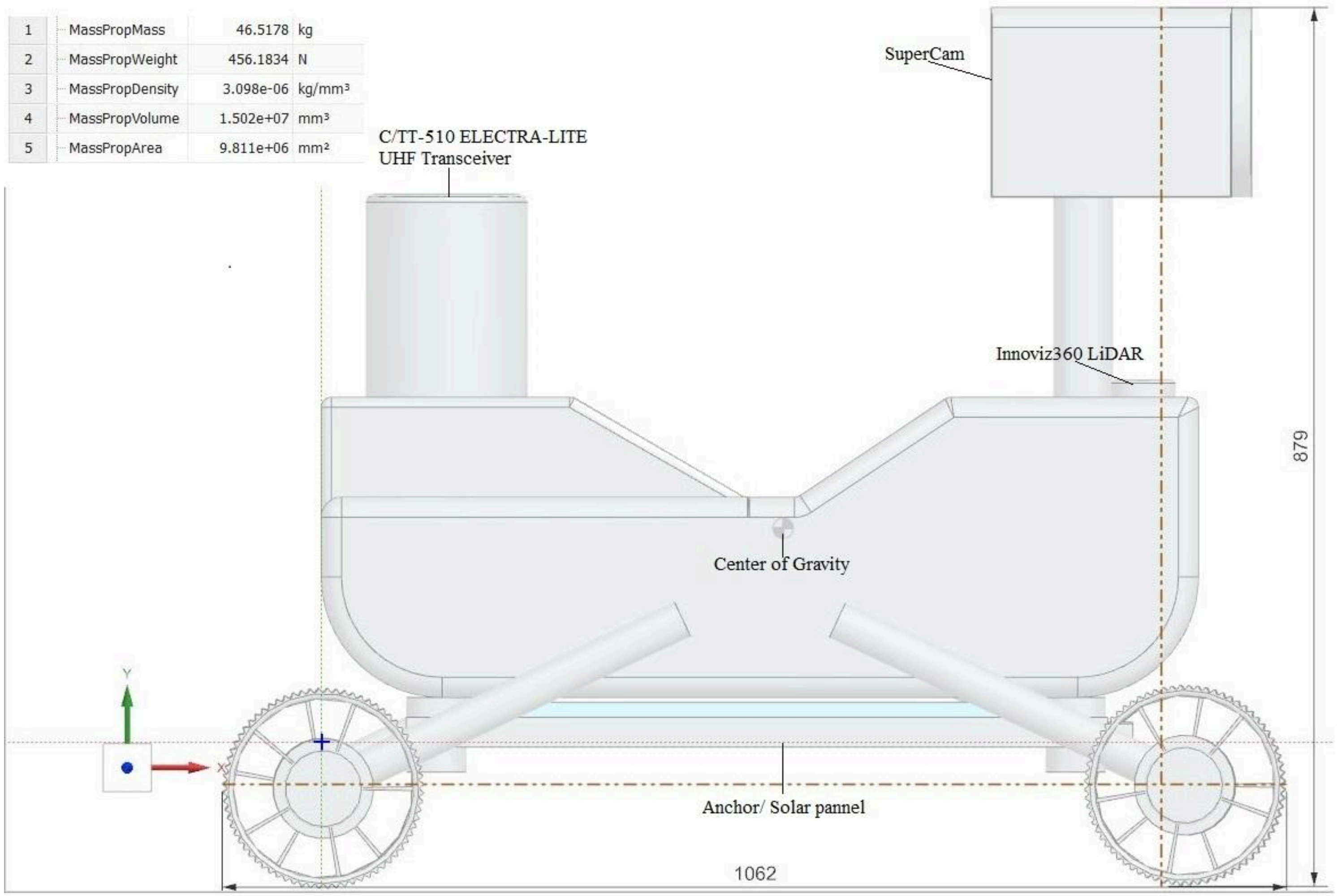
Science Instrument Trade Study					
Criteria	**Explanation**	**Grade**	**Weight**	**CheMin**	**SuperCam**
Range	It would be beneficial for our science instrument to be able to take samples from farther, unreachable ranges.	5 = high 3 = medium 1 = low	10%	1	4
Resolution	The degree of examining that the instrument carries out to identify what minerals and chemicals are present within the test.	5 = high 3 = medium 1 = low	35%	5	3
Power Watt/Hr	Due to limitations in weight and power capacity a low power option is optimal for power consumption.	5 = high 3 = medium 1 = low	20%	1	5
Weight	Entire design is limited to 50kg, so the lower the weight possible is favored.	5 = high 3 = medium 1 = low	15%	1	3
Versatility	The instrument's ability to test for either chemicals, minerals, or both.	5 = high 3 = medium 1 = low	20%	5	5
		TOTAL	**100%**	**64.00%**	**78.00%**

For the science instrument trade study the team decided to ultimately only decide between two instruments, the CheMin and SuperCam. The ChemCam was initially considered but after doing more research, it was discovered that the SuperCam is the improved, second iteration of the ChemCam, so it was replaced. The five criteria considered for the science instrument are its range, resolution, power consumption, mass and versatility. Although the quality of data gathered was most important when deciding upon the science instrument, the team ultimately decided to use the SuperCam for the mission. Its degree of examination is not as thorough as the CheMin, but it easily has an advantage in every other criteria, besides versatility. SuperCam’s resolution is great, but in comparison to CheMin, it is not as good. SuperCam will fit the mission far more suitably because of the mission's nature. SoCoLD will only have enough power for about a week. So power consumption was also an important factor to consider in this decision. With SuperCam having a low power consumption of 17.9 watts, it helped push its case for this being used in this mission. The criteria in which the chemical and mineral sensors systems were evaluated can be seen in Table 17.

Overall Vehicle and System Design

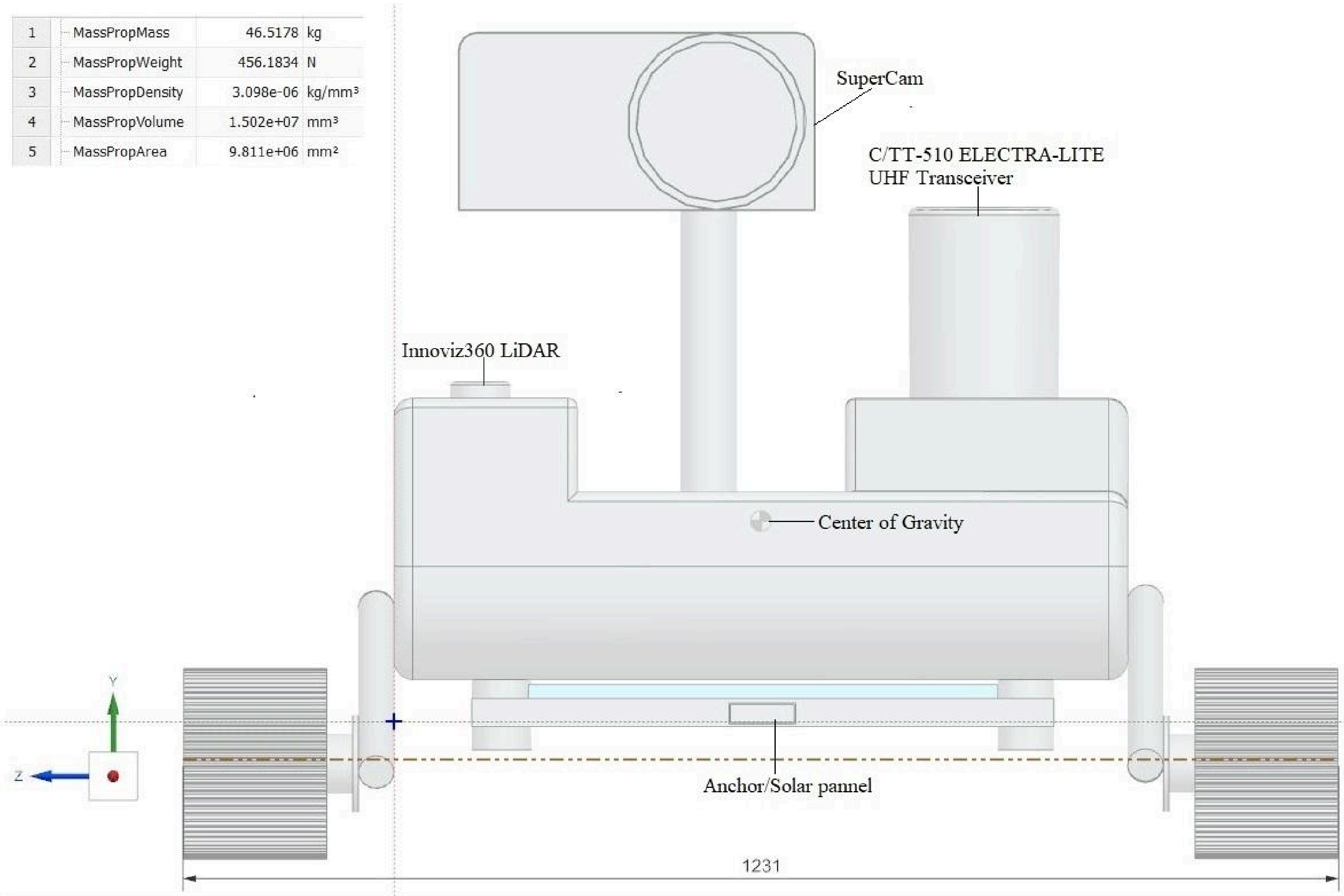
3.1. Selection, Design, and Verification

3.1.1. System Overview



1	MassPropMass	46.5178	kg
2	MassPropWeight	456.1834	N
3	MassPropDensity	3.098e-06	kg/mm³
4	MassPropVolume	1.502e+07	mm³
5	MassPropArea	9.811e+06	mm²

Figure 12: *Rover Side view Dimensions*

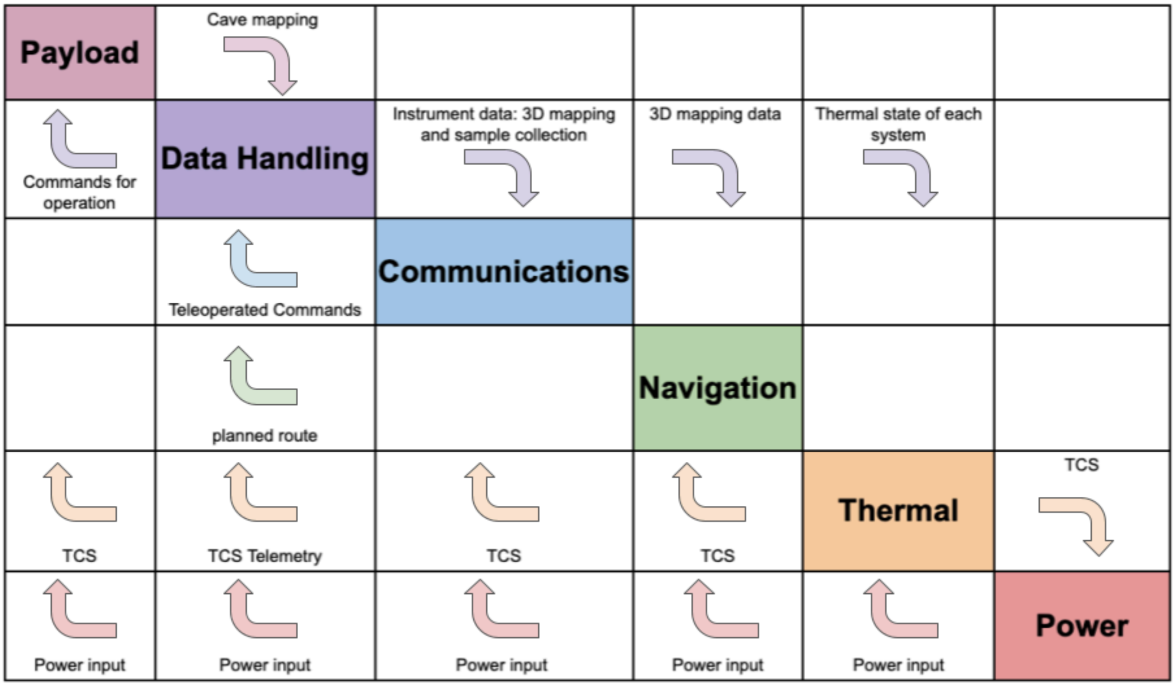


1	MassPropMass	46.5178	kg
2	MassPropWeight	456.1834	N
3	MassPropDensity	3.098e-06	kg/mm³
4	MassPropVolume	1.502e+07	mm³
5	MassPropArea	9.811e+06	mm²

Figure 13: *Rover Front view Dimensions*

The Rover system consists of a four wheel independent suspension system that gives high ground clearance and mobility for the exploration of the Mars lava tube. The Rover is designed to traverse the tube and safely allow the instruments to collect data. The Rover's primary systems consist of mechanical, electrical, data processing/communication, and thermal control. With each system controlling a specific part of the Rover it is necessary for each system to communicate and act as one complete assembly for the mission to be successful. The physical dimensions for the Rover are (1.231 x 1.062 x 0.879)m and a total mass of 46.5178kg. The Rover and each of its systems was designed to maintain conformance to the project's requirements as well as mission objectives. As each system was developed, consideration in how communication and interaction would occur between all systems. This interaction was determined and a visualization was created as shown in the graphs below. The N2 chart in Figure 14 shows a general breakdown of the interaction occurring between each system. While some systems may only interact with only one other system other systems will play a larger impact with all systems. To further break down this interaction into its subgroups and specific electronics a block system diagram was created which further shows the Rover interconnections.

N2 Chart / Block Diagram



. **Figure 14:** *N/2 Chart, System Communication Overview*

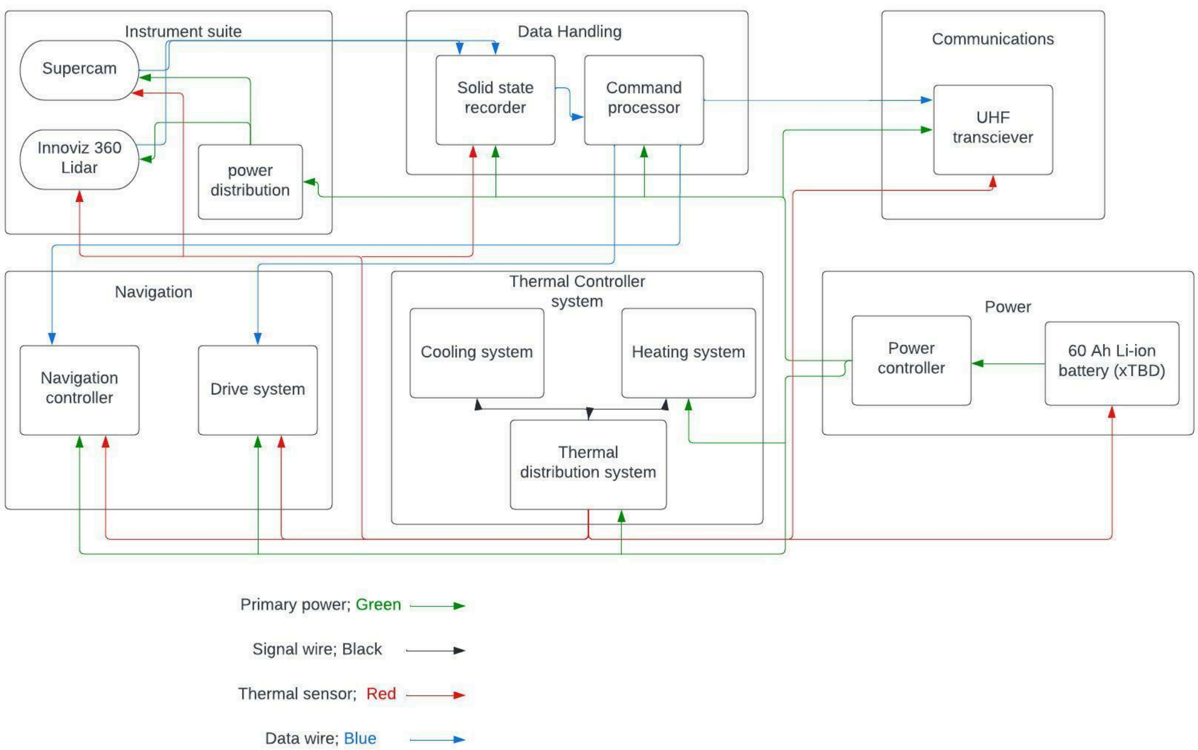


Figure 15: *Block Diagram, System Communication Breakdown*

Due to the need for each subsystem to operate and communicate together a breakdown of how each subsystem interacts was created and is shown in Figures 14 and 15. Certain subsystems may only have the need to receive or send input to one other system while others such as the temperature and power systems will be connected throughout the Rover. Since each subsystem needs to be electrically powered the power management controller will need to be connected and distribute power to each system as needed. As power is consumed throughout the Rover by each subsystem heat is generated and is monitored by the thermal management subsystem. The thermal subsystem will monitor and either add or remove heat from the system maintaining operating temperatures for all sensors and equipment. Data passed between all subsystems goes through the data handling subsystem that takes in raw sensor data and programmed analysis to control the Rovers actions. The three subsystems of Navigation, Instruments, and Communications pass data back to the Data handling to process data and based on the data processed send data or instructions back to each respective subsystem.

3.1.2. Mechanical System Overview

3.1.2.a. Rovers body

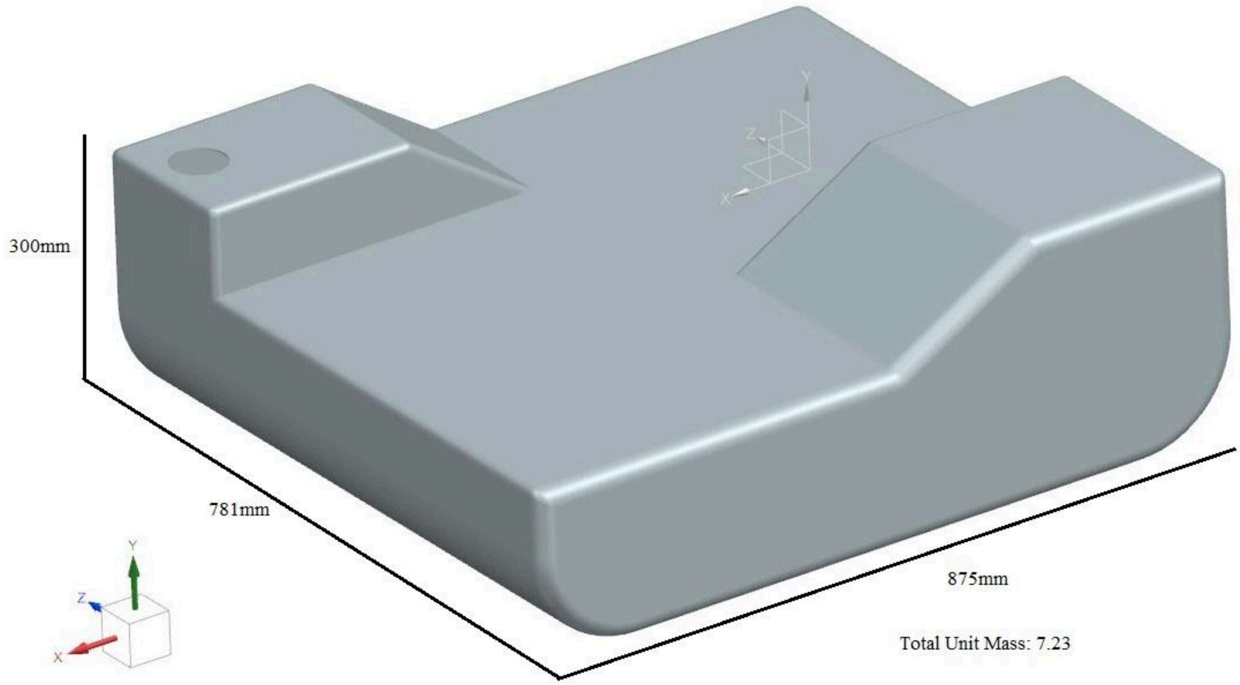


Figure 16: *Rover Body Design*

The Rover's body as seen in Figure 16 is the key structure that holds all systems within. The Rover's body is made of formed carbon fiber to give a yield and tensile strength of 2500 MPA and 4000 MPA respectively. This gives confidence for the structure ability of the Rover to withstand the extreme environment and nature of the mission. The Rovers body has a volume of (781 x 875 x 300)mm and a total mass of 7.23kg. All systems are incorporated and balanced within the Rovers body to establish a low center of gravity to provide stability as the Rover is within operiaton. While the body has no moving parts or independent systems it itself plays a key role in the Rovers mission.

3.1.2.b. Egress System

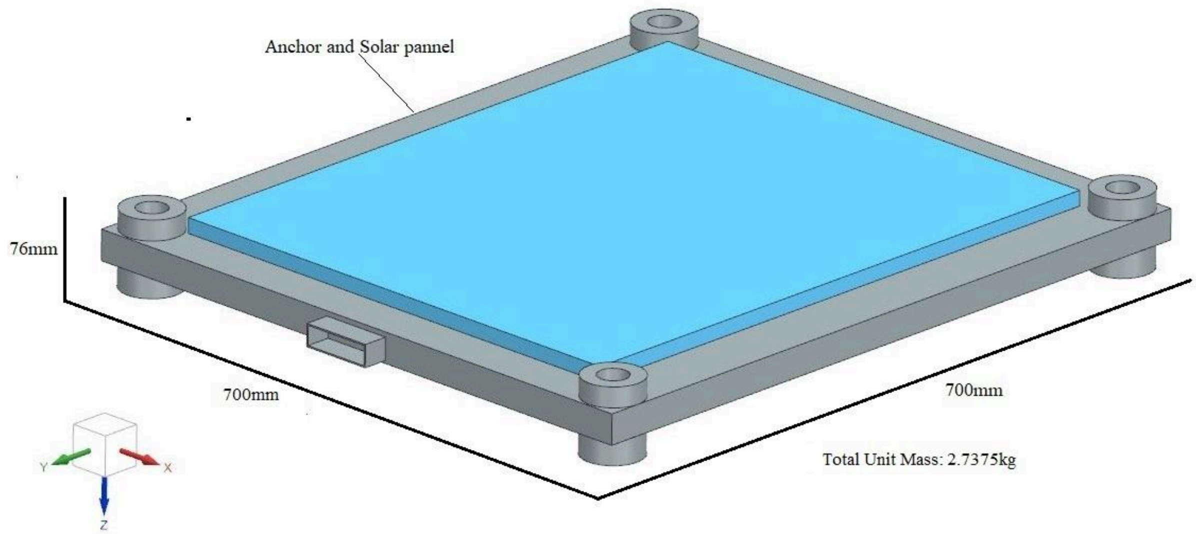


Figure 17: *Rover Anchor Base Plate Design*

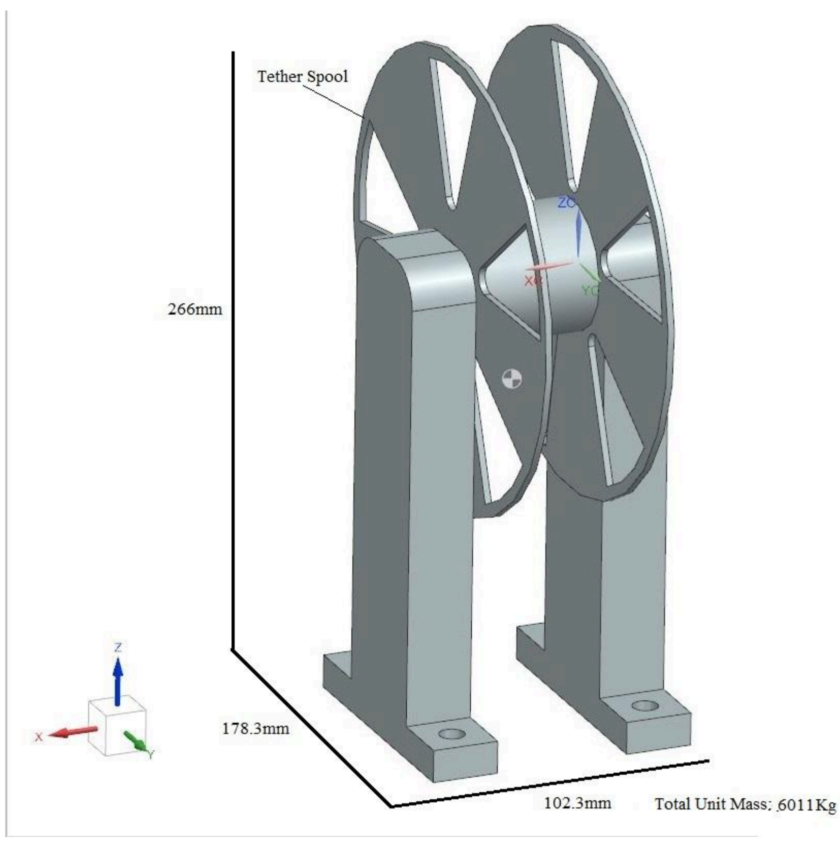


Figure 18: *Rover tether Spool Mechanism*

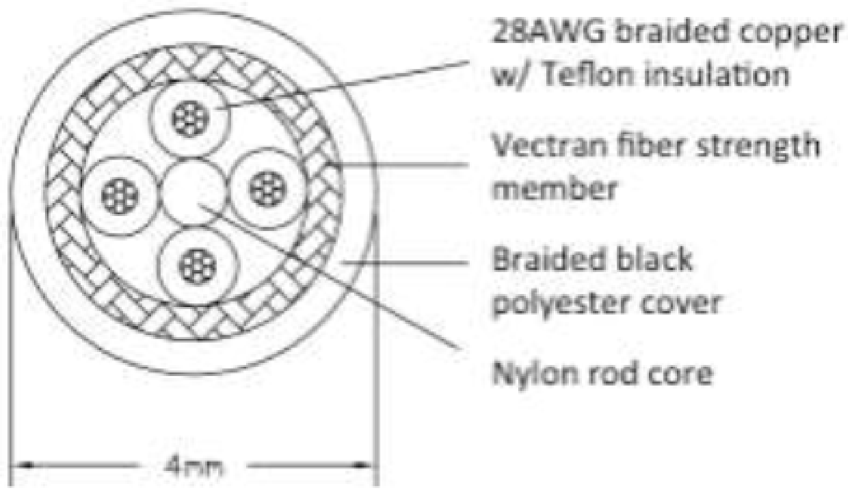


Figure 19: *Rover tether Spool Cable [27]*

The egress system consists of three main components used for the safe descent of the Rover from the skylight down to the lava tube's surface. The three systems consist of an anchor, tether, and spooled connector. The anchor for the Rover is attached at the bottom of the Rover's body until ready for deployment. The anchor is lowered and placed on the ground where its procedure for anchoring into the ground begins. To provide the strength needed to support the Rover as it descends the anchor employs metal rod anchoring pins that are shot into the ground at each corner location through the use of powder loads. The anchor bolts grab the ground and secure the anchor for safe use. To connect the Rover to the anchor a tether system is used.To reach the bottom of the tube from the skylight the tether can reach a length of 60m. Within the tether is a vectran fiber and nylon structure with electrical wire connecting the solar panel within the anchor to the charger connected on the other end. The tether itselfs primary job is to support the mass of the Rover as to prevent any damage during descent the tether is rated to withstand 750N of force [27].The tether and its internal structure can be seen in Figure 19. Lastly the spooled connector of the egress system is located at the rear of the Rover. The electric spool controls the descent of the Rover and is held in place by locking pins. This system allows for the spool to be disconnected for further operations within the cave and can be reattached for when the Rover enters rest mode. The reconnection of the egress system allows for the Rover to recharge off its solar panel providing additional power for the UHF transceiver to send the data back to the primary lander.

3.1.2.c. Wheels

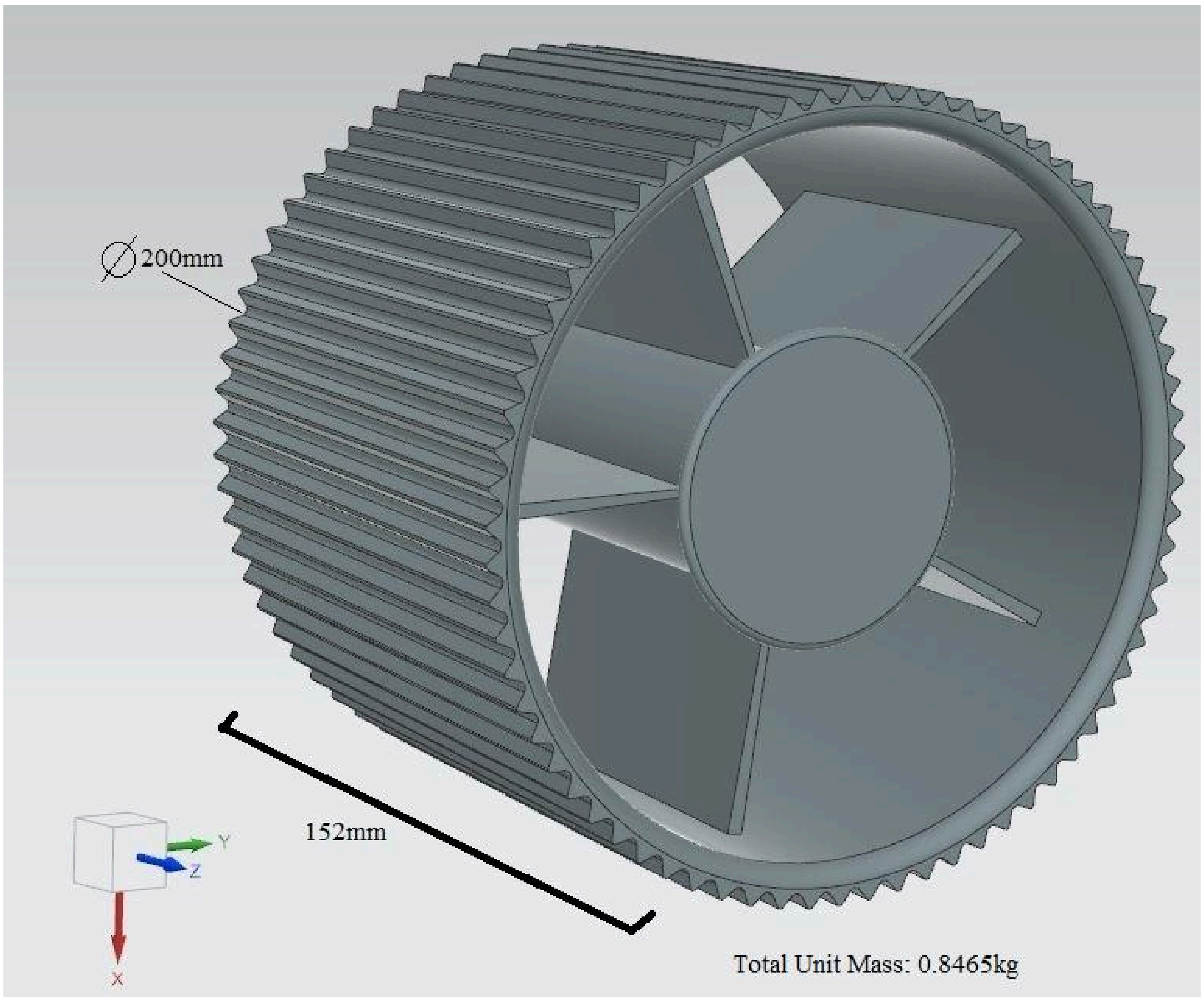


Figure 20: *Rover Wheel Design*

The wheels of the Rover are designed to produce traction as well as mobility. With four wheels on the Rovers body each wheel is made of carbon fiber and synthetic rubber for the treads. The dimensions of each wheel are 200mm diameter by 152mm wide to give more stability for the Rover while also keeping mass down. With each wheel having a mass of .8465kg it is important to keep the weight as low as possible due to multiple wheels being needed. This can quickly increase mass to the Rover. The materials chosen are to keep a high yield strength while keeping density as low as possible.

3.1.2.d. Suspension System.

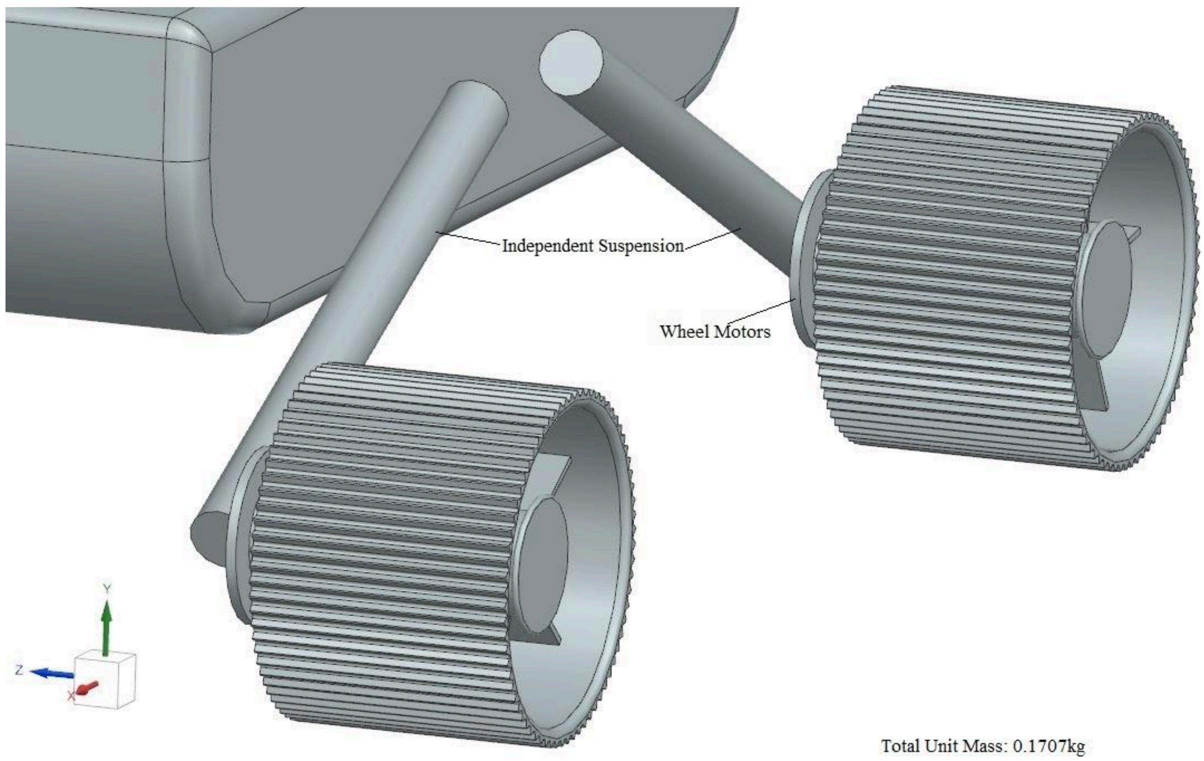


Figure 21: *Rover Suspension Design*

The independent front suspension of the Rover system allows for the Rover to adjust each wheel independently of the others. This system consists of electric actuators and air shocks to smooth out vibrations from driving on the rough ground. The linkages of each suspension arm also allows for the Rover to adjust its height for different operations tasks, to bring its center of gravity lower to ground for more stability, or to pass over large obstructions. The suspension structure consists of carbon fiber tubing containing the dampening system and connector joints that hold the electric motors. The motors used to drive and operate the suspension are the Maxon 108828 motors with four motors being used to drive each wheel.

3.1.2.e. Mechanical System Requirements

The mechanical system is designed to meet or exceed the set requirements for the system. With the mass of the mobility system being 7.08 kg, it does not exceed the mass given in the requirements as well as other components such as power consumption, and cost. The system is designed to overcome the expected rough steep terrain within the cave and give the Rover its mobility to operate.

3.1.2.f. Manufacturing Plans

Table 18: *Mechanical System, Manufacturing Plans*

Product Name	Material	COTS / In-House	Manufacturing Company	Start Manufacturing Phase	End Manufacturing Phase
Rover Body	Carbon Fiber	In-House	GSFC	C	D
Anchor Base	Aluminum 6063	In-House	GSFC	C	D
Tether Stand	Aluminum 6063	In-House	GSFC	C	D
Tether Spool	Carbon Fiber	In-House	GSFC	C	D
Tether	Multi-	In-House	JPL	C	D
Independent Suspension	Carbon Fiber	In-House	GSFC	C	D
Wheels	Multi-	In-House	GSFC	C	D
Motors	Multi-	COTS	Maxon	C	D

The manufacturing of each of these systems will be done in house due to the lack of availability of majority systems. Certain systems such as the wheels can be 3D printed with carbon fiber filament to shape the rims while the more complex equipment will have to be assembled in pieces to incorporate the individual motors, electronics, and dampeners. The time span of the manufacturing of these parts will begin in the third year with the fabrication of the test Rover for system verification. Skilled team members with the ability to fabricate and construct these items based on their respective CAD model designs will be needed to ensure fit and function of each part.

3.1.2.g. Integration Plan

The integration of the mechanical system takes place before all other systems. This is due to the base and initial structure of the Rover taking place. While systems such as power will occur at the same time due to the systems being closely connected. As the system is integrated, V&V is occurring to verify the operation and capability of each component.

3.1.2.h. Verification & Validation

Table 19: Mechanical System, Verification and Validation

Req #	Requirement	Verification Success Criteria	Verification Method	Result	Facility	Phase
MEC-0.1	The mechanical system shall not exceed a weight of 15 kg	1. Aggregate mass of system does not exceed indicated limit	Inspection		GSFC	B-D
MEC-0.2	The power consumption of the mechanical system shall not exceed 100 Watts	1. Driving motors consume 96 Watts	Test		GSFC	C-D
MEC-0.3	The cost of the mechanical system shall not exceed 5% of the total budget	1. Aggregate cost of components does not exceed indicated limit	Inspection		GSFC	B-C
MEC-0.4	The mechanical system shall provide a way of entering the cave	1. Egress system incorporates an anchor teether system to safely lower the Rover into the cave.	Demonstration		GSFC	C-D
MEC-0.5	The mechanical system shall provide a way of traversing the cave's terrain	1. Wheels powered by electric motors provide mobility of the Rover.	Demonstration		GSFC	C-D

MEC-0.5.1	The mechanical system shall have adequate traction to traverse sandy, rocky, and loose terrain	1. Wheels constructed from materials to provide traction to the rocky surface. 2. Wheels are widened to provide additional surface area.	Demonstration		GSFC	C-D
MEC-0.5.2	The mechanical system shall provide a method to maneuver over and around potential obstructions	1. Independent suspension provides the ability to increase/ decrease ground clearance. 2. Suspension maintains contact with ground and maintains the body parallel to the ground.	Demonstration		GSFC	C-D

Each of the mechanical systems will be tested and demonstrated in a simulated test environment of what will be expected within the cave. The egress system will be tested to verify that it can withhold the mass of the Rover as well as prove the anchoring process works as intended. The wheels can be simulated and tested to observe how much traction and stability is added to the structure of the Rover.

3.1.3. Power System Overview

This section describes the power system in depth. Firstly, an explanation will be given on the components of the power system, which includes the batteries, solar panel, and charging mechanism. Secondly, to aid in the discussion, the power consumption of all Rover components will be presented individually, then in groups depending on which components are active during each Rover mode. Following this, a timeline of Rover activities is provided, as well as graphs tracking the power consumption and battery level over time. Lastly, this section will discuss manufacturing plans, integration plans, and V&V procedures

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3.1.3.a. Power System Components

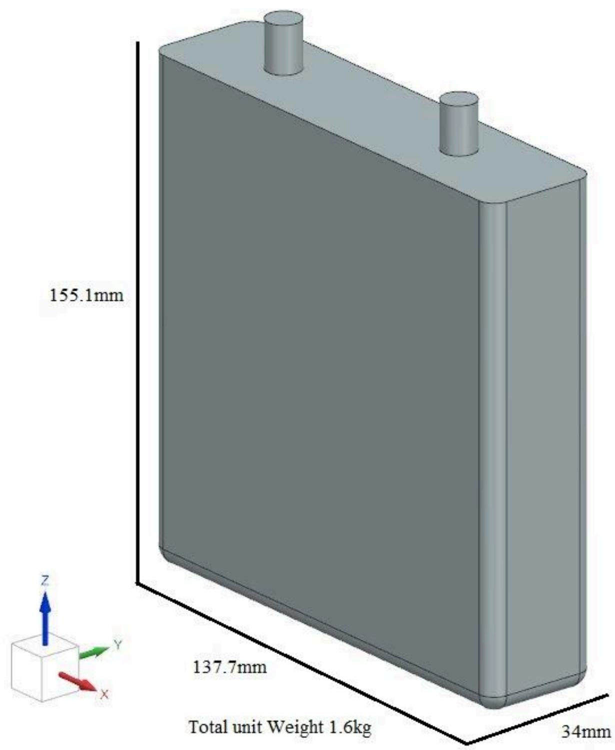

Figure 22: *Lithium-ion Battery Design*

The power system consists of a total of 7 lithium ion LP 33037 60Ah 4.1V batteries. Each battery has a volume of (137.7 x 34 x 155.1)mm and a mass of 1.6kg. Four batteries will be allocated to the Rover, while the remaining three will be allocated to the solar panel associated with the Egress subsystem. The Rover has a power supply of 984 Wh, while the solar panel has a power supply of 738 Wh. Each battery has the ability to discharge at a max rate of 250 A, and the ability to charge at a rate of 12 A.

The solar panel is (0.5800 x 0.6007)m and has an area of 0.348 m^2. This Rover uses the same solar cells as the Ingenuity helicopter, the IMM Space Solar Cell from SolAero. To predict the energy output of this mission's solar panel, the wattage per unit area of the IMM solar cell was predicted using Ingenuity's figures. Ingenuity's solar panel has an area of 0.434 m^2 and produces 350W [28]. Then, it can be inferred that the IMM solar cell produces around 4991 W/m^2. This mission's solar panel has an area of 0.348 m^2, so it produces 1736W every Martian day, or 144.7W for every hour of sunlight.

3.1.3.b. Rover Components

Below is a table displaying the power consumption of Rover components, as well as the battery capacity of the Rover and the solar panel.

Table 20: *Power Consumption of Rover Components and Battery Capacity*

Rover Components			
Power Consumption of Rover Systems		**Power Supply**	
Component/System	Power Consumption (W)	System (# of batteries)	Power Provided (Wh)
Supercam	17.9	Rover (4)	984
LiDAR	25	Egress/Solar Panel (3)	738
Motors (x16)	96		
UHF (**active**)	65		
UHF (**standby**)	15		
Main Computer	12		
Thermal System	48-77		

3.1.3.c. Rover Modes

In terms of power consumption, the Rover has three distinct modes: i) Data Collection, ii) Sending Data, and iii) Full Rest. The power consumption of each mode depends on the time of day, as that determines whether or not the thermal system needs to be active in order to maintain a stable temperature. This is explained in more depth in Section 3.1.6.

As shown in the table below, Data Collection is more efficient during night hours because the thermal system is not in use. Also, note the difference in power consumption of Full Rest and Sending Data. During day hours, this is 50W, but during night hours, this is only 1.4W. The opportunity cost of sending data during the day is much greater than it is during the night. Therefore, it is more reasonable to send data over night. This rationale is employed timeline seen in Section 3.1.3.d

Table 21: *Power Consumption of Rover Modes*

Rover Modes			
Data Collection Mode (**Day)**		Data Collection Mode (**Night)**	
Component/System	Power Consumption (W)	Component/System	Power Consumption (W)
Supercam	17.9	Supercam	17.9
LiDAR	25	LiDAR	25
Motors (x16)	96	Motors (x16)	96
UHF (**standby**)	15	UHF (**standby**)	15
Thermal System	76.4	Main Computer	12
Main Computer	12	**Total**	**165.9**
Total	**242.3**		
Rest Mode (Sending Data, **Day**)		*Rest Mode (Sending Data, **Night**)	
Component/System	Power Consumption (W)	Component/System	Power Consumption (W)
UHF (***active***)	65	UHF (***active***)	65
Main Computer	12	Main Computer	12
Total	**77**	**Total**	**77**
Rest Mode (Full Rest, **Day**)		Rest Mode (Full Rest, **Night**)	
Component/System	Power Consumption (W)	Component/System	Power Consumption (W)
UHF (***standby***)	15	UHF (***standby***)	15
Main Computer	12	Thermal System	48.6
Total	**27**	Main Computer	12
		Total	**75.6**

**Sending Data was split into two sub-tables despite consuming the same power for all hours. This was done simply to remain visually consistent with the rest of the table*

3.1.3.d. Rover Activity After Entry

Below is a table outlining what mode the Rover is in at any given hour. Note that the final column is time 24:40:00. This is because a Martian day is approximately 24 hours and 40 minutes on Earth. In truth, a Martian day is 24:37:22, but this was rounded for the sake of simplicity. To briefly explain, the Rover battery level increases when the Rover is drawing power from the solar panel. This can be seen in the table below, where battery level decreases during night and when the Rover is away from the skylight to collect data. Also, the solar battery level only increases when the Rover is collecting data because, at those points, the Rover is not charging or drawing power directly from the solar panel.

Table 22: *Rover Activity, Power Consumption, and Battery Level Timeline*

Rover Activity After Entry					
Time (hr)	Rover Status	Power Consumption (W)	Rover Battery Level (Wh)	Solar Battery Level (Wh)	Day/Night
1:00:00	Data Collection	165.9	130.7	738.0	Night
2:00:00	Sending Data	77	176.7	615.0	Night
3:00:00	Resting	75.6	224.1	492.0	Night
4:00:00	Resting	75.6	271.5	369.0	Night
5:00:00	Resting	75.6	318.9	246.0	Night
6:00:00	Resting	75.6	366.3	123.0	Night
7:00:00	Resting	27	462.3	0.0	Day
8:00:00	Resting	27	580.0	0.0	Day
9:00:00	Resting	27	697.8	0.0	Day
10:00:00	Resting	27	815.5	0.0	Day
11:00:00	Resting	27	933.3	0.0	Day
12:00:00	Resting	27	984.0	0.0	Day
13:00:00	Resting	27	984.0	117.7	Day

14:00:00	Resting	27	984.0	235.5	Day
15:00:00	Resting	27	984.0	353.2	Day
16:00:00	Resting	27	984.0	471.0	Day
17:00:00	Resting	27	984.0	588.7	Day
18:00:00	Resting	27	984.0	706.4	Day
19:00:00	Resting	75.6	908.4	738.0	Night
20:00:00	Data Collection	165.9	742.5	738.0	Night
21:00:00	Sending Data	77	665.5	738.0	Night
22:00:00	Resting	75.6	589.9	738.0	Night
23:00:00	Data Collection	165.9	424.0	738.0	Night
24:00:00	Sending Data	77	347.0	738.0	Night
24:40:00	Resting	75.6	296.6	738.0	Night
	Total	1556.7			

**Total power consumption is calculated by summing the previous 24 hours, then adding time 24:40:00 weighted accordingly*

When creating this timeline, two objectives were kept in mind: i) collect more solar power than the amount of power consumed in a day and ii) maximize hours of data collection per day. The first objective was deemed more important because the Rover's ability to fulfill the mission's science objectives is ultimately dependent on the duration of the mission. As a benchmark, the total power consumption throughout the day had to remain below 1736W, which is the power output of the solar panel in a day. It was important to design a timeline that makes efficient use of the power because the power output of the solar panel is expected to decrease over the duration of the mission due to dust accumulating on the surface of the solar cells.

The above timeline is visualized in the three graphs below. To summarize, the Rover spends all day hours resting to replenish its power supply. Then, during the night, it conducts data collection and makes occasional stops to the skylight entrance in order to send data and to briefly replenish its power supply using power collected by the solar panel during the day.

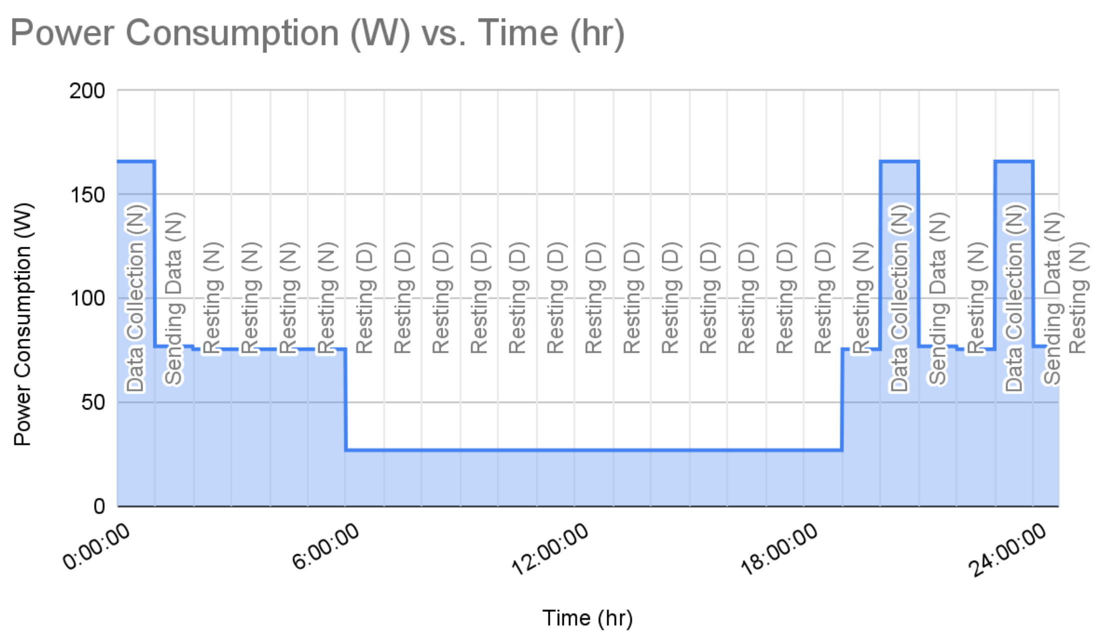

Figure 23: *Power Consumption vs Time*

This plot demonstrates the power consumption of the Rover throughout a single Martian day. The three spikes indicate the three hours of data collection. After each hour of data collection, the Rover will return to the skylight in order to send the data to the primary lander and rest in order to replenish its power supply. The graph plateaus during the day hours because the Rover no longer needs to employ the thermal subsystem to maintain a stable temperature.

The graph below illustrates the battery level of i) the Rover's battery bank and ii) the battery bank associated with the solar panel.

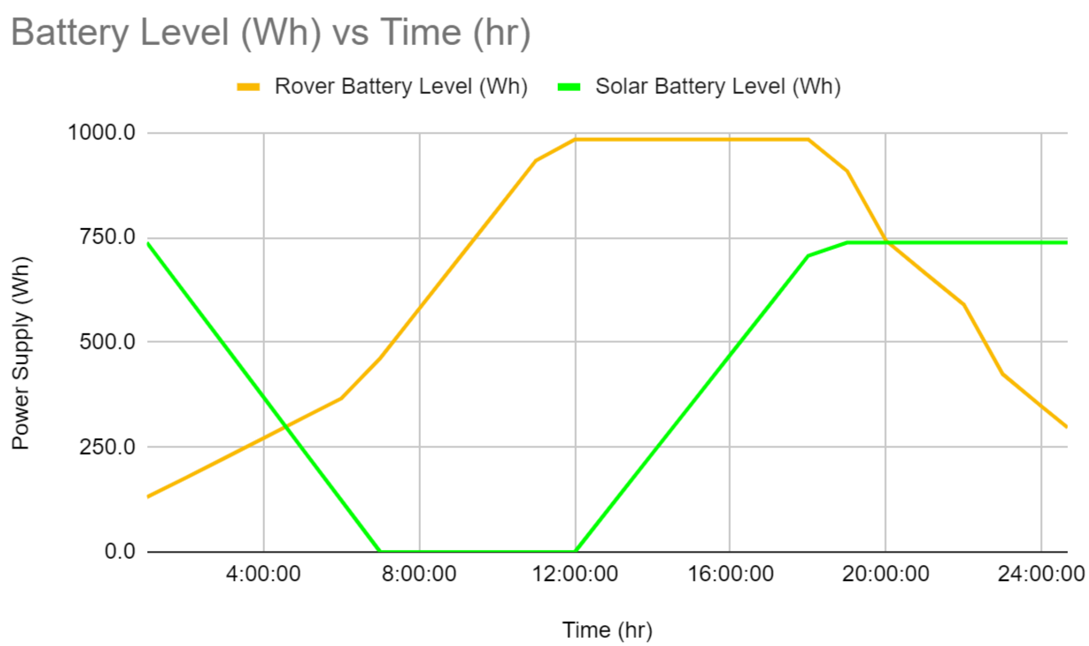

Figure 24: *Rover Battery Level vs Time*

As discussed previously, the Rover spends the night time conducting data collection within the lava tube. This can be seen in the downward trend of the yellow line during hours 20:00 - 24:00. From time 0:00 to 1:00, the Rover conducts its last hour of data collection and begins tapping into the battery bank associated with the solar panel. This is demonstrated by the downward trend of the green line and the upward trend of the yellow line from hours 1:00 to 7:00. Then, during day hours, the Rover uses the solar panel to first recharge its internal battery bank, then the external battery bank.

The graph below combines the two previous graphs into one visual. As in the previous graphs, the blue series is the Rover's power consumption, the yellow series is the Rover's battery level, and the green series is the solar bank's battery level.

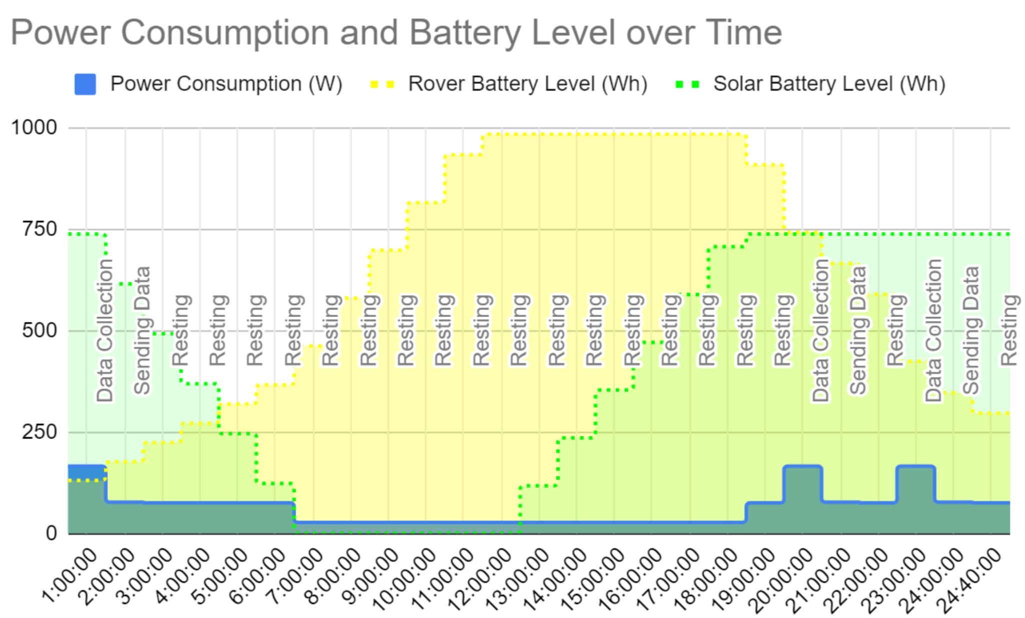

Figure 25: *Power Consumption and Rover Battery Level vs Time*

3.1.3.e. Manufacturing Plans

Table 23: *Power system, Manufacturing Plans*

Product Name	Material	COTS / In-House	Manufacturing Company	Start Manufacturing Phase	End Manufacturing Phase
Lithium-ion Cell 60Ah Space Cell	Lithium-ion	COTS	EaglePitcher Technologies	C	D
Space Solar Cell	Metamorphic N on P	COTS	SOLAERO Rocket Lab	C	D

The batteries used in the Rover are manufactured by the company EaglePicher Technologies and typically have a lead time of months before product delivery. The off the shelf solution was desired due to the testing and performance of these batteries shown in previous missions. As for the tether charger cable and connector they will have to be made in house at the manufacturing facility.

3.1.3.f. Integration Plans

The integration of the power system occurs at the same time as the mechanical system. The electrical connections and powering of all the systems requires the power system to be integrated at an earlier time than systems such as data handling and payload. The power systems integration will come after it V&V to ensure that the system will be able to withstand the mission conditions and no changes will be required.

3.1.3.g. Power System Requirements

The power system is designed to provide all power for the operation of the Rovers for the duration of the mission. To undergo this process it is critical that the power of the rove meet its specified system requirement. As defined in Table 2, it shows the need to keep the mass low and power density high for extending out the mission. The battery cells must also be able to handle the power demands of all other systems in the case all systems are active at the same time.

3.1.3.h. Verification and Validation

Table 24: *Power system, Verification and Validation*

Req #	Requirement	Verification Success Criteria	Verification Method	Result	Facility	Phase
POW-0.1	The total mass of the power system shall not exceed 7.0 kg	1. Aggregate mass of system does not exceed indicated limit	Inspection		GSFC	B-D
POW-0.2	The power system shall provide energy to each subsystem	1. Battery bank provides <200 Watts	Test		GSFC	C-D
POW-0.2.1	The power system shall provide enough energy to sustain the system for a minimum of 3 days	1. Battery bank shall have a energy capacity of < 200 Watts 2. Battery charging system produces 180W/hr	Test		GSFC	C-D
POW-0.2.1.1	While in active mode, the power system shall provide sufficient energy to each subsystem	1. Battery Bank shall have a capacity of <200 Watts 2. Battery cells shall have a max discharge rate of 200A	Test		GSFC	C-D
POW-0.2.1.2	While in rest mode, the power system shall provide sufficient energy to maintain the vehicle's operating temperatures	1. Battery bank shall provide power to CHD and Thermal distribution system to maintain operational temperatures.	Test		GSFC	C-D
POW-0.3	The cost of the power system shall not exceed 10% of the total budget	1. Aggregate cost of components does not exceed indicated limit	Inspection		GSFC	B-C

Each of the systems will be tested in a demonstration to test and prove the ability of the power system to undergo the mission. Placing the battery cells within a simulated power consumption and environmental condition it will be seen if the batteries will be able to handle the conditions for the mission. This simulation can also be used for the verification of the solar panel to charge the batteries and maintain power for the duration of the mission.

3.1.4. Communication Overview

3.1.4.a. Antenna system

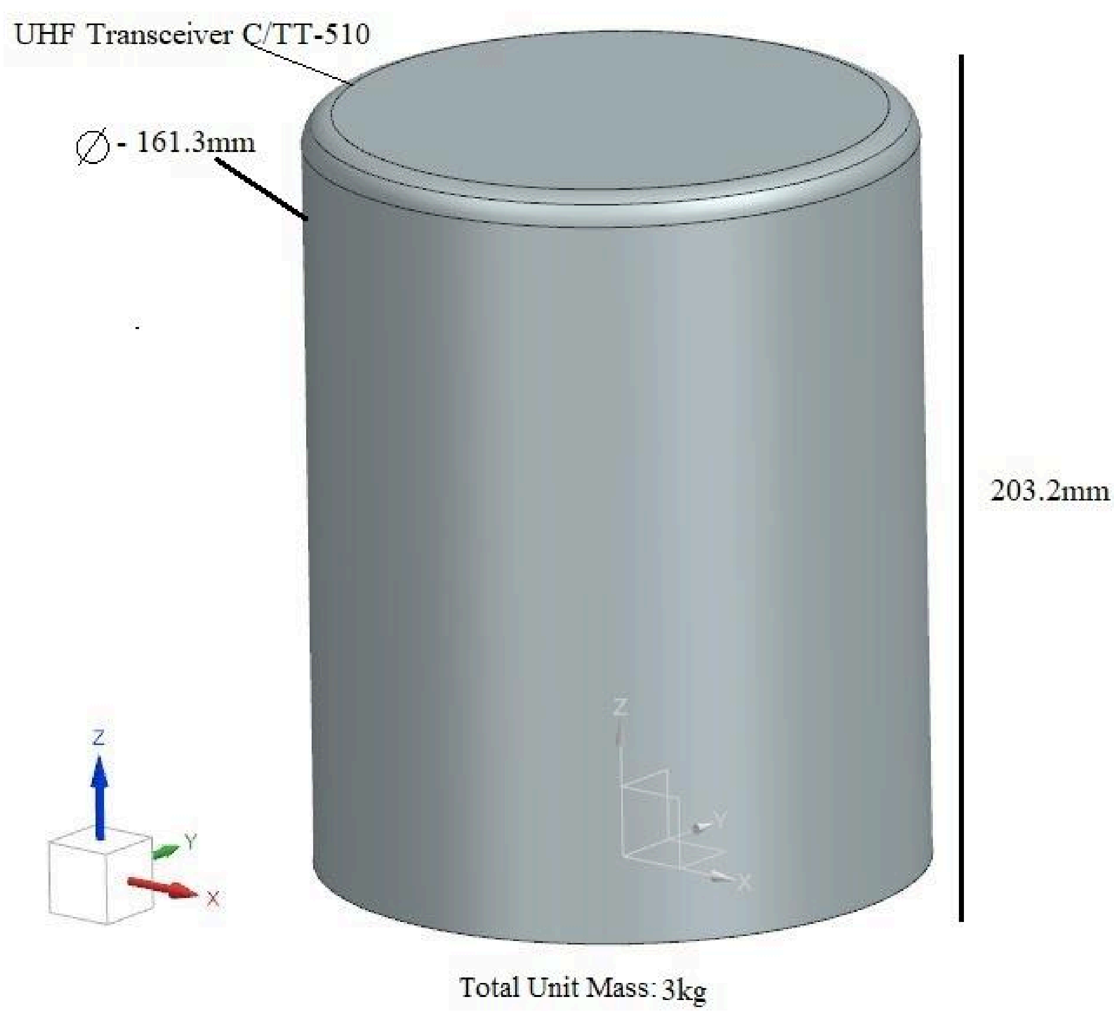

Figure 26: *UHF Transceiver Design*

For communication between the Rover and the primary lander a high powered UHF transceiver was chosen. The C/TT-510 Electra-Lite UHF transceiver was chosen as it is a legacy system used in previous Rovers with high ability to communicate large data to midway points such as to the primary lander. This transceiver operates in a high frequency band of 390 to 450 MHz allowing for the avoidance of noise from entering the signal. With a small footprint the transceiver holds a volume of (Dia 161.3 x 203.2)mm. The power consumption of the system is 65w when in operation and 15w when in standby mode. The unit can send 1 to 10 Mbps of data back to the primary lander allowing for the data to be collected and transmitted during planned stopping points. [25]

3.1.4.b. Communication Requirements

The requirements for the communication systems were implemented to ensure communication between the Rover and the primary lander. With design challenges due to environmental conditions special care must be considered when picking and designing the system. Power consumption, mass, and cost are significant factors that affect the system farther reaching signals typically require more power. The high loads of data that will need to be sent and received by the Rover also requires the system to operate fully as expected.

3.1.4.c. Manufacturing Plans

Table 25: Communication System, Manufacturing Plans

Product Name	**COTS / In-House**	**Manufacturing Company**	**Start Manufacturing Phase**	**End Manufacturing Phase**
(C/TT-510) ELECTRA-LITE UHF Transceiver	COTS	L3HARRIS	C	D

The manufacturing of the C/TT-510 Electra-Lite will be accomplished by the manufacturer L3Harris. The supply of this UHF transceiver allows for orders to be placed with a few months of lead time for delivery of the component. The off self option was considered best as the component is a legacy item that has been previously used on past Rovers showing competence in use in harsh environments.

3.1.4.d. Integration Plan

The communication systems integration occurs after the mechanical, and power and data handling systems have been integrated together. The attachment of the communication system to the rest of the Rover will allow for the system to be tested in the V&V with the Rover's own power sources. This method will allow the communication system to be integrated and proven within its ability of operation and to further test others systems ability to operate as intended.

3.1.4.e. Verification & Validation

Table 26: *Communication System, Verification and Validation*

Req #	Requirement	Verification Success Criteria	Verification Method	Result	Facility	Phase
COMM-0.1	The Communication system shall not exceed 4kg	1. Aggregate mass of system does not exceed indicated limit	Inspection		GSFC	B-D
COMM-0.2	The power consumption of the Communication system shall not exceed 75 Watts	1. The UHF transceiver consumes 65 Watts in operational mode 2. UHF transceiver consumers 15 Watts in standby mode	Test		GSFC	C-D
COMM-0.3	The cost of the Communication systems shall not exceed 8% of the total budget	1. Aggregate cost of components does not exceed indicated limit	Inspection		GSFC	B-C
COMM-0.4	The Communication system shall maintain contact with the primary lander	1. Transceiver communicates with responder from a minimum distance of 150m	Test		GSFC	C-D

COMM-0.4.1	The Communication system shall provide a method of communicating with the primary lander while inside the cave	1. Transceiver produces A high frequency data wave to overcome signal loss.	Test		GSFC	C-D
COMM-0.4.2	The Communication system shall deliver instrument data to the primary lander	1. Transceiver must have upload data rate of <5 mbps	Test		GSFC	C-D
COMM-0.5	The Communication system shall receive instrument data from the CDH system	1. Transceiver must have download data rate of <5mbps	Test		GSFC	C-D

V&V of the Rovers communication system will be completed by the use of testing the communication to simulate high data loads at great distances. Since the primary mission will be within the lava tube below the surface the communication system will require power to communicate with the primary lander located at the mouth of the skylight. By testing in a simulated environment to verify data can be sent and received without corruption to the signal will be key to ensuring success for the mission.

3.1.5. Data Handling and Controller Overview

3.1.5.a. Data Controller

Figure 27: *RAD750 3U CompactPCI [29]*

The RAD750 is the Rovers primary avionics board controlling all aspects of the Rovers systems. Special features integrated into this single board computer is its radiation hardened protection allowing its use in hazardous missions. The board is capable of processing data as well as integrated with real time data observation. Linking live data from systems such as thermal management gives the controller the ability to self monitor and respond to needed changes from within the system. Due to the high importance of this controller two will be installed within the Rover to act as a redundant system in case on board fails.

3.1.5.b. Data Handling and Control Requirements

The data handling and controller for the Rover must not exceed a weight of 4kg as well as have a high power consumption. The RAD750 board operates at a 12.2W power consumption allowing for a low demand and high advantage controller integrated to connect all other systems together. The data handling of the RAD750 must be able to process data collected by instrumentation as well as live data from within the Rovers subsystems and appropriately interpret and handle the data. Data that needs to be collected and stored for the rest phaze shall not be corrupted and be sent to the communication system for transmitting out.

3.1.5.c. Manufacturing Plans

Table 27: *Data/ Control Manufacturing plan*

Product Name	Material	COTS / In-House	Manufacturing Company	Start Manufacturing Phase	End Manufacturing Phase
RAD750 3U CompactPCI	Circuit board	COTS	BAE Systems	C	D

The RAD750 board is a special equipment controller that can be produced for the mission upon ordering. The board itself has been used in many past Rover missions and has proven itself capable for the Rovers mission. Due to the Rover requiring two of these boards an order will need to be placed as early as possible. This is also due to the need of an additional two boards for the use within the prototype test Rover to prove its ability.

3.1.5.d. Integration Plan

The integration of the data & command system will take place after the power and mechanical system has been integrated. The data and command system as it is integrated will be connected to the past integrated system to allow for communication. The primary function of verifying communication between all systems will take place in parts as new systems get added and tested. The V&V process will take place at the same time as new systems get added.

3.1.5.e. Verification & Validation

Table 28: *Command & Data Handling, Verification and Validation*

Req #	Requirement	Verification Success Criteria	Verification Method	Result	Facility	Phase
CDH-0.1	The Command & Data Handling system shall not exceed 1 kg	1. Aggregate mass of system does not exceed indicated limit	Inspection		GSFC	B-D

CDH-0.2	The power consumption of the Command & Data Handling system shall not exceed 15 Watts	1. Command & Data Handling does consume more than 15 Watts	Test		GSFC	C-D
CDH-0.3	The cost of the Command & Data Handling system shall not exceed 8% of the total budget	1. Aggregate cost of component does not exceed indicated limit	Inspection		GSFC	B-C
CDH-0.4	The Command & Data Handling system shall allow the vehicle to operate autonomously	1. The component must be self evaluating in cases of no communication	Demonstration		GSFC	C-D
CDH-0.4.1	The Command & Data Handling system shall have the ability to receive and act on teleoperated commands	1. The component must have communication between Navigation instruments and process data based on software guidance	Demonstration		GSFC	C-D
CDH-0.4.2	The Command & Data Handling system shall communicate the navigation plans to the mechanical system	1. The component must have communication between itself and the mechanical system	Test		GSFC	C-D
CDH-0.5	The Command & Data Handling system shall be able to send commands to each major subsystem	1. The component must have communication between all major subsystems	Test		GSFC	C-D
CDH-0.5.1	The Command & Data Handling system shall send commands to the PAY system as needed by operational procedures	1. The component must have communication to the PAY systems for data collection	Demonstration		GSFC	C-D
CDH-0.5.2	The Command & Data Handling system shall send the cave mapping from PAY to NAV system	1. The component must have communication and process the data from PAY for deliverance to NAV system	Demonstration		GSFC	C-D
CDH-0.6	The Command & Data Handling system shall collect data and other telemetry from each subsystem	1. The component must be able to perform telemetry checks for each system	Test		GSFC	C-D
CDH-0.6.1	The Command & Data Handling system shall gather telemetry from the instrumentation	1. The component must be able to perform telemetry and calibration of instruments	Test		GSFC	C-D

CDH-0.6.2	The Command & Data Handling system shall collect data on the thermal state of each subsystem	1. The component must act as a thermal management system to verify internal temperatures and control heating and cooling operations	Test		GSFC	C-D
CDH-0.6.3	The Command & Data Handling system shall receive navigation plans from the NAV system	1. The component shall have communication from the NAV system	Test		GSFC	C-D
CDH-0.7	The Command & Data Handling system shall have the ability to send telemetry to other subsystems	1. The component shall be able to send data to all subsystems that requires inputs from other systems	Test		GSFC	C-D
CDH-0.7.1	The Command & Data Handling system shall deliver instrument data to the COMM system	1. The component shall be able to send data collected from instrumentation to the COMM system for data send back	Test		GSFC	C-D
CDH-0.7.2	The Command & Data Handling system shall communicate the thermal state of each subsystem to the Thermal system	1. The component shall be able to verify internal temperatures and report system health to thermal system	Test		GSFC	C-D

The V&V for the data & command system shall be accomplished by the use of testing and observation of the system's ability to meet all set requirements. The RAD750 must be able to support the Rover in its ability to collect the data from the instruments and deliver it to the communication for delivery to the primary lander. The testing will show that the RAD750 has open communication throughout all systems of the Rover to ensure proper data collection and commanding of each system can occur.

3.1.6. Thermal Management System Overview

3.1.6.a. Thermal Electric Heaters

Figure 28: *Silicone Heating Patches [18]*

Thermal Management is accomplished by the use of the thermal management system and the data handling system. The data handling device RAD750 3U compactPCI has the ability to monitor and repeatedly check system component temperature through the use of thermoresistors. This monitoring of each system will allow for the data handler to ensure that the Rover is maintaining operational temperature. When the temperature becomes too low within the Rover the data handle sends the information to the thermal management system indicating heat must be added to the Rover. The method of applying heat to each system will be accomplished by the use of silicone rubber heaters. These heaters are applied directly to the system and can produce temperatures as high as 200 °C. The heater elements produce heat with regards to power consumed with a maximum voltage of 600v. Each patch has a max Watt density of 9.30 W/cm^2. These patches also come in a variety of shapes and sizes allowing for custom application to systems. When conditions within the Rover become too hot a cooling system can be used to bring the temperature within lower. The use of a dedicated cooling panel located on the side of the Rover can be used to remove heat from within and expel it to the much colder air outside. The cooling of the system will be accomplished by the use of contact cooling that connects all systems to copper air cooling channels. These channels lead to the cooling panel where when connected allows the heat to be drawn out of the systems and expelled through the panel. [18]

3.1.6.b. Thermal System Requirements

The thermal system is intended as a key system for maintaining operations. The ability to heat and cool the Rover are needs that must be met as well as allowing for stability of temperature within the Rover. The system should be flexible and size variable to accommodate the different system sizes seen throughout the Rover while still maintaining costs below the 5% range of the budget.

3.1.6.c. Manufacturing Plans

Table 29: *Thermal System, Manufacturing Plan*

Product Name	COTS / In-House	Manufacturing Company	Start Manufacturing Phase	End Manufacturing Phase
Silicone Rubber Heaters	COTS	Thermo Heating Elements LLC	C	D

The heating portion of the thermal system can be manufactured by the outside company Thermo Heating Elements LLC. These silicone patches are designed and form fit their intended applications requiring the customer to provide dimensions for manufacturing. The lead time of these heaters is much shorter than other systems giving a fast production time to implement the heating system. For the cooling system, it will be developed and manufactured in house within the manufacturing facility. Due to components of the cooling system being part of the Rovers body, it would be impossible to outsource the manufacturing of the system as a whole. The other issue is with placement of each system as the placement of each would affect the fabrication of the cooling channels.

3.1.6.d. Integration Plan

The Integration of the thermal system will be last after all previous systems have been installed. This is to properly add thermal protection to all components and allow for testing of the thermal system. The system itself will be form fitted to each component to fit size and need. The V&V of the thermal system will occur when the system is integrated and testing can begin in simulated environments.

3.1.6.e. Verification & Validation

Table 30: *Thermal Management System, Verification and Validation*

Req #	Requirement	Verification Success Criteria	Verification Method	Result	Facility	Phase
THM-0.1	The thermal system shall not exceed a weight of 2 kg	1. Aggregate mass of system does not exceed indicated limit	Inspection		GSFC	B-D
THM-0.2	The power consumption of the thermal system shall not exceed 50 Watts	1. Thermo-Electric heaters consumes 40 Watts	Test		GSFC	C-D
THM-0.3	The cost of the thermal system shall not exceed 5% of the total budget	1. Aggregate cost of components does not exceed indicated limit	Inspection		GSFC	B-C
THM-0.4	The thermal system shall maintain vehicle's operating temperatures throughout the duration of the mission	1. Thermal-Electric heaters maintain internal temperatures with +-5 degrees Celsius of operation temperatures.	Demonstration		GSFC	C-D
THM-0.4.1	The thermal system shall maintain a temperature within the range [-40 C, 40C]	1. Heaters add heat to the system increasing or maintaining temperature 2. Coolers remove heat or maintain temperature	Demonstration		GSFC	C-D
THM-0.4.2	The internal temperature of any given subsystem shall not deviate from its operating temperature by more than +-5 degrees Celsius	1. Thermal distribution system shall monitor internal system temperatures and accurately indicate temperature and systems thermal needs.	Demonstration		GSFC	C-D
THM-0.4.3	The thermal system shall generate heat to sustain operating temperatures during operations	1. Heaters shall be able to increase internal heat when exposed to lowest possible temperature of -113 Celsius.	Test		GSFC	C-D
THM-0.4.4	The thermal system shall receive telemetry on the thermal state of each subsystem from the CDH system	1. Communication verification CDH system and Thermal system	Demonstration		GSFC	C-D

The thermal management system can be verified and validated by the use of computer simulation and demonstration. By simulating cold or hot environments, the system can be tested and observed at how efficient it can add or remove heat.

3.1.6.f. Expected Thermal Conditions and Heat Flow Maps

Recall from the previous subsection that the Rover's operating temperature is [233K, 313K]. The site is expected to have an average day-time temperature of 240K and an average night-time temperature of 150K (this is discussed further in Section 3.1.8). These favorable temperatures allow the Rover to remain within its operating temperature without the use of the thermal system in most scenarios. As previously discussed in Section 3.1.3.c, there are essentially six distinct thermal scenarios (3 Rover modes, 2 times of day). The Rover's mode determines its power consumption, and thus, the heat generated by its electrical components. It was assumed that for every Watt the electrical components consume, one Watt of heat is generated. The time of day determines environmental temperature.

The following graph compares the heat lost to the environment to the heat generated by the electrical components during each mode. When heat lost is equal to heat generated, the Rover is able to maintain a stable operating temperature without the need for the thermal system. In the graph below, this is seen when a curve intersects with a horizontal line. To explain the plots on the graph further, the orange and blue curves denote the heat lost to the environment as a function of the Rover's temperature. The functions for the two curves in the graph below are:

$$Q_{out,\,day}(T_V) = \epsilon\sigma FA({T_v}^4 - 240^4) + \frac{A}{\Sigma R}(T_V - 240)$$

$$Q_{out,\,night}(T_V) = \epsilon\sigma FA({T_v}^4 - 150^4) + \frac{A}{\Sigma R}(T_V - 150)$$

The above formulas are discussed in further detail in the paragraphs following the heat flow maps, but to offer some explanation, heat is primarily lost through radiation and conduction. Here, 240K is the day-time average temperature, while 150K is the night-time average temperature.

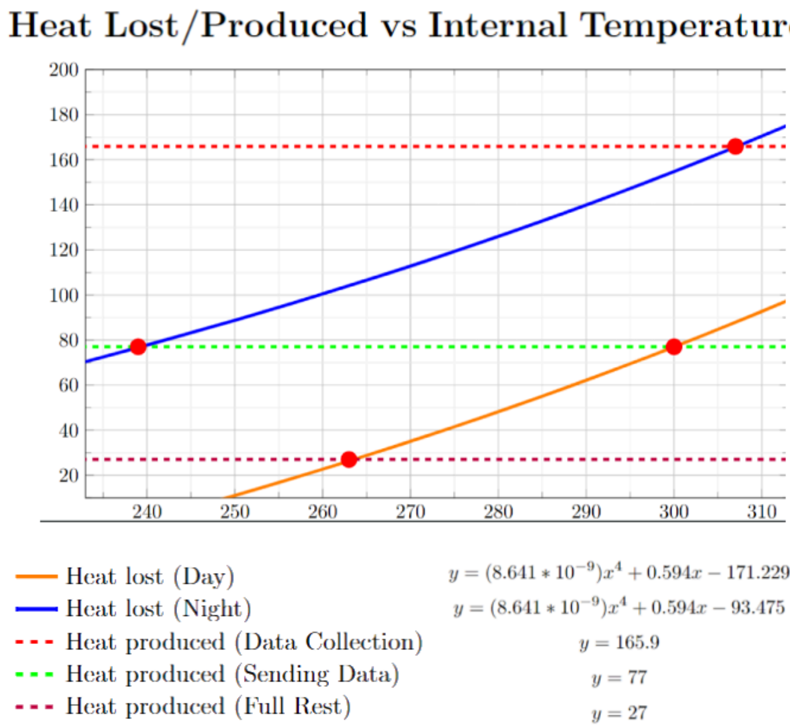

Figure 29: *Heat Lost and Heat Generated by Rover*

As explained earlier, the blue and orange curves describe the outward heat flow as a function of the Rover's temperature. The three horizontal lines describe the heat generated by the electrical components during each mode, as described in Section 3.1.3. To reiterate, Data Collection consumes 165.9W, Sending Data consumes 77W, and Full Rest consumes 27W. When any of the horizontal lines intersect with the curve, it indicates that the Rover can stay within its operating temperature without using the thermal system. For example, at point (307, 165.9), the Rover generates heat at 165.9W, but it is also losing heat at 165.9W. This indicates that the Rover is at a stable temperature at 307K when conducting Data Collection during night hours. Therefore, as shown by the graph, the Rover can maintain a stable temperature in four scenarios:

- Day: Full Rest, Sending Data
- Night: Sending Data, Data Collection

The thermal system only needs to be used during:

- Day: Data Collection
- Night: Full Rest

The following heat flow maps illustrate the two scenarios in which the thermal system must be used to maintain a stable temperature.

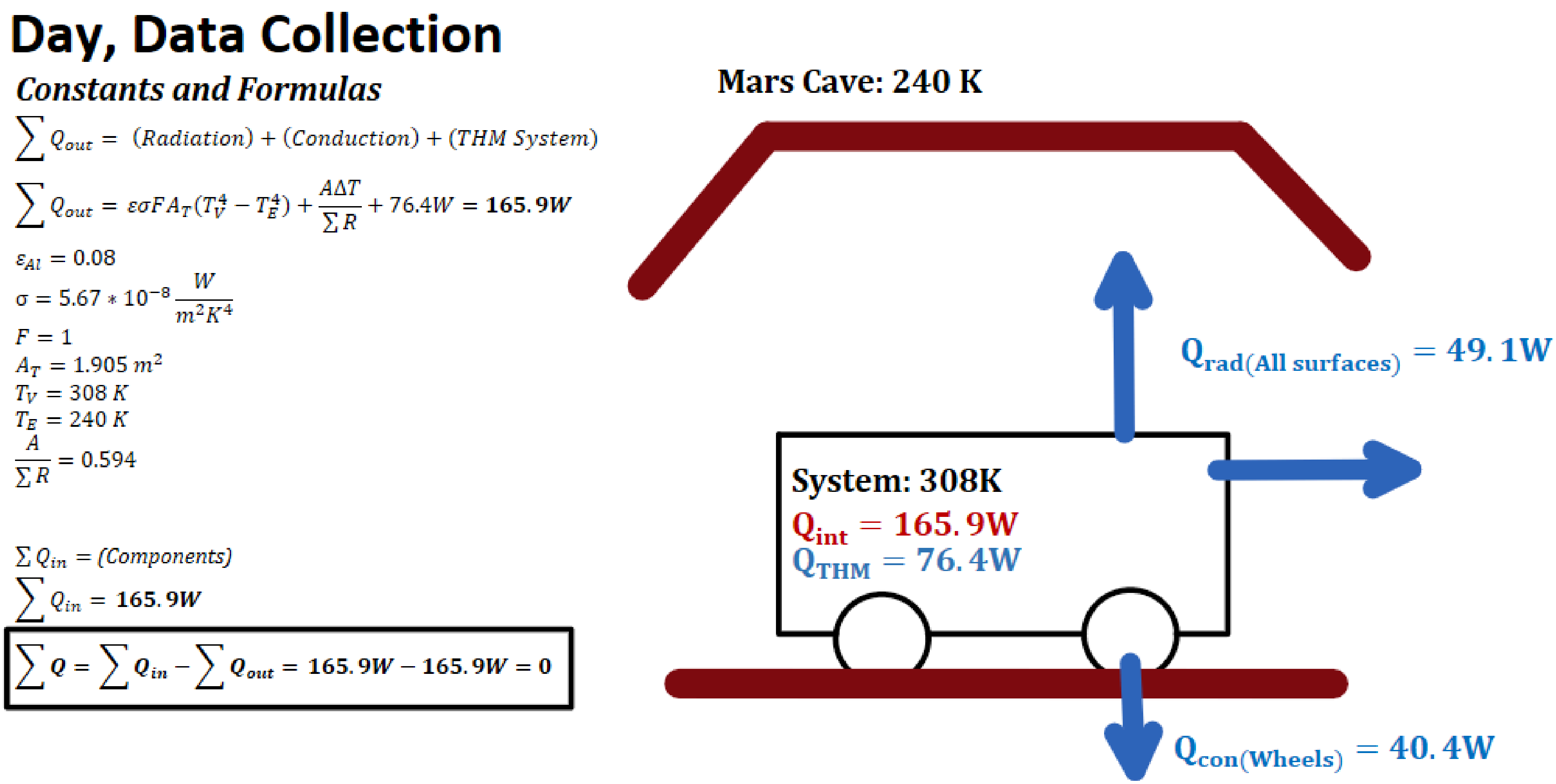

Figure 30: *Heat Flow Map of Rover in Data Collection Mode during the day*

Night, Rest

Constants and Formulas

$$\sum Q_{out} = (Radiation) + (Conduction)$$

$$\sum Q_{out} = \varepsilon\sigma F A_T(T_V^4 - T_E^4) + \frac{A\Delta T}{\sum R} = \mathbf{75.6W}$$

$\varepsilon_{Al} = 0.08$

$\sigma = 5.67 * 10^{-8}\frac{W}{m^2K^4}$

$F = 1$

$A_T = 1.905\ m^2$

$T_V = 238K$

$T_E = 150K$

$\frac{A}{\sum R} = 0.594$

$\sum Q_{in}$ = (Components)+(THM System)

$$\sum Q_{in} = 27W + 48.6W = \mathbf{75.6W}$$

$$\boxed{\sum Q = \sum Q_{in} - \sum Q_{out} = 75.6W - 75.6W = 0}$$

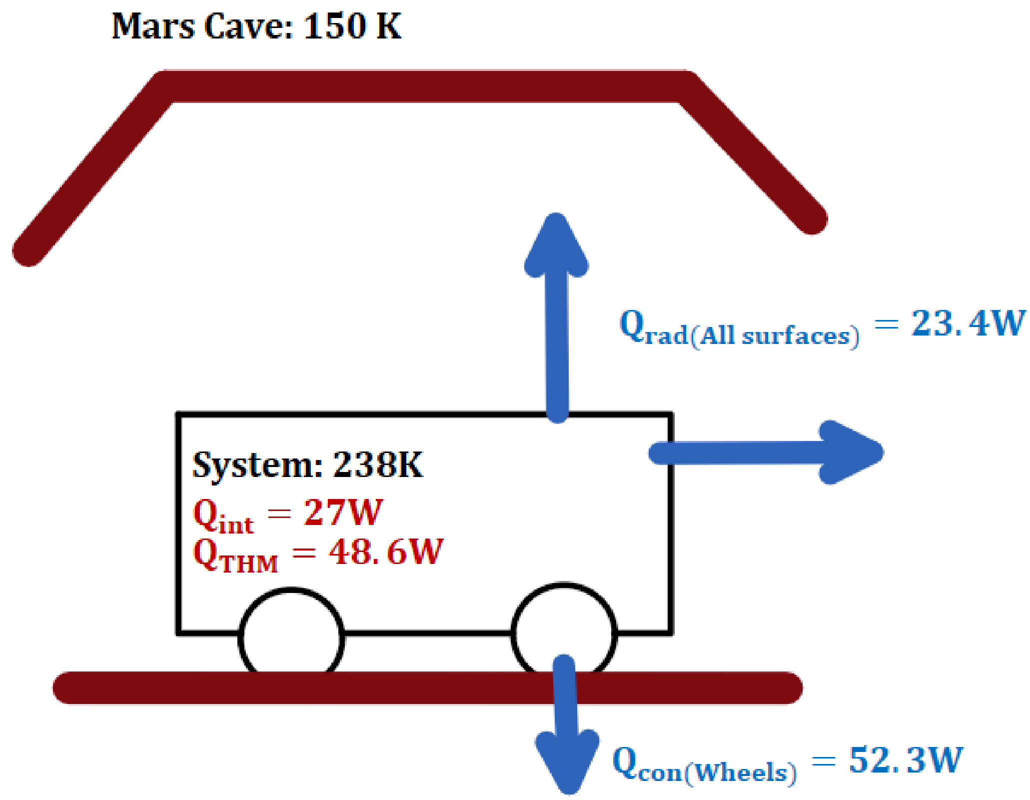

Figure 31: *Heat Flow Map of Rover in Full Rest during the night*

3.1.6.g. Constants and Formulas

When calculating the heat lost to radiation, the emissivity of Polished Aluminum Alloy 75ST was used, which is 0.08. Sigma denotes the Stefan-Boltzmann constant, which is $5.67 * 10^{-8} W/(m^2 K^4)$. The view factor, *F*, was taken to be 1 because the Rover spends the majority of the mission below the surface, surrounded by the terrain of the cave. Through NX, the Rover's surface area *A* was determined to be 1.905m^2. The term $Q_{rad(All\ surfaces)}$ was calculated by considering the heat lost to radiation across all surfaces of the Rover. This was done with the assumption that the cave's roof is around the same temperature as the cave's floor.

When calculating the heat lost to conduction, the following formulas were used:

$$Q_{con} = \frac{A\Delta T}{\Sigma R} \quad (1)$$

$$\Sigma R = \Sigma \frac{l_n}{k_n} \quad (2)$$

Formula (1) gives the heat lost to conduction when conduction occurs through multiple materials. Formula (2) determines ΣR, which can be thought of as the combined resistances of the materials. Here, l_n denotes the length of material n, and k_n denotes the conductivity of the same material n. In this case, conduction occurs through a wheel made of carbon fiber($k = 1000\ W/(mK),\ l = 0.200m$) with rubber padding ($k = 0.5W/(mK),\ l = 0.020m$). Thus, ΣR was taken to be $0.0402K/W$. The A term in (1) denotes the contact patch of the four wheels. A single wheel was estimated to have a contact patch of around $0.006m^2$. Simplifying these constants, the term $\frac{A}{\Sigma R}$ can thus be taken to be $0.597\ W/K$.

As shown by the heat flow maps, the thermal system needs to be able to dispel heat at a rate of 76.4W when the Rover is collecting data during the day, and to generate heat at a rate of 48.6W when the Rover is resting during the night. Per the timeline in Section 3.1.3, the Rover will not be conducting data collection during the day. However, the thermal system may still need to use its cooling capabilities to adjust for unexpected conditions during the mission. Lastly, as discussed in the beginning of this section, the heating pads used by the thermal system have a max Watt density of 9.30 W/cm^2. Therefore, the system will be able to generate sufficient heat

3.1.7 FMEA and Risk Mitigation

Vehicle and System Design Risk Summary

Table 31: *Mission Risk Evaluations*

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Mobility system is damaged during ascension or descension of lava tube	1	4	**→ - unchanged**	R	The system is being designed to travel within a Martian lava tube for a distance of 20m. With the inability to move the objectives of the mission will not be achievable.	R
2	System losses communication with communication satellite	2	3	**→ - unchanged**	R	If communication is lost with the system all data collected will be lost. With no communication to the system direction can no longer be sent bringing risk of loss of system.	M
3	Rover is damaged upon egression into lava tube	2	3	**→ - unchanged**	R	Upon descent from skylight the system will experience a sharp change in altitude giving risk of fall and damage to the equipment and sensors.	R
4	Power system is damaged due to environmental conditions	1	2	**↓ - Decreasing (improving)**	R	Damage to power cells during operation can affect the available power within the system causing a reduction in mission duration.	A
5	Instruments and internal components exceed operating temperature	1	5	**↓ - Decreasing (improving)**	R	Damage to the batteries, electronics and computer can cause the system to not function as well or at all.	W
6	Difficulty with generating power within martian cave	1	3	**↓ - Decreasing (improving)**	R	If the power system is not able to generate sufficient power for the rest of the systems, then the mission will not be able to continue.	W
7	Instruments are damaged by the environment.	1	3	**↓ - Decreasing (improving)**	R	Damage to instruments during a mission will affect the performance of data gathered.	W

L = Likelihood (1-5)	**LxC Trend**	**Approach**	**Criticality**
1 = not likely	**↓ - Decreasing (improving)**	A - accept	**HIGH**
5 = extremely likely	**↑ - increasing (worsening)**	M- mitigate	**MED**
C = Consequence (1-5)	**→ - unchanged**	W - watch	**LOW**
1 = low consequence	**NEW - added this month**	R - research	
5 = high consequence			

Table 32: *Mission Risk Mitigation and Evaluation*

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention
Communication system is damaged to a point where Rover cannot communicate with primary lander, satellite or back to Earth.	UHF/Tether is damaged.	Earth will not receive any data in return	100	Damaged by fall during egress, and/or environmental damage	20	Encase the UHF and tether in durable materials.
	LiDAR and/or communication link is damaged and inoperable.	Rover will need to depend on autonomous decisions.	70	Damaged by fall during egress, and/or environmental damage	20	Encase the LiDAR and communication link in durable material. Fine tune autonomous system and avoid obstacles.
	SuperCam and/or communication link is damaged and inoperable.	Rover will need to depend on autonomous decisions. May not be able to gather scientific data.	70	Damaged by fall during egress, and/or environmental damage	20	Encase the LiDAR and communication link in durable material. Fine tune autonomous system and avoid obstacles.
Mobility/mechanical system is damaged to the point where the Rover is considered to be immobile.	Rover body becomes dented and/or impaled.	Internal components may be damaged and cause further failure	80	Damaged by fall during egress, and/or environmental damage	20	Fine tune autonomous system and avoid obstacles.
	One or more wheels are very damaged.	Rover may be deemed immobile and end the mission at that point.	95	Damaged by fall during egress, and/or environmental damage	20	Fine tune autonomous system and avoid obstacles.
	One or more leg suspensions are extremely damaged,	Rover may be deemed immobile and end the mission at that point.	95	Damaged by fall during egress, and/or environmental damage	20	Fine tune autonomous system and avoid obstacles.
Thermal management system (TMS) is unable to keep all instruments and other systems in their respective operating temperature.	Power is depleted.	Mission timeline would be decreased.	100	More than expected power is used.	90	Reduce power consumption of components when they're not needed.

	TMS is damaged	Internal components and science instruments will reach extreme temperatures and become inoperable.	95	TMS is damaged	20	Ensure TMS is durable.

3.1.8. Performance Characteristics and Predictions

During the course of its mission, the Rover will be exposed to extreme conditions. When designing the Rover, the conditions at the Martian landing site CC0769 (Figure 32) were analyzed to give some forewarning about what would come.

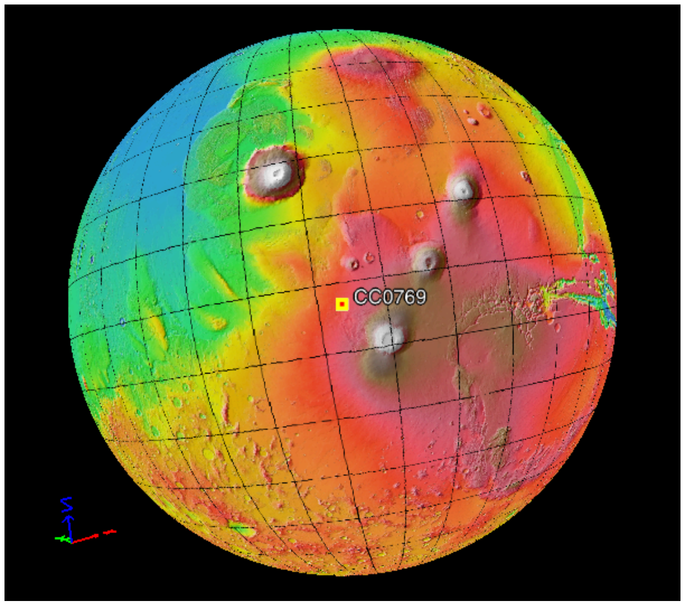

Figure 32: *Global position of site CC0769, per JMARS*

Site CC0769 is located in the Tharsis region, which is just below Mars' equator. The site's proximity to the equator lends to higher temperatures, which the mission seeks to take advantage of in order to decrease the burden on the thermal management system. However, these extreme temperatures also increase the likelihood of dust storms. To best avoid these dust storms, the summer and fall seasons were deemed undesirable even though they would provide the highest temperatures helping with keeping the Rover stay in operating temperatures. Similarly, the winter and early spring seasons were deemed too cold and possibly too much for the thermal system to handle, causing failure of components. With this in mind, a launch date of November 24th, 2026 was decided upon with the mission beginning on the Mars surface July 6th, 2027. At this time of year, Mars is transitioning from winter to summer, meaning average daily temperatures are increasing (Figure 33). The expected temperature range for this time of year was estimated to be [150K, 290K] (Figure 34), giving an advantage to the thermal system and requiring less demand for electrical power.

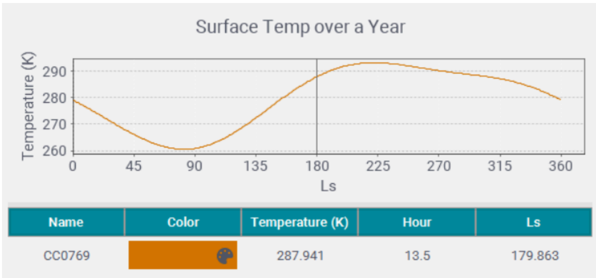

Figure 33: *Yearly surface temperature of CC0769, per JMARS KRC Layer*

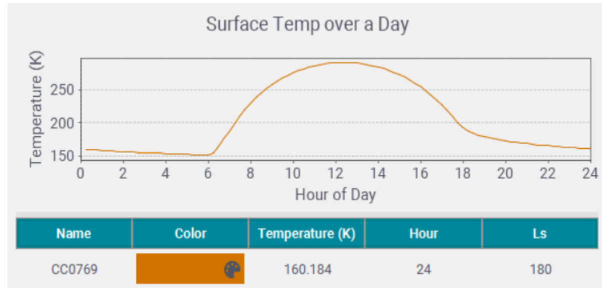

Figure 34: *Daily surface temperature of CC0769, per JMARS KRC Layer*

Temperatures within the lava tube are expected to be lower than the temperatures above. The lack of information on the cave made it difficult to determine the temperature difference between the surface and the subsurface. An estimate was made, deeming the subsurface ~10K lower than the surface, meaning the daily subsurface temperature range will be around [140K, 280K]. As a reminder, the Rover is expected to maintain an operating temperature of [233K, 313K]. This makes the subsurface temperature range ideal, as the thermal system essentially only needs to operate during night hours, saving crucial energy.

The subsurface environment of this mission provides some protection against hazards like wind and dust. However, site CC0769 is in close proximity to two other skylights, namely sites CC0770 and CC0771 (Figure 35).

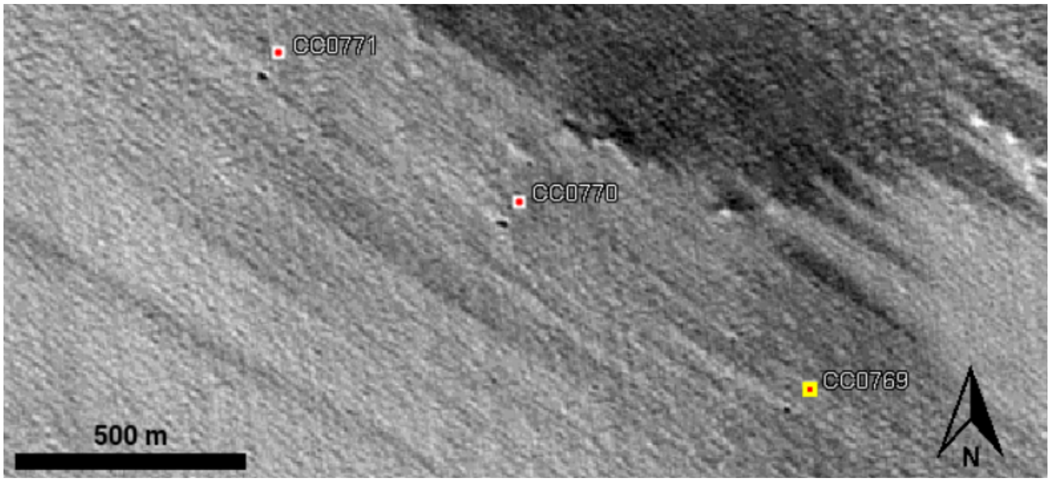

Figure 35: *Image of CC0769, CC0770, CC0771, per JMARS*

Each skylight is separated by around 1000m. The proximity of these skylights means each of these sites may be connected to the same lava tube. If this is the case, this would make wind and dust slightly more prevalent within the mission environment. This extra wind and dust is not expected to have any major impact on the functionality or performance of any subsystem (aside from instrumentation, which is discussed in depth in Section 4.1.6), but to prepare the Rover for these conditions, each subsystem was investigated to determine its operational capabilities. The primary danger for the mission is keeping the Rover at an operating temperature. To ensure this, the thermal system was designed to run off electrical power and generate heat within the Rover. The power consumption for the thermal system will vary due to heat generated from other components or temperature changes as the day progresses. To retain heat and mobility, the Rover's design is small and compact in order to efficiently heat and reduce mass drag. The mobility of the Rover has been tested during its verification phase, ensuring that the Rover will be able to navigate in a possible rocky or sandy environment. The results expected from the Rover are to descend down to a depth of 50m into the lava tube to allow for the instruments to sample and collect data on the unknown environment.

3.1.9. Confidence and Maturity of Design

Throughout the design iterations for the Rover, concepts and designs have been changed to better prepare the Rover for its mission. From the shape of the body to provide strength and protection from possible contact of rock to the mobility and drive of the system. Each system was designed to allow for exploration of the lava tube. While the body provides strength and protection from the ground in case contact occurs the wheels and suspension drive the Rover and place it out of harm's way. The wheels are designed and tested to undergo rocky/sandy terrain to provide grip and stability for the Rover. The individual linkage of each wheel allows for the Rover's body to be elevated 0.223m above the surface giving clearance from rocks. To test the ability of the Rover, conditions similar to those found on Mars can be used to test that the Rover can drive and operate in the expected terrain. Since the concept of the mobility is similar to other Rover designs the TRL for the wheels and motors are a level 5 due to the motors and concept design being achieved in other Rover missions. Other TRL for sensors such as the Supercam would be higher due to the system being actively used on previous Rover missions. With this the Supercam has a TRL rating of a 7 due to its test ability but in a new environment. The other sensor of the Innova360 LiDAR sensor is a new sensor that has not been tested in an environment experienced in the mission. The sensor while in theory and initial testing shows that it should be able to operate within conditions remains a potential risk. This places the LiDAR sensor at a TRL level of 4 due to its testing being done in laboratory environments only waiting to be tested further. To better ensure that the risk of the LiDAR sensor not operating fully simulated conditions such as temperature and enclosed area can be tested to verify performance. All other systems have been actively used on other Rover missions giving more confidence in ability and predictable behavior.

3.2 Recovery/Redundancy System

The current design of the mobility system includes the use of four electric motors powering each wheel with each wheel also having its own independent suspension. The wheels can take minor structural damage and still be able to operate, however once the damage reaches a point where a wheel no longer is in operation mobility can still be maintained through the use of the other wheels. Depending on the type of damage caused the wheel could either be left for stability and become electrically dead or be lifted to prevent the induction of drag to the Rover.

The power system is a single battery pack consisting of the four lithium battery cells and as such does not have redundancy. This battery system is located within the center of the Rover protected from outside factors that could cause it damage. To possibly reduce the effect of a damaged cell from affecting the Rover, the power management system can analyze and isolate a possible dead battery cell to further the mission at the cost of available power.

In its current design iteration, the Rover's main form of communication would be a UHF transceiver C/TT-510 Electra-Lite. The communication system relies on this transceiver to send and receive signals from the primary lander. Due to the system being a single component with no backup there is no redundancy. Possible recovery of the system can be achieved by self diagnosis or by the use of a secondary communication device located on the primary lander.

There is no alternative back-up plan to heat the internals and instruments of the Rover. At this moment it is solely relying on silicone rubber heating pads attached to the internals. In order to cool the Rover, the thermal management system (TMS) will use radiators along the inside surface of the body. There is no other way to cool the Rover besides using these radiators at the moment. It would be possible to turn off the heating system and allow the environment to cool off the Rover, but this will not likely be done since the bigger problem is to keep it heated. The TMS utilizes thermometer sensors and thermal switches to actively control both heating and cooling systems. There would be multiple sensors and switches, in case another failed.

The main operating computer for the Rover is the RAD750 3U Compact PCI board which controls the data handling within the Rover. This main controller has a secondary backup board within to act as a redundant component for the Rover. In the event of failure of the primary board the secondary will detect and act as the primary data handling device.

3.3. Payload Integration

LiDAR

The LiDAR sensor will be located towards the front of the Rover's body. This anterior positioning, along with its elevation will allow the sensor to take advantage of its 360 ° x 64 ° FOV. The lower, rectangular portion of the sensor will be embedded into the Rover's body while the cylindrical portion will rest above the body.

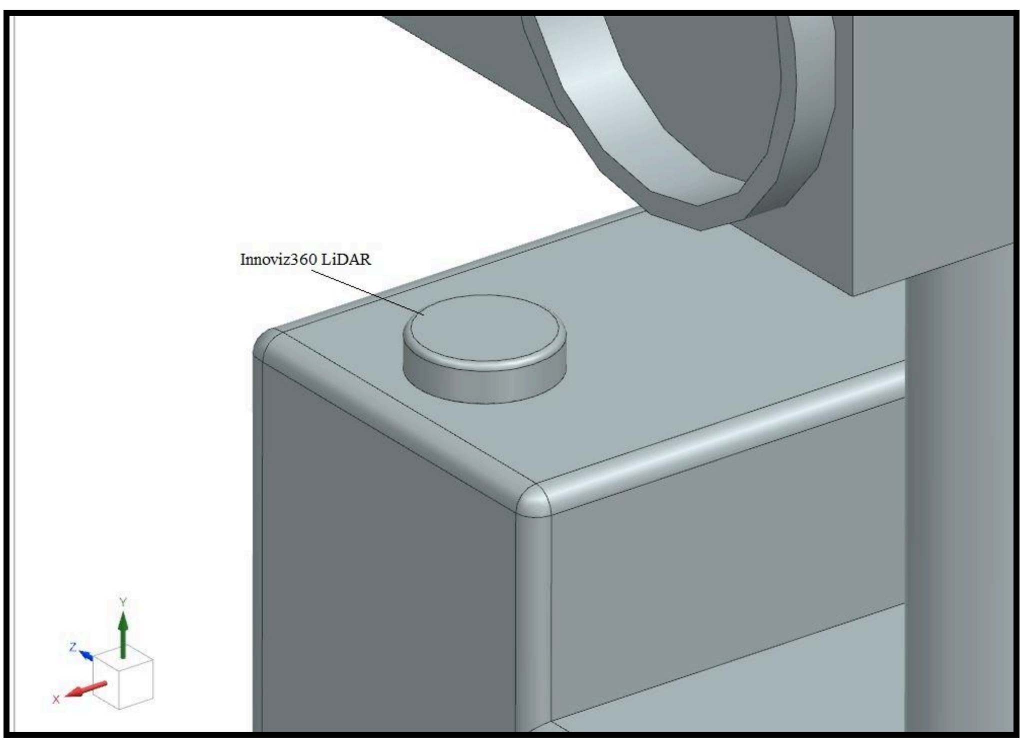

Figure 36: *Integrated Rover LiDAR Sensor*

SuperCam

The SuperCam suite consists of two units, a Mast Unit (MU) and a Body Unity (BU). The BU will be integrated within the Rover's body while the MU will be mounted onto the Rover's mast. The mast will be placed towards the front of the Rover as well. The mast will have the ability to rotate along a pitch axis, allowing the MU to lay flat on the back of the Rover when in stowed configuration.

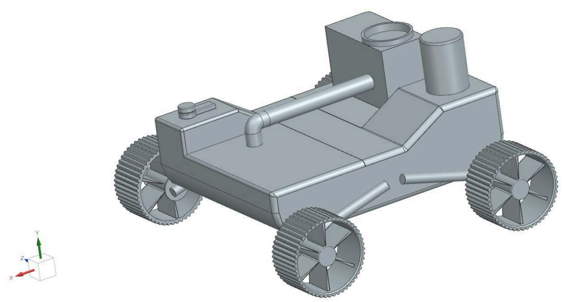

Figure 37: *Storage Configuration*

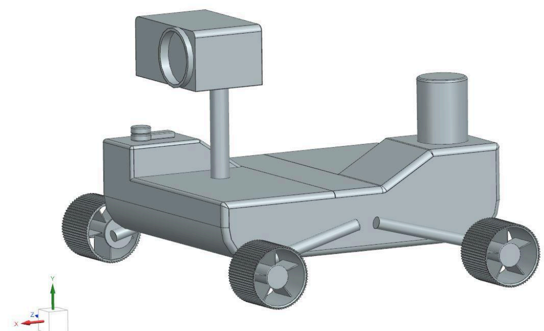

Figure 38: *Operational Configuration*

4. Payload Design and Science Instrumentation

4.1. Selection, Design, and Verification

4.1.1. System Overview

The payload subsystem consists of the science instrumentation – the SuperCam and the Innoviz 360 LiDAR – and power distribution mechanics. The payload subsystem interacts with three other subsystems: thermal, power, and data handling. (See Figure 39; the payload subsystem is outlined in purple) The power controller in the power subsystem sends power to the payload subsystem, which sends the required power to each science instrument. Within the thermal subsystem is a thermal distribution system, which works with the science instruments to regulate their temperatures to ensure they do not overheat or are exposed to harsh temperatures under which they cannot operate. Once the science instruments gather data, it is sent to the data handling subsystem, where the solid-state recorder can transfer the information gathered to the command processor.

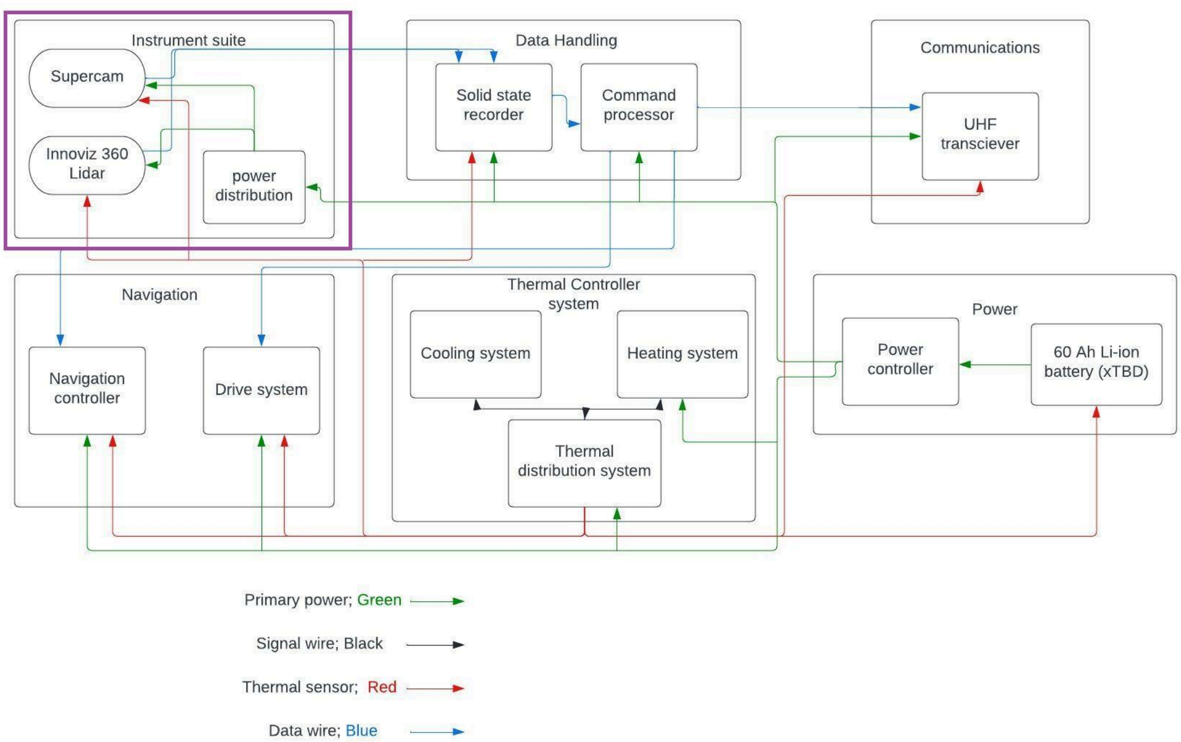

Figure 39: *Block Diagram Science Instruments Data Path*

4.1.2. Subsystem Overview

Instruments within this subsystem include the SuperCam instrument suite and the Innoviz360 LiDAR sensor. The Innoviz360 LiDAR sensor is expected to consume 25W of energy when in use. The sensor’s operating temperatures are [-40°C, 85°C]. Data from the LiDAR describes distance measurements, along with timestamps. This data will be sent to the Command & Data Handling System. The SuperCam suite is a heritage instrument which includes a 1064-nm laser (used to perform various methods of spectroscopy) and a Remote Micro-Imager (RMI). The suite as a whole, when in use, is expected to consume an average of 17.9 Watts. First used by Perseverance, the SuperCam suite can operate in temperatures between [-40°C, -5°C]. Data gathered by SuperCam will be recorded and sent to the Command & Data Handling system.

4.1.3. Manufacturing Plan

Table 33: *Payload Subsystem, Manufacturing Plan*

Product Name	COTS / In-House	Manufacturing Company	Start Manufacturing Phase	End Manufacturing Phase
SuperCam	COTS	Lockheed Martin	C	D
Innoviz360 LiDAR	COTS	Innoviz Technologies	C	D

SuperCam

SuperCam is a heritage science instrument and the manufacturing is planned to be outsourced to Lockheed Martin Corporation. The schedule for delivery is expected to be 36 months.

LiDAR

The Innoviz 360 LiDAR sensor is a Commercial-Off-The-Shelf instrument which will be purchased from the vendor, Innoviz Technologies.The schedule for delivery should be relatively quick and should not affect integration.

4.1.4. Verification and Validation Plan

This section describes the Verification and Validation Plan for the Payload & Science Instrumentation System. The procedures outlined here serve to ensure that the system complies with established requirements and customer expectations. The requirements imposed on this system (listed in Section 1.2.2) are derived from the mission's science goals and objectives (outlined in the Science Traceability Matrix, Section 4.2.2).

This section will first give an introduction to each component of the Payload & Science Instrumentation System. Then, a Verification Matrix will be provided for the purpose of tracking the progress of V&V. This will be followed by an in depth explanation of each requirement and the corresponding verification method. This section will then end with a summary of how V&V results will be reported and implemented.

The Payload & Science Instrumentation System includes the Innoviz360 LiDAR sensor, which is responsible for scanning the terrain of the cave for the purpose of navigation and mapping. It should be noted that the data the LiDAR sensor collects will be sent to a computer in order to generate a three-dimensional map. The system also includes the SuperCam instrument suite, which is responsible for conducting soil analysis, detecting olivine, and taking images of the soil. V&V on the Payload System will be conducted by the Engineering team and Science team.

Verification Matrix

Table 34: *Payload Verification*

Req #	Requirement	Verification Success Criteria	Verification Method	Result	Facility	Phase
PAY-0.1	The sum of payload components shall not exceed 15 kg	1. Aggregate mass of system does not exceed indicated limit	Inspection		GSFC	B-D
PAY-0.2	The cost of the payload components shall not exceed 30% of the total budget	1. Aggregate cost of components does not exceed indicated limit	Inspection		GSFC	B-C
PAY-0.3	The system shall map the terrain of the Martian cave	1. System is capable of taking a 360° scan of an environment	Demonstration		GSFC	C-D
PAY-0.3.1	The method used to map the cave shall have a range of at least 30m	1. System can read a distance of >30m	Test		GSFC	C-D
PAY-0.3.2	The mapping of the cave shall be accurate to the nearest 10cm	1. Within its range, the system can distinguish difference in terrain to the magnitude of 10 centimeters	Test		GSFC	C-D
PAY-0.4	The system shall search for olivine in the Martian cave	1. System is capable of detecting the presence of olivine	Demonstration		GSFC	C-D
PAY-0.4.1	The method used to find olivine shall have a range of at least 5m	1. System is capable of detecting olivine using a scan taken >5m away	Test		GSFC	C-D

PAY-0.5	The system shall determine the mineral composition of the regolith within the cave	1. System is capable of distinguishing different minerals/chemicals within regolith 2. System is capable of identifying the minerals/chemicals within regolith	Test		GSFC	C-D
PAY-0.5.1	The method used to analyze the soil shall have a range of at least 5m	1. System is capable of taking a reading at a range of > 5m 2. System is capable of distinguishing and identifying minerals/chemicals using a scan taken > 5m away	Test		GSFC	C-D
PAY-0.6	The system shall produce images of soil/rocks within the Martian cave	1. System is capable of taking images while under vehicle operating temperature [-40°C, 40°C]	Demonstration		GSFC	C-D
PAY-0.6.1	The images produced by the system shall have a resolution of at least 60 μm	1. Resolution of images are greater than or equal to 50 μm	Test		GSFC	C-D
PAY-0.6.2	Long-range images produced by the system shall have a resolution of within 300-500 μm	1. Resolution of images are within the specified range	Test		GSFC	C-D
PAY-0.7	The power consumption of the payload system as a whole shall not exceed 45 Watts	1. LiDAR component consumes 25 Watts 2. SuperCam component consumes 17.9 Watts	Analysis		GSFC	C-D

LiDAR

The LiDAR sensor must remain in compliance with mass and power requirements, as well as performance expectations. To ensure that each of these facets are met, verification tests will be held throughout the duration of the development phases. Below are the requirements for the LiDAR component and corresponding verification methods.

PAY-0.1: “The sum of payload components shall not exceed 15 kg”

Phase B-D (Inspection): Teams will measure the mass of the LiDAR sensor to ensure it does not exceed 15 kg.

PAY-0.3, 0.3.1, 0.3.2: “The system shall map the terrain of the Martian cave… have a range of at least 30 meters… [and] *shall be accurate the the nearest 10 centimeters”*

Phase C (Test): In order to gauge the performance of the sensor, tests will be held in a controlled facility. Teams will test the sensor’s ability to detect objects in varying ranges. Teams will also make observations on any losses to accuracy due to distance.

Phase C (Demonstration): To test the sensor’s ability to map cave-specific terrain, teams will deploy a prototype sensor into a known cave. The sensor will be placed in different angles/positions within the cave while teams take note of which conditions allow for the best performance.

Phase D (Demonstration & Test): After integration, teams will develop a simulated environment that mimics the expected temperature, light, and geographical conditions of the mission. The team will then deploy a prototype Rover to i) test the system’s ability to accurately map the environment and ii) to demonstrate the Rover’s ability to navigate using the LiDAR data.

Phase D (Test): After assembly, teams will again deploy a prototype Rover into a known cave to determine the sensor's ability to map cave-specific terrain while experiencing cave-specific conditions. This test will quantitatively assess the sensor's ability to create a detailed map

PAY-0.7: "The power consumption of the system as a whole shall not exceed 45 Watts"

Phase C (Analysis): The team will analytically determine the wattage of the sensor using data from the manufacturer.

Phase D (Test): During prototype testing after integration, the team will deploy the prototype Rover and track the power consumption of the sensor as it operates.

SuperCam

Similarly, the SuperCam instrument suite must also remain in compliance with mass and power requirements, as well as performance expectations. The SuperCam is responsible for three science objectives, so V&V plans related to this instrument will be more rigorous. Below are the requirements for the SuperCam suite and corresponding V&V methods.

PAY-0.1: "The sum of payload components shall not exceed 15 kg"

Phase B-D (Inspection): Teams will measure the mass of the SuperCam suite to ensure it does not exceed 15 kg.

PAY-0.4, 0.4.1: "The system shall search for olivine within the Martin cave… [and] *shall have a range of at least 5 meters"*

Phase C (Test): To determine the detection and range capabilities of the instrument, teams will analyze rock samples containing olivine to evaluate the sensor's ability to detect the mineral. Further, the team will use the instrument at varying ranges to evaluate any losses in accuracy and establish a range bound.

Phase D (Demonstration): To evaluate the instrument's ability to operate in a mission setting, the team will construct a prototype Rover to test the instrument and deploy it into a cave. This will expose the instrument to mission-like conditions, such as jagged surfaces, obstruction by terrain and dust, and low light levels. The team will qualitatively observe any losses to performance or functionality that result from exposure to these conditions

Phase D (Test): The team will again deploy a prototype Rover into a cave. This test will evaluate the instrument's performance by quantitatively measuring and analyzing any losses to performance or functionality that result from exposure to the cave's conditions.

PAY-0.5, 0.5.1: "The system shall determine the mineral composition of the regolith within the cave… [and] *shall have a range of at least 5 meters"*

Phase C (Test): To determine the analytical and range capabilities of the instrument, teams will analyze soil samples of known composition using the instrument. The team will use the instrument at varying ranges to evaluate any losses in accuracy. Soil samples from Earth will be tested, Additionally, teams will prepare samples that closely mimic Martian regolith in order to further test the instrument's capabilities against expected values.

Phase D (Demonstration): To evaluate the instrument's ability to operate in a mission setting, the team will construct a prototype Rover to test the instrument and deploy it into a cave. This will expose the instrument to mission-like conditions, such as jagged surfaces, obstruction by terrain and dust, and low light levels. The team will qualitatively observe any losses to performance or functionality that result from exposure to these conditions

Phase D (Test): The team will again deploy a prototype Rover into a cave. The Rover will navigate through the cave and take soil samples along the way. This test will evaluate the instrument's performance by quantitatively measuring and analyzing any losses to accuracy and precision that result from exposure to the cave's conditions. Teams will then compare the results of the soil analysis from the instrument with an independent, analytical approach to evaluate the instrument's accuracy.

PAY-0.6, 0.6.1, 0.62: "The system shall produce images of soil/rocks within the Martian cave… [with] *a resolution of at least 50 μm* (for short range)... [and] *a resolution of within 300-500 μm* (for long range)"

Phase C (Demonstration): The team will first assess the instrument's ability to produce images while experiencing mission-like conditions. The instrument will be tested under low-light levels and experience temperatures within [-40°C, 40°C]. Any losses to image quality/resolution will be qualitatively observed.

Phase D (Test): The team will then capture images of rock samples using the instrument at varying ranges. Results will be analyzed and quantitatively analyzed to determine if the images are within the specified resolution requirements.

Phase D (Test): The team will test the instrument's ability to capture images while experiencing mission-like conditions. The instrument will be mounted on a prototype Rover which will be deployed into a test environment. Teams will quantitatively observe changes to image quality that result from mission conditions and changes in orientation due to the Rover.

PAY-0.7: "The power consumption of the system as a whole shall not exceed 45 Watts"

Phase C (Analysis): The team will analytically determine the wattage of the sensor using data from the manufacturer.

Phase D (Test): During prototype testing after integration, the team will deploy the prototype Rover and track the power consumption of the sensor as it operates.

The results from these V&V procedures will be tracked by the Lead Systems Engineer and Administration Team. The results of each verification procedure will be recorded in a document containing the Verification Matrix seen above (Table 33). The full, detailed results will be analyzed and summarized in a report which will be presented to the Lead Systems Engineer and the Chief Scientist. As V&V Plans are carried out on the Payload and Science Instrumentation, the Lead Systems Engineer and Chief Scientist will update relevant documents to track which requirements have been satisfied. If requirements have not been met, the Science and Engineering teams will make the necessary changes (as decided by the team leads) to verify that the Payload and Science Instrumentation complies with mission requirements.

4.1.5. FMEA and Risk Mitigation

FMEA Chart

Table 35: *Risk Analysis and Recovery*

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Innoviz360 LiDAR	Unable to do full 360 rotation	- Harder to identify current location of Rover within lava tube - Incomplete scan of environment	80	- Damage to unit during mission	20	- Ensure unit is protected when not in use	90	190	- Identify how much rotation is actually available to Rover - Consider not going as deep into the lava tube
SuperCam: Remote Micro-Imaging (RMI)	Camera is unable to focus	- Blurred images	50	- Dust or damage to unit during mission	10	- Ensure unit is protected when not in use	90	150	- Test other distances; if persists, discontinue use
SuperCam: Raman spectrometer	Laser shifts from original position	- Not testing the correct area	75	- Dust or damage to unit during mission	10	- Ensure unit is protected when not in use	80	165	- Account for difference from original to actual location
SuperCam: Laser Induced Breakdown Spectrometer (LIBS) and Visible/Near-Infrared Spectroscopy (VISIR)	LIBS or VISIR malfunctions	- Less confidence in confirming mineral composition	60	- Dust or damage to unit during mission	10	- Ensure unit is protected when not in use	80	150	- Extend margin of error for samples taken after damage is detected

Table 36: *Payload Risk Assessment*

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Lidar provides inaccurate mapping and rover encounters hazard	2	3	↓ - Decreasing	Mitigate	If Lidar does not accurately map out the cave, the rover will be unable to safely traverse the cave and may bump into an object that would cause damage to the instrumentation on the rover	M
2	SuperCam is not correctly calibrated	1	3	↓ - Decreasing	Mitigate	Inaccurate calibration of the SuperCam instrument would lead to inaccurate data collection and we would not achieve our Science Goals	M
3	SuperCam is unable to be deployed	2	4	↓ - Decreasing	Mitigate	If SuperCam cannot be deployed from storage mode, it would be nearly impossible to collect data	M
4	Lidar is obstructed and cannot function	2	4	↓ - Decreasing	Mitigate	If Lidar is damaged or becomes obstructed by an object, it would no longer be able to provide mapping or navigation	M

Risk Matrix

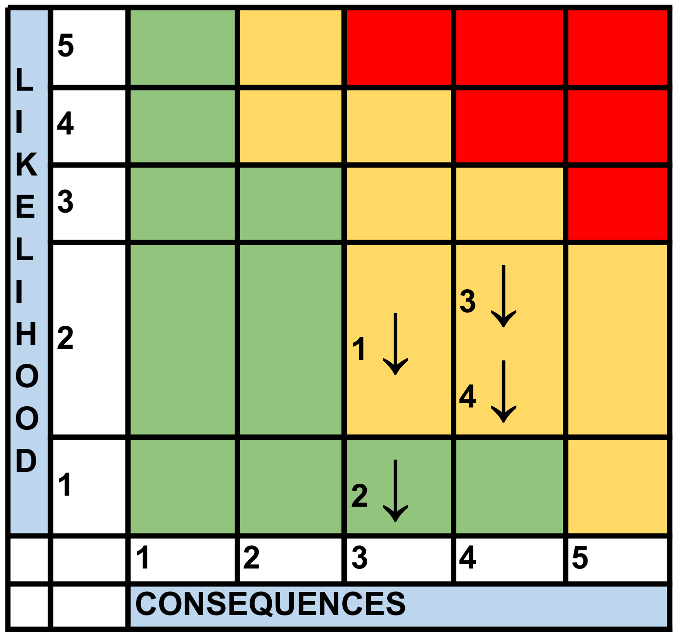

Figure 40: *Risk Matrix Diagram*

Many science related risks are mitigated by redundancy present in the mission's instruments. SuperCam would be able aid in navigation if the LiDAR fails since SuperCam is able to capture images. These images could potentially be used for navigation purposes in case of emergency. SuperCam is composed of multiple instruments that are able to analyze the regolith of the Martian cave. If one of SuperCam's instruments fails, useful data would still be collected by SuperCam given that it has multiple instruments.

4.1.6. Performance Characteristics

This section discusses how the Payload & Science Instrumentation is expected to operate within the context of the mission's conditions. For the purposes of this discussion, below is a list of environmental conditions that may hinder the abilities of the Payload & Science Instrumentation:

- Obstruction due to dust
- Obstruction due to terrain
- Temperature conditions
- Low light levels

The following section discusses how the above conditions may impact the ability of each instrument to perform, as well as any design features and mission choices that have been made to mitigate effects on instrumentation.

4.1.6.a Dust

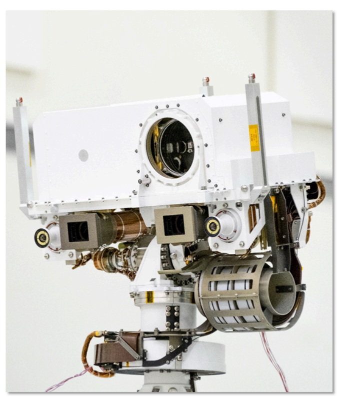

Figure 41: *SuperCam's Mast Unit mounted on Perseverance's mast [4]*

The SuperCam instrument suite was first used by the Perseverance Rover. One method the SuperCam suite uses to analyze rocks is laser spectroscopy via its 1064-nm laser [8]. As demonstrated by Perseverance [9], the shock-wave created by this laser is capable of clearing surface-level dust. This allows the other instruments within the SuperCam suite to take data samples without concern of dust. Additionally, SuperCam is mounted on a mast that allows for rotation along a pitch axis [8] (Figure

41). This enables SuperCam to clear dust on the surface of its window by simply tilting downward.

Figure 42: *The Innoviz360 sensor [5]*

The Innoviz360 LiDAR sensor also features design aspects that allow it to function in an environment with dust. The cylindrical portion of the instrument is the only part that will be exposed to the air; the lower end can be embedded into the Rover's body. The sensor scans using its curved face. Therefore, any dust that may accumulate on the flat top face of the sensor has no effect on the functionality of the sensor. Additionally, any airborne dust particles scanned by the sensor can be "filtered" out of the three-dimensional map using a specialized algorithm, as described in a paper by Afzalaghaeinaeini et al [10]. This likely isn't necessary because multiple scans of any given region will be taken.

To reiterate, the Rover is set to explore the cave beginning July 2027. The choice of year serves to mitigate the possibility of encountering a global dust storm. These typically occur every 5 - 6 Earth years (the last global dust storm occurred in 2018), meaning it is unlikely that the Rover will encounter a global dust storm. It is possible that the Rover will encounter a normal dust storm, but because this mission investigates the subsurface of Mars, any dust that reaches the mission environment should be minimal. Nevertheless, the features described above ensure that the instruments onboard the system are adequately prepared to perform within the context of the mission.

4.1.6.b. Terrain

The site this mission will investigate is CC0769, which is a lava tube. Due to the way lava tubes form, it can be inferred that CC0769 lacks the extreme verticality demonstrated by other tunnel systems. Also, the lack of liquid water means minimal erosion and weathering occurs within this cave. The lack of water also means no stalactites or stalagmites. In short, CC0769 is not expected to have much, if any terrain that disrupts the performance of the instrumentation. Even so, the instruments remain prepared to navigate around such issues.

Obtrusive terrain can be defined as any geological feature that may obstruct the view of an instrument, such as a protrusion from the ground, wall, or roof. The LiDAR is specifically used to avoid such features. The Innoviz360 sensor, specifically, can be used to produce real time three-dimensional images of an environment. This can be used to determine if some instrument, namely the SuperCam, has its line of sight obstructed by any terrain. In such a case, a path can be generated by the Navigation system to relocate the Rover to a point where it can take the data sample undisturbed.

4.1.6.c. Temperature

The Rover deploys in July 2027, which is around late spring and early summer. Below is a plot (also seen in Section 3.1.8) of the estimated surface temperature at CC0769 during the mission timeframe. This plot was generated by the KRC Layer on JMARS, which calculates temperature using thermal inertia, albedo, and topographical data taken from the Mars Global Surveyor (MGS).

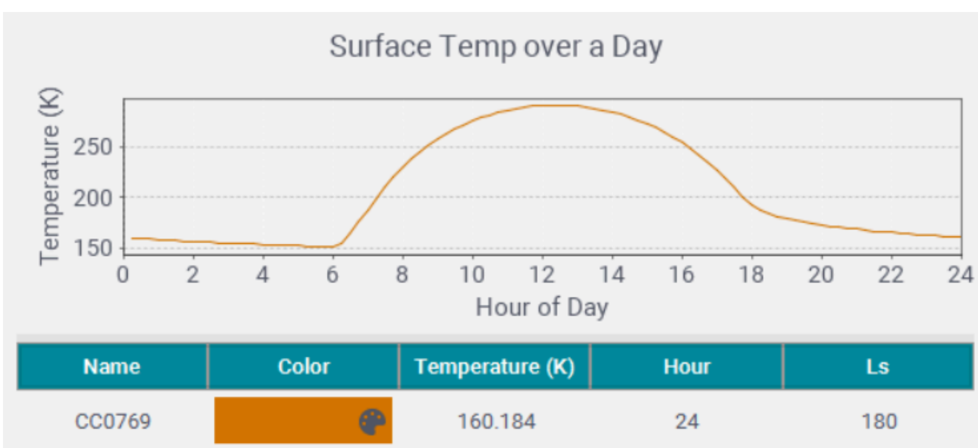

Figure 43: *Daily surface temperatures at CC0769, per JMARS KRC Layer*

Here, temperatures are predicted to reach a daytime average of around 240K (-33°C) and a night time average of around 160K (-113°C). Using its thermal system, the Rover will maintain an operating temperature in the range [-40°C, 40°C] (per system requirements). The Innoviz360 is capable of function in these temperatures as it has an ambient operating temperature of [-40°C, 85°C] and an ambient stored temperature of [-40°C, 105°C]. Similarly, the SuperCam unit used on the Perseverance Rover was kept at a temperature > - 40°C [11]. The continued success of the Perseverance Rover serves as a testament to the SuperCam's ability to endure the harsh temperatures of Mars.

4.1.6.d Light level

The subsurface setting of the mission leads to a lack of visible light. The lack of visible light has no effect on the Innoviz360 LiDAR sensor, nor the spectrometers within the SuperCam suite. These instruments themselves emit photons and do not rely on outside sources of photon emission to capture data. The Remote Micro-Imager (RMI) within the SuperCam suite, however, is a camera, so it does rely on outside sources of light.

On-flight tests during Perseverance's cruise to Mars have proven the RMI's ability to perform in low-light environments [12].To explain, the RMI has two functions that assist it in producing images within the low-light environment, namely *auto-exposure* and *high-dynamic ranging* [12]. Firstly, the auto-exposure function allows SuperCam to take images at varying exposure times and choose the most effective exposure time for later use. Photographers often use long exposure times in low-light environments to allow more light to come into the camera. Secondly, the high-dynamic ranging function allows SuperCam to combine images of different exposure times, producing an image with a greater range of dark and light tones. These functions in tandem increase the RMI's ability to produce high quality images despite low light levels.

4.2. Science Value

4.2.1. Science Payload Objectives

The science goals of this mission are to map out the terrain and geography of the lava tubes located at CC0769 and to investigate the minerals located within this cave, with an emphasis on searching for the mineral olivine. The science payload on the Rover aims to achieve these goals by using LiDAR sensing for the mapping of the cave and by using SuperCam to investigate the mineral composition.

The mineral olivine is believed to have the potential to support microbial life within Martian caves which is why this mission aims to further investigate it. This mission hopes to gather reconnaissance information about this specific cave in hopes to aid a future mission in the search for potential microbial life. Through the use of SuperCam, the Rover will conduct spectroscopy to extensively study the elemental and mineral composition of the rocks present in the cave which will perhaps provide information on how they were formed. SuperCam will also take high-resolution images of the samples analyzed which will provide great visual context for the spectroscopy analysis conducted on the minerals.

4.2.2. Science Traceability Matrix

Science Goal: Conducting reconnaissance to expand the knowledge known about the Martian cave environment [26]

Table 37: *Science Mission Objective 1*

Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
	Physical Parameters	Observables					
Determine the terrain of the lava tube located at CC0769	Take geographic scans of the Martian lava tube to a minimum depth of 20m	Completion of a map indicating the characteristics of the structure within the lava tube	Range	30 m Min	40-100 m	Innoviz360 LiDAR sensor	SYS-0.5: The system shall provide mapping of the cave formation
			Accuracy	±10 cm	±10 cm		
			Spatial Resolution	(0.5 - 1.0) ° x (0.5 - 1.0) °	(0.25) ° x (0.50) °		
			Update Rate	5 - 20 fps	10 fps		

Table 38: *Science Mission Objective 2*

Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
	Physical Parameters	Observables					
Capture images of the inside of the lava tube	Take a minimum of 2 high resolution images inside of the lava tube	Take a long-range image when LiDAR scan is complete (300-500 μm), and close-range images of sample sites (minimum 60 μm)	Range	1.4 m - 100 m	1.4-100 m	SuperCam: Remote Micro-Imager (RMI)	SYS-0.8: The system shall provide images of soil/rock samples within the Martian cave
			Calibration Target	1 - 3 cm	3 cm		
			Resolution	60 μm minimum	100 μm		
			Data Return	15.5 megabits	15.5 megabits		

Table 39: *Science Mission Objective 3*

Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
	Physical Parameters	Observables					
Determine if the presence of the mineral olivine is present within the Martian lava tube.	Identify the amount of olivine within the soil found within the Martian lava tube	Detect the presence of olivine at a range of 7 meters	Range	5-10 m	7 m	SuperCam: Raman Spectroscopy	SYS-0.7: The system shall search for olivine within the Martian cave
			Calibration Target	10 - 15 mm	12 mm		
			Wavelength Range	535 - 835 nm	535 - 835 nm		
			Data Return	15.5 megabits	15.5 megabits		

Table 40: *Science Mission Objective 4*

Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
	Physical Parameters	Observables					
Determine the mineral composition of the regolith within the Martian lava tube.	Identify the 3 most common minerals within the soil found within the Martian lava tube	Detect the presence of minerals found at a range of 7 meters	Range	5-10 m	7 m	SuperCam: Laser Induced Breakdown Spectrometer (LIBS) and Visible/Near-Infrared Spectroscopy (VISIR)	SYS-0.6: The system shall analyze soil composition to an accuracy of 95%
			Calibration Target	10 - 15 mm	12 mm		
			Wavelength Range	245 - 835 nm	245 - 835 nm		
			Data Return	15.5 megabits	15.5 megabits		

4.2.3. Payload Success Criteria

4.2.3.a SuperCam

Table 41: *SuperCam Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Investigate and analyze the regolith within the Martian cave using all of SuperCams' instruments: Remote Micro-Imager (RMI), Remote Raman Spectroscopy, Visible/Near-Infrared Spectroscopy (VISIR), Laser Induced Breakdown Spectroscopy (LIBS). Utilize RMI to capture images of selected sample sites Conduct spectroscopy of minerals using Remote Raman Spectroscopy and VISIR Identify elemental composition of regolith using LIBS Utilize VISIR to identify molecular composition of regolith and detect presence of olivine, phosphates, carbonates, sulfates, and metal oxides	- RMI spatial resolution of at least 55 μm [1] - Remote Raman Spectroscopy pixel resolution $< 4\ cm^{-1}$ and a full width half maximum (FWHM) resolution $< 12\ cm^{-1}$ [2] - VISIR instrument should be conducted at an absolute radiometric calibration better than 10% and relative calibration better than 1% [14]. - LIBS instrument should observe and determine the presence of elements to at least 300 parts per million (ppm) [3]
Minimum Success	SuperCam must at least capture images using RMI and identify minerals using VISIR	- VISIR instrument should be conducted at an absolute radiometric calibration better than 10% and relative calibration better than 1% [14]. - RMI spatial resolution of at least 55 μm [1]
Associated Failure Mode	SuperCam is unable to conduct any spectroscopy analysis and only the RMI is able to be used to capture images for analysis	- RMI spatial resolution of at least 55 μm [1]

4.2.3.b LiDAR

Table 42: *LiDAR Success Criteria*

Success Level	Description	Performance Criteria
Complete Mission Success	Utilize Innoviz360 LiDAR to provide detailed 3D mapping of the terrain and geography inside the Martian cave. The 3D mapping should be accurate enough to allow for the Rover to safely traverse the cave and for adequate analysis of the cave's macroscopic features.	- LiDAR should be able to map up to a range of 200 meters
Minimum Success	LiDAR is not accurate enough for analysis of macroscopic features but it is still able to aid in mapping a route for the Rover	- LiDAR should be able to map up to a range of 200 meters
Associated Failure Mode	LiDAR is very limited in mapping and only large objects can be identified. SuperCam's RMI would then have to be used to aid in navigation	- N/A

4.2.4. Experimental Logic, Approach, and Method of Investigation

This section elaborates on the operational procedures of the Rover described in the ConOps (Section 1.2.4). Additionally, this section also provides rationale behind the formulated procedure.

Procedure

Upon deployment onto the Martian surface, the Rover will calibrate all science instruments to ensure functionality and adequate performance within the given environment. The LiDAR sensor will then be used to locate the entrance to the lava tube and the egress into the cave will begin.

The next phase of the mission will begin inside the cave where the Rover will utilize the LiDAR sensor to map out the first 20m of the cave. This data will be processed by the computer to produce a three-dimensional representation of the environment. The region encompassed by this initial 20m scan will be denoted as a sample space, which denotes the area that the Rover will investigate using SuperCam.

While in this sample space, the Rover will begin by using SuperCam’s RMI to capture multiple long distance images to identify potential sample sites for evaluation. This data is then processed by the Rover. Once sample sites have been chosen, a route to the selected sample sites is created by the navigation system.

The Rover will approach each sample site to within 5m to begin its in-depth analysis. Firstly, the RMI will be used to take a close-range image of the sample site. Then, the Rover will utilize SuperCam’s 1064-nm laser to perform LIBS. Aside from aiding in spectroscopy, this laser also creates a shock wave strong enough to clear surface dust, giving a full view of the sample. SuperCam will then be used to perform its passive methods of spectroscopy, VISIR and Raman. Finally, SuperCam will approach the sample to a distance of 1.5m to take another high-resolution image of the sample. Once all actions are completed at the sample site, it will then travel to the next identified sample site. Importantly, the LiDAR will be active throughout the duration of the Rover’s investigation into the sample space.

When all sample sites within the sample space have been visited, the Rover will navigate further into the cave until it exits the investigated sample space. The LiDAR will then be used to scan a new section of the cave to identify a new sample space and repeat the above procedure. This cycle will continue until the Rover determines its batteries are low. To be specific, during its trek along the lava tube, the Rover will keep track of its proximity to the skylight entrance. The distance to the skylight will be used to determine the minimum power needed to reach the recharge point near the entrance. Before this minimum power percentage is reached, the Rover will return to the skylight entrance and enter rest mode. In this mode, the Rover will charge its batteries and send data back to the primary lander

Rationale

The procedure above was formulated with two primary goals in mind: i) conducting thorough analysis of the lava tube and ii) efficiently managing the Rover's power supply.

Firstly, by partitioning the cave into "sample spaces," the Rover is forced to localize its investigation to a single, prioritized area. This limits the number of sample sites available to the Rover, making it easier to determine an efficient route that passes over each of them. It forces the Rover to thoroughly investigate the cave because the Rover cannot leave the sample space until all chosen sample sites have been analyzed. Further, the assigned sample spaces can be identified in the three-dimensional map produced by the LiDAR. This can aid in post-mission analysis because it contextualizes each sample site based on their position within the cave.

Secondly, the use of the RMI for long-distance images serves to identify potential sample sites. This is similar to how Perseverance used its Mastcam-Z. Mastcam-Z has a greater resolution than the RMI, but SoCOLD's mission environment is much smaller than that of Perseverance, meaning the RMI's resolution is suitable for the mission's purposes. Using long-distance RMI images to evaluate potential sample sites helps to characterize the sample sites and to ensure diversity of samples.

4.2.5. Testing and Calibration Measurements

Prior to launch, several rounds of V&V will have occurred to ensure that the instruments are able to perform within the setting of the mission. These tests will have characterized any factors that may affect the performance of each instrument, such as temperature, pressure, dust, etc. Once at the mission location, tests will be done to calibrate the instruments and to quantify the expected effects on instrument accuracy due to mission conditions.

LiDAR

The intrinsic parameters of the Innoviz360 sensor will be calibrated in advance. These include focal length, lens distortion, and skew. Tests prior to launch will be held to ensure these parameters are in line while the sensor experiences mission conditions. The purpose of conducting LiDAR calibration is to test extrinsic parameters, such as position and orientation. It is key that the coordinate system of the vehicle is in sync with that of the LiDAR sensor.

Innoviz, the manufacturer of the chosen LiDAR sensor, uses “perception software” to conduct “continuous calibration” to ensure that the sensor coordinate system and vehicle coordinate system establish and maintain a correspondence. An initial calibration will be conducted after landing. To test the sensor’s performance, the Rover will use the sensor while in uniform and nonuniform motion. The primary lander will be used as a calibration target since its dimensions are available. Impacts of acceleration on the accuracy of the sensor will be measured. The data from this test will be compared with lab data to perform any necessary adjustments.

SuperCam

On site calibration for the SuperCam will be conducted upon landing. Being a heritage instrument, calibration procedures have been established for the SuperCam suite. SuperCam carries a set of 36 calibration targets, referred to as the SuperCam Calibration Target (SCCT), pictured and labeled in the image below [13]. For the purposes of this mission, a replica of this assembly may be used which omits target 0.8 (which is a slab of Martian meteorite NWA 10170). Perseverance included this meteor as an homage to its science goal of sample return; it does not serve as a calibration target for any of the instruments.

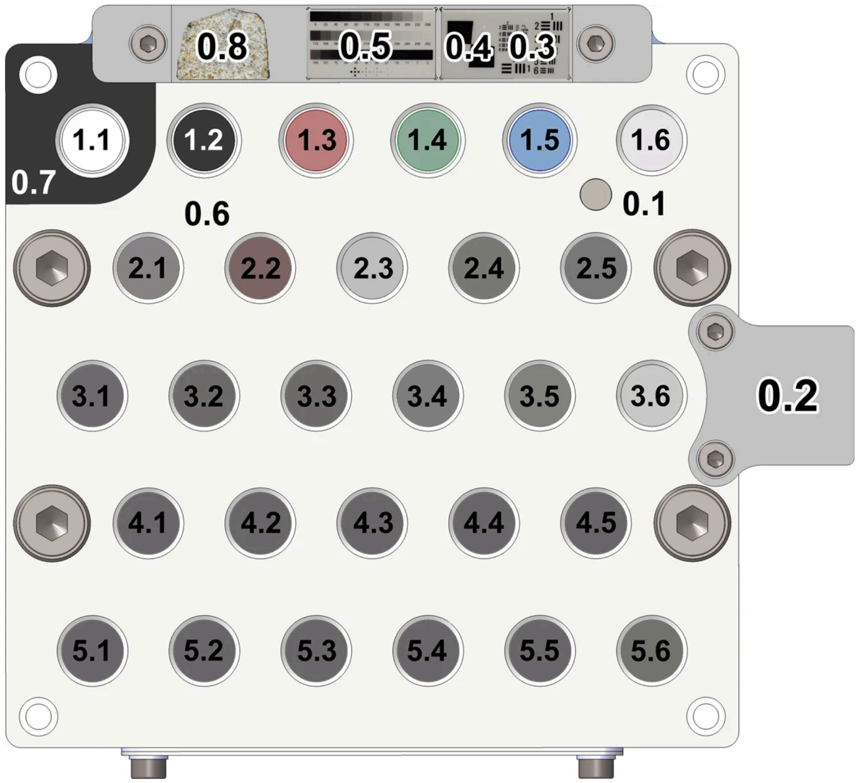

Figure 44: *SuperCam Calibration Target [13]*

The RMI will be calibrated using targets 0.3 - 0.5 and 1.1 - 1.5. Targets 0.3 - 0.5 serve to calibrate the dynamic ranging and resolution of the RMI. Target 0.3 is a USAF resolution chart, which can quantitatively assess the resolution of the RMI. Target 0.4 is a slanted edge, which is used to find the modulation transfer function (MTF) of the camera. The MTF can be used to assess the resolution and contrast of the camera Target 0.5 features 3 grayscale which scale linearly (top band) and logarithmically (middle and bottom bands). These scales test the dynamic range modes of the RMI. Targets 1.1 and 1.2 provide a black and white standard for image balancing, while 1.3 - 1.5 provide standards for color balancing.

To calibrate the several spectrometers (LIBS, VIS, IR, TRR/L), targets 0.1, 0.2, 1.1 - 5.6 are used. Target 0.1 is a diamond, which is used to calibrate the Raman instruments (TRR/L). Target 0.2 is a titanium plate, which is used to determine the shift in wavelength due to temperature and atmospheric pressure for the LIBS, VIS, and TRR/L. Targets 1.1 - 1.5 are used to measure the spectral response for the VISIR.

Target 1.6 tests the TRR/L ability to detect organic samples. The remaining targets (2.1 - 5.6) are a series of geological samples that are of interest. The contents of these samples were chosen to calibrate the spectrometers specifically in preparation for the minerals and compounds expected to be found during the mission. Target 3.3, for example, is an olivine sample of known composition. Targets 5.1 - 5.5 are silicates doped with different elements, including, but not limited to copper, zinc, and barium. The composition of each of these samples are known. These samples will be used to test the accuracy and precision of the LIBS, TRR, and VISIR. The results from these tests will be used to determine changes in performance over time, and changes in performance due to the environment. Since the composition of these samples are known, the results from these calibration tests can be compared with lab results to make necessary adjustments.

4.2.6. Precision and Accuracy of Instrumentation

LiDAR

LiDAR image accuracy is often impacted when a vehicle experiences a “road bump.” The setting of this mission lends to an abundance of such obstacles. While the Rover’s suspension system does aid in the Rover’s ability to navigate uneven terrain, slight changes in orientation due to terrain are to be expected.

The Innoviz360 sensor has two preset FOV configurations. This mission intends to use the configuration that provides the greatest three-dimensional FOV, illustrated below by the manufacturer (Innoviz).

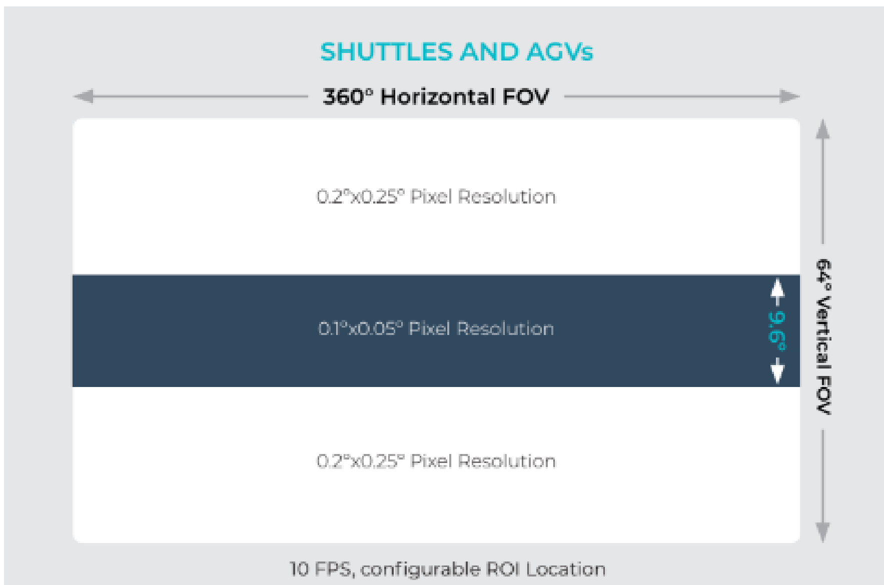

Figure 45: *Innoviz360 LiDAR FOV [5]*

This configuration provides the greatest vertical FOV. While in this configuration, the scanner has a 0.1° x 0.05° pixel resolution in along a central band, and a 0.2° x 0.25° pixel resolution in the remaining FOV. Information on the pixel accuracy could not be found, but using the above resolution figures, it can be inferred that the sensor has an accuracy of ±(0.5° x 0.25°) within the central band, and an accuracy of ±(1.00° x 1.25°) in the top and bottom bands. By comparing with other LiDAR sensors, it can be inferred that this error margin may be magnified by a factor of 2 when the Rover is accelerating or experiences an unexpected change in orientation. The sensor also runs at 10FPS, meaning a full scan is conducted every 100 ms. The time stamps for each of these are accurate to the nearest 10 μs.

SuperCam

SuperCam uses various methods of spectroscopy to identify elements and quantify their abundance within a sample. Factors such as the temperature and atmospheric pressure, which causes shifts in wavelengths, can have an effect on the accuracy of the spectrometers. SuperCam uses LIBS spectroscopy to determine elemental composition, and a combination of VISIR and Raman to identify various compounds. These methods can be used to identify the percent composition of the regolith within the cave.

The LIBS method, which is used for determining elemental composition, has a 10% accuracy at ranges of up to 7m [8]. While seemingly large, this margin remains small enough for different rock classes to be distinguished.

The VISIR and Raman methods, used for identifying minerals and their abundance, are capable of detecting minerals with abundances around the range of 1-10% [11]. To be specific, these methods can detect carbonates, sulfates, phosphates, and importantly olivine at an abundance of 1% [15]. Organics and metal oxides can be detected at an abundance of 5%. Pyroxenes can be detected at an abundance of 10% [15]. These occur at ranges of up to 7m.

Along with spectroscopy, the SuperCam will also produce images using the RMI. At 1.5 meters, the RMI has a minimum spatial resolution of 60 μm [16]. The accuracy of RMI images is not expected to affect analysis, as these images serve only to provide visual context behind the spectroscopy data.

4.2.7. Expected Data & Analysis

LiDAR

The LiDAR sensor produces a point cloud, which is a set of data points which each, in this case, describe a spatial coordinate and the time the data sample was taken. This data set is processed by a program in order to produce a visual representation of the environment. Below is an example of such a visual representation.

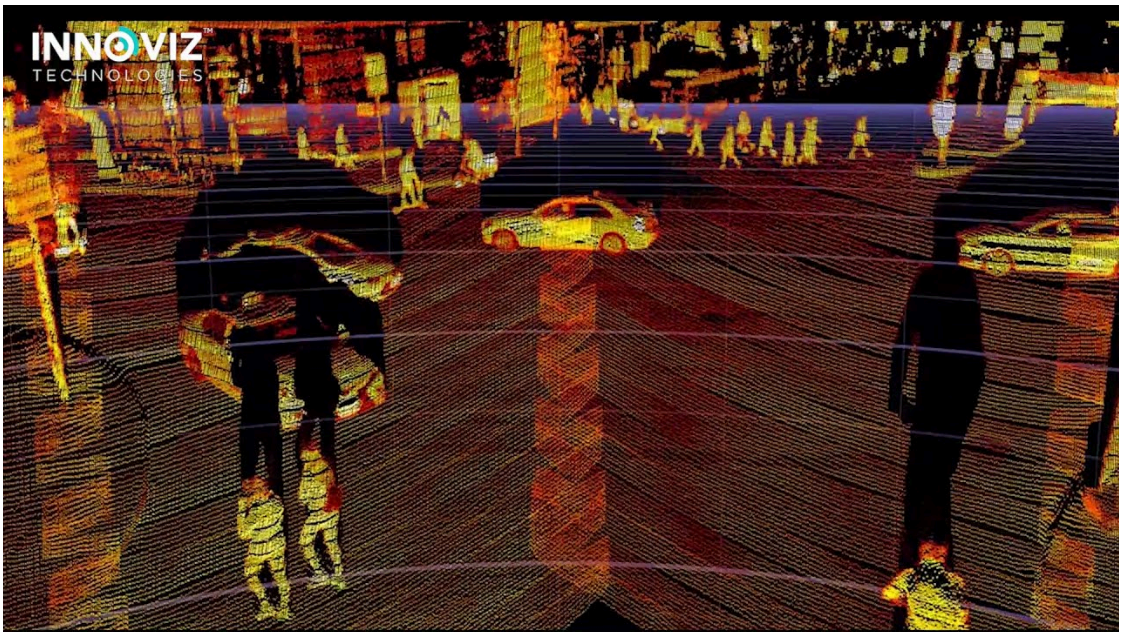

Figure 46: *InnovizOne 3D Point Cloud, per Innoviz*

This image was taken from a demonstration of the InnovizOne sensor, a predecessor to the Innoviz360. In this image, multiple LiDAR sensors are being used. This is made evident by the strips of increased density, which indicate an overlap between two sensors. Unlike this demonstration, the Rover for this mission uses a sensor with an FOV of 360° x 64°, meaning only one sensor is needed to capture an entire environment.

This mission seeks to create a three-dimensional representation of the lava tube's interior using data from the LiDAR sensor. As demonstrated in the image above, point density is inversely proportional to distance from the sensor. Because this mission explores a lava tube, the environment that will be scanned is expected to be small and compact, unlike the open environment seen in Figure 46. Additionally, the Innoviz360 has a greater angular resolution than the InnovizOne. Further, the sensor will be used continuously while the Rover is active, meaning multiple scans of the Rover's surroundings will be taken, allowing for an accurate and considerably precise three-dimensional reconstruction of the lava tube. This map will then be used during the mission to determine immediate navigation plans for the Rover. Importantly, it will also be used to study the cave's internal structure. The three-dimensional map generated by the LiDAR data will be used to qualitatively and quantitatively characterize the cave. For example, the 3D map can be used to determine the length of the lava tube, its width at any given point, and its uniformity.

SuperCam

SuperCam performs three primary methods of spectroscopy: LIBS, VISIR, and Raman. Figure 47 is an example data set for SuperCam's LIBS method. [8]

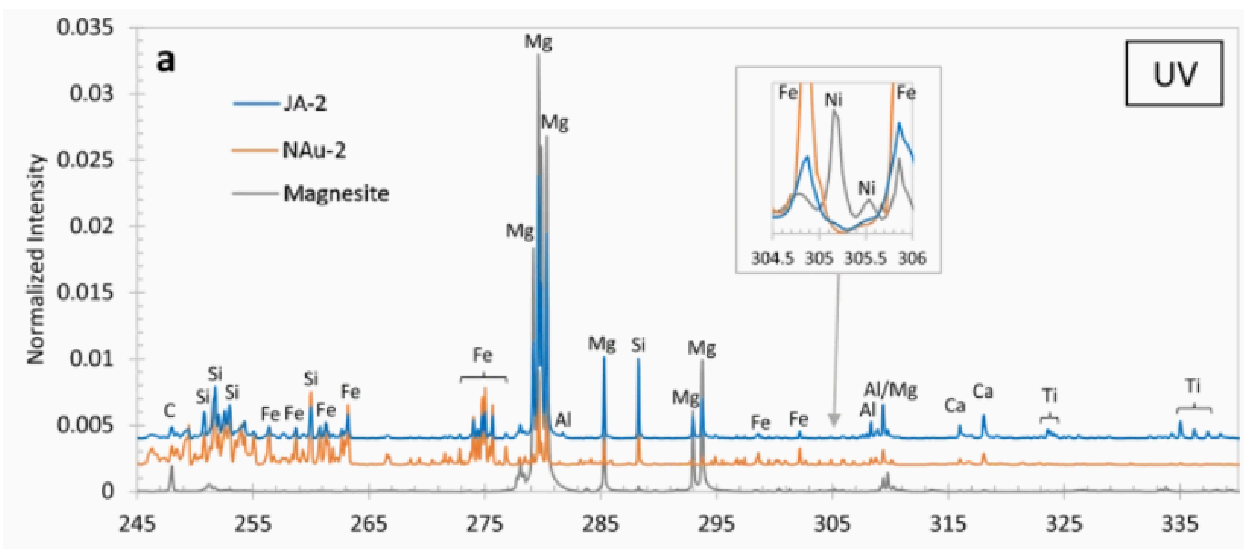

Figure 47: *LIBS results, SuperCam [8]*

This data was produced by tests ran on SuperCam at Los Alamos National Laboratory [8]. Emission spectra are intrinsic to elements, which is why spectroscopy allows for the identification of specific elements. Additionally, spectroscopy is often used to identify the abundance of elements within a sample. Magnesium (Mg), for example, has an emission spectrum that spikes at around 285 nm. Any sample containing a considerable amount of Mg will then emit at 285 nm at a considerable intensity, as shown in Figure 47.

For this mission, a large concentration of silicon and iron is expected. Oxygen may also appear in considerable amounts as Martian regolith contains several metal oxides. This method will be used to determine the elemental composition of the regolith within the cave. Emission intensity spikes will be identified and quantified to determine percent compositions of the soil. Once the composition has been determined, the composition of the cave's regolith may be compared with that of the surface regolith. This can provide insight into the conditions under which the cave formed, which could in turn yield further insight into the early development of Mars.

Figure 48 depicts the infrared spectral results for VISIR [7].

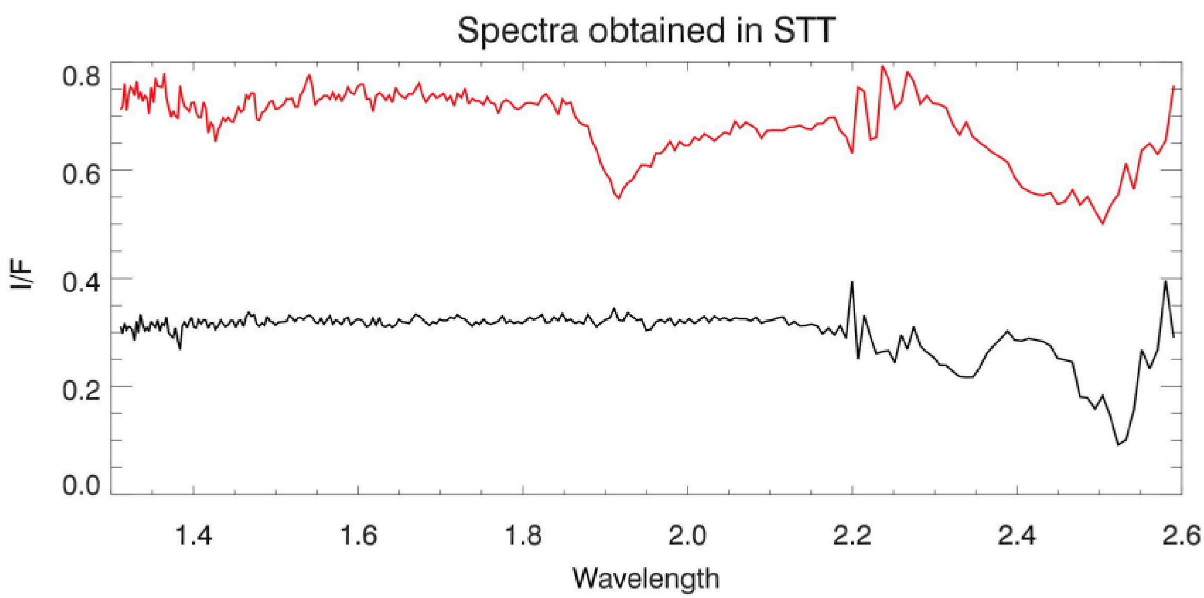

Figure 48: *VISIR Results, SuperCam [8]*

VISIR (also referred to separately as VIS and IR) allows SuperCam to identify minerals at distant outcrops within the mm-state. This data is test data from the System Thermal Test (STT) at the Rover level for Perseverance right before it was shipped to its launchpad before heading to Mars. The black line shows the spectra for Calcite, and the red line shows the spectra for Gypsum. The raw data would then be converted to radiance by using calibrated wavelengths. [14]

For this mission, VISIR will be collecting the light reflected from the samples within the lava tube to identify the mineral composition. This breakdown will allow for a better understanding of how much olivine is present, along with other minerals such as iron oxides. Near-infrared spectroscopy (covered partially by VISIR) can also be used to analyze the abundance of magnesium and iron within an olivine sample. The abundance of these components may provide insight into the temperature conditions under which the olivine formed.

Figure 49 is an example data set for SuperCam's Raman spectrometry method [8].

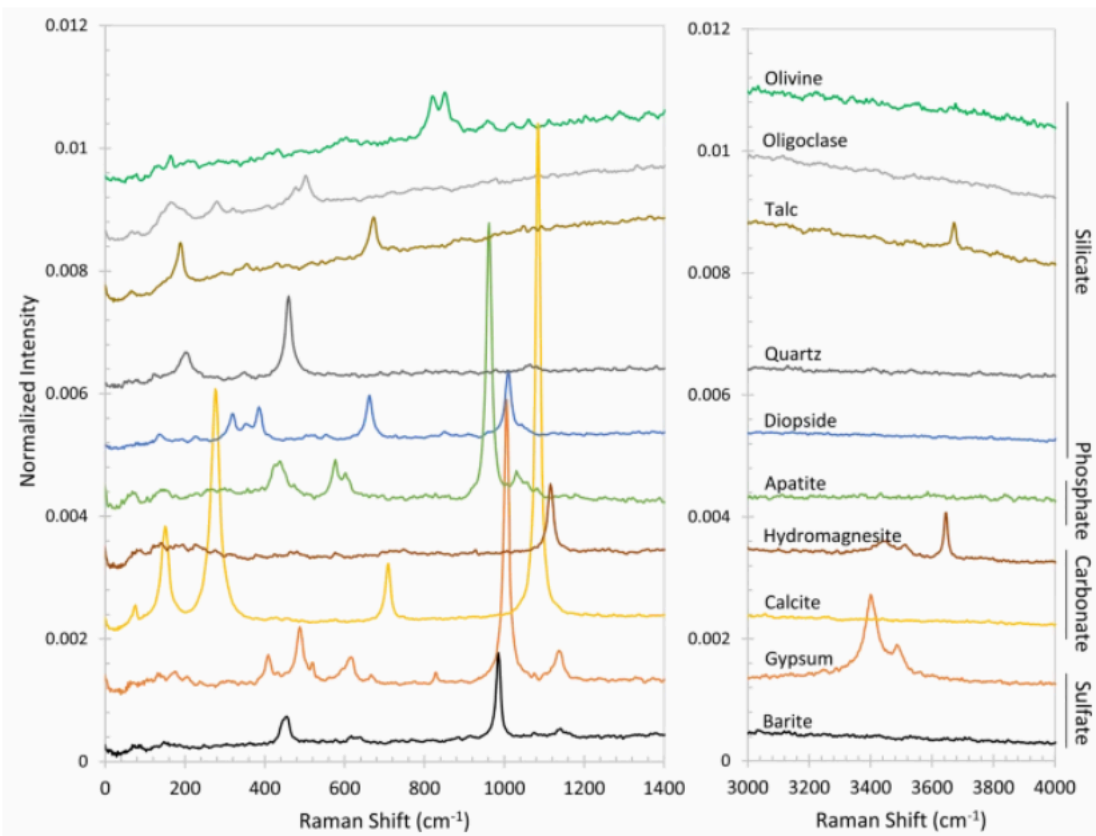

Figure 49: *Raman Spectroscopy Results, SuperCam [8]*

Raman spectroscopy is another method SuperCam will use to analyze the cave regolith. Raman will prove to be the most effective for detecting the presence of olivine and it can do so at only a 1% abundance [15]. The graph on the right of Figure 49 illustrates a control sample used to detect several samples, including olivine, which this mission is interested in. The compounds above have known emission spectra. Data on the emission spectra from cave samples can be compared with emission spectra of laboratory samples in order to identify the presence of key minerals.

Data from Mars, however, is expected to have more background noise due to non-ideal temperatures and grain sizes. The size of grains can slightly magnify emission intensity, but using RMI images, the grain sizes can be determined (or estimated) and accounted for in error calculations. Also, as with each of the spectroscopy methods, shifts in wavelength may occur due to temperature and atmospheric pressure. These will be identified during the calibration procedures. The data from this method will be used to determine the abundance of olivine within the cave. This data will be added to the existing measurements of olivine abundance across Mars. Existing data indicates a low presence of olivine within the Tharsis region, which CC0769 is located in. The discovery of olivine in this cave could provide new insight into the conditions under which Mars formed. Additionally, olivine is a mineral that is known to support certain chemolithotrophs, which are microorganisms that are capable of inorganic compounds as a source of energy. Discovering olivine within a cave environment may provide insight into the possibility of microscopic life on Mars.

Along with spectroscopy, SuperCam will also produce images using its Remote Micro-Imager (RMI). Figure 50 is an example image from the RMI [8].

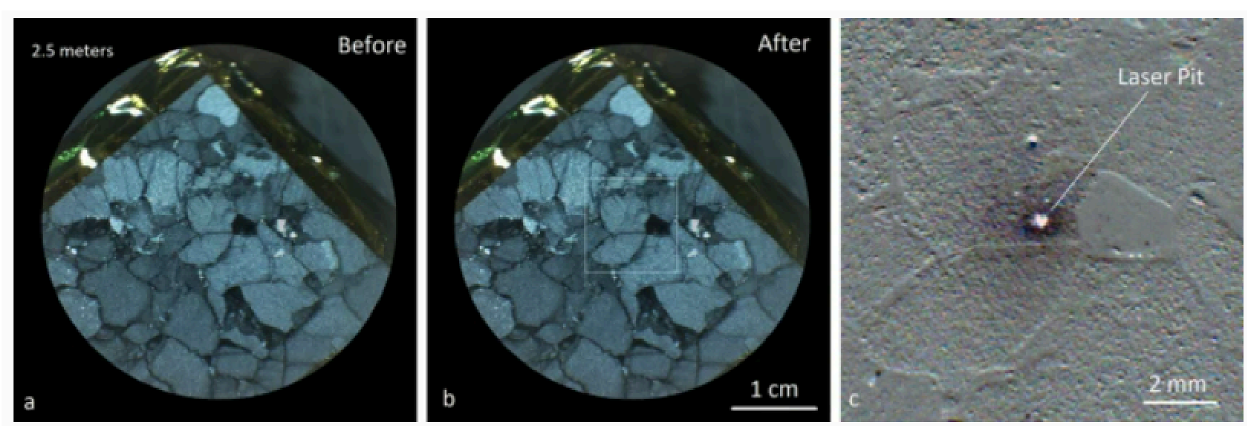

Figure 50: *RMI Results, SuperCam [8]*

Similar to Perseverance, this mission seeks to capture an image of each sample site before and after spectroscopy is conducted in order to contextualize each data sample. Figure 50 is that of a sample on Earth taken during testing. On Mars, images are expected to be of the same resolution. The contents of the image, however, are expected to change. Firstly, the subsurface context of this mission will lead to a lack of light. As discussed in section 4.1.6, the RMI contains functions that allow it to produce images in low-light environments. Nevertheless, a loss in quality should be expected. From the images taken by the RMI, the sample sites can be characterized geologically. The images, for example, can be used to identify signs of weathering or erosion on rocks or grains. Also, as previously stated, the images provided can be used to estimate the grain size in order to quantify any impacts on the Raman measurements. The images provided by the RMI provide small-scale details into the cave’s terrain; this can be used alongside analysis of the LiDAR mapping to fully understand the internal structure of the cave.

5. Safety

5.1. Personnel Safety

5.1.1. Safety Officer

The designated safety officer for the duration of the mission is Monica Aguilar. For the mission, it was determined that credible safety risks are present affecting personnel as well as potential Rover systems. The acting safety officer has the responsibility of identifying and mitigating risks to protect all personnel and systems for the mission. Using past knowledge from previous missions it was possible to research and understand what potential hazards will be present during each phase of the mission. Resources such as the Glenn Research Center Safety Manual were used to build the safety requirements implemented for this mission [18].

5.1.2. Personnel Hazards

When dealing with electrical work, common hazards include: electrostatic shock; energized systems; interactions between electrical apparatuses and systems; de-energized (isolated) systems; battery systems; instrument transformers; and fuzes.The hazards present can lead to sharp pains, damaged nerves or possible death if hazards are not identified and mitigated. [20]

SoCoLD power and thermal system will consist of thermoelectric heaters. Whether intended or not each system will generate heat as it operates and in such care must be taken for each electronics. The first hazard present is the possibility of burns occurring when touching components while active. Another present hazard is the creation of hot spots where oil from the hand is left from contact. This can cause components to retain heat and cause burnout or damage to critical circuit components. [20]

During the manufacturing of the SoCoLD systems dangers to personnel will be present due to the exposure of heavy machine equipment. These machines create pinch points, sharp cutting edges, and high levels of noise. While they are necessary for the creation of each system of the Rover special care must be taken to prevent personnel from heavy injury. [22]

Within confined areas biological hazards can have negative effects on workers with the spread of health hazards. Within areas of close contract transmission rates are higher and can lead to the spread of sickness. Transmission can take form in direct or indirect contact where the carrier spreads the sickness onto surfaces or directly to other workers. [23]

Chemical hazards are common in manufacturing environments. While within one building hundreds of different chemicals can be found and handled by personnel, each chemical can have an adverse reaction to workers. Some examples of possible hazards from exposure are: irritation, rash, burns, cancer, and nerve damage. Some reactions occur within a period of time of repeated exposure and others can happen instantaneous. [23]

5.1.3. Hazard Mitigation

To mitigate electrical hazards, it is important to ensure that only qualified personnel should be working and operating electrical equipment. There should also be trained managers in the following positions to ensure safety protocols are being followed: high voltage systems manager; low voltage systems manager; electrical systems manager; control systems manager; and communication systems manager. Additional mitigation practices regarding electrical hazards include: the use of electrically safe tools that are rated for the level of voltage of the system; the correct Personal Protection Equipment (PPE) is provided to protect personnel from energized systems, including but not limited to insulated gloves, shoes, hardhats, eye protection, and hot sticks; the use of circuit isolators; and frequent circuit testing, which includes running protective system circuits, high voltage, and low voltage tests. [20] Lockouts are also an effective way to mitigate electrical hazards. Lockouts are physical locks or tags that can lock away a circuit for maintenance to prevent the energizing of a system. Only the qualified operator who has locked out a circuit would have the key to unlock and reactivate the system. This ensures that a system with isolated circuit breakers can isolate an area of the system off safely. Because a lockout is a physical disconnect rather than a digital disconnect, it can further prevent the possibility of the system being reenergized. This method can apply to electrical, pneumatic, and hydraulic systems. [21]

For the mitigation of burns and heat damage to electrical systems it is important for personnel to wear proper PPE. Gloves can prevent the spread of oil onto electrical systems as well as provide insulation from hot electronics. Thermal heaters can heat rapidly as well as retain heat even after de-energizing and as such should not be touched by unprotected hands. Hot gloves should be used to prevent burns and to protect circuit components from contamination resulting in shortened life expectancy of components. [20]

To mitigate risk caused by manufacturing equipment special safety procedures are set in place depending on the type of danger exposed to. When around pinch points where the machine is able to crush or grab onto a body part, shields or physical barriers are the preferred method of separation from the machine. While most machines will have this safety measure installed from the manufacturer it is also prudent to incorporate a secondary safety measure to ensure safety. This secondary measure can take the form of two handed button pushing to ensure that both hands of the personeel are away from the machine before it is turned on. This safer mitigation strategy can also go for machines that have sharp edges or rotating cutting tools. The maintaining of the distance between the personnel and the machine provides the best safety for both. To reduce the effect of hearing loss caused by machines generating a decabile range of higher than 70Db hearing protection is required. Training all personnel working in loud areas how to properly insert ear plugs or fitting for over ear plugs will provide the protection needed to prevent hearing loss. [22]

The biohazard within the working environment is caused by personnel working together in close contact. To mitigate exposure from sickness the best mitigation strategy is for the infected personnel to stay out of the workplace till the hazard is removed. Other methods that can keep a workplace free from biohazards is the use of cleaning areas of heavy use. Personnel can often share areas of work or tools allowing for easy spread of biohazards. Regular cleaning with sanitizer can remove germs or any other biohazard from surfaces and keep the workplace clean. [23]

Chemicals within a workplace will each need to be mitigated in their own respective way. While each chemical can have a different reaction effect all must be understood and PPE provided for the protection of the personnel using the chemical. With each chemical a Material Safety Data Sheet (MSDS) is created giving direction as to the dangers present and the proper handling of the chemical. The creation of a database holding all MSDS is required and access to it be given to all personnel to ensure proper compliance to the manufactures safety requirements. When not in use all chemicals must be safely stored within approved cabinets that keep exposure or accidental contact from occurring. [23]

6. Activity Plan

6.1. Budget

Table 43: *Mission Budget Breakdown*

	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6
Science Personnel:	7	7	5	5	7	7
Engineering Personnel:	7	7	10	10	5	5
Administration Personnel:	5	5	5	5	5	5
Management Personnel:	5	5	7	7	5	5

Soil Composition and LIDAR Detection (SoCoLD) in Martian Lava Tubes - Budget

Year	Yr 1 Total	Yr 2 Total	Yr 3 Total	Yr 4 Total	Yr 5 Total	Yr 6 Total	Cumulative Total
PERSONNEL							
Science Personnel	$ 560,000.00	$ 560,000.00	$ 400,000.00	$ 400,000.00	$ 560,000.00	$ 560,000.00	**$ 3,040,000.00**
Engineering Personnel	$ 560,000.00	$ 560,000.00	$ 800,000.00	$ 800,000.00	$ 400,000.00	$ 400,000.00	**$ 3,520,000.00**
Administration Personnel	$ 400,000.00	$ 400,000.00	$ 400,000.00	$ 400,000.00	$ 400,000.00	$ 400,000.00	**$ 2,400,000.00**
Project Management:	$ 750,000.00	$ 750,000.00	$ 750,000.00	$ 750,000.00	$ 750,000.00	$ 750,000.00	**$ 4,500,000.00**
Total Salaries	$ 2,270,000.00	$ 2,270,000.00	$ 2,350,000.00	$ 2,350,000.00	$ 2,110,000.00	$ 2,110,000.00	**$ 13,460,000.00**
Total ERE	$ 633,557.00	$ 633,557.00	$ 655,885.00	$ 655,885.00	$ 588,901.00	$ 588,901.00	**$ 3,756,686.00**
TOTAL PERSONNEL	$ 2,903,557.00	$ 2,903,557.00	$ 3,005,885.00	$ 3,005,885.00	$ 2,698,901.00	$ 2,698,901.00	**$ 17,216,686.00**
TRAVEL							
Total Flights Cost	$ 25,000.00	$ 25,000.00	$ 25,000.00	$ 25,000.00	$ 25,000.00	$ 35,000.00	**$ 160,000.00**
Total Hotel Cost	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 20,000.00	**$ 70,000.00**
Total Transportation Cost	$ 5,000.00	$ 5,000.00	$ 5,000.00	$ 5,000.00	$ 5,000.00	$ 10,000.00	**$ 35,000.00**
Total Per Diem Cost	$ 3,000.00	$ 3,000.00	$ 3,000.00	$ 3,000.00	$ 3,000.00	$ 6,000.00	**$ 21,000.00**

Total Travel Costs	$ 43,000.00	$ 43,000.00	$ 43,000.00	$ 43,000.00	$ 43,000.00	$ 71,000.00	**$ 286,000.00**
OUTREACH							
Total Outreach Materials	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	**$ 60,000.00**
Total Outreach Venue Costs	$ 35,000.00	$ 35,000.00	$ 35,000.00	$ 35,000.00	$ 35,000.00	$ 35,000.00	**$ 210,000.00**
Total Outreach Costs	$ 45,000.00	$ 45,000.00	$ 45,000.00	$ 45,000.00	$ 45,000.00	$ 45,000.00	**$ 270,000.00**
DIRECT COSTS							
|> Science Instrumentation	$ -	$ -	$ 10,001,500.00	$ 10,001,500.00	$ -	$ -	**$ 20,003,000.00**
|> Other Payload Costs	$ -	$ -	$ 10,000.00	$ 10,000.00	$ -	$ -	**$ 20,000.00**
Total Payload Costs	$ -	$ -	$ 10,011,500.00	$ 10,011,500.00	$ -	$ -	**$ 20,023,000.00**
|> Mechanical Subsystem	$ -		$ 28,131.77	$ 28,131.77	$ -	$ -	**$ 56,263.54**
|> Power Subsystem	$ -	$ -	$ 70,000.00	$ 70,000.00	$ -	$ -	**$ 140,000.00**
|> Thermal Control Subsystem	$ -	$ -	$ 5,000.00	$ 5,000.00	$ -	$ -	**$ 10,000.00**
|> Comms/Data Handling Subsystem	$ -	$ -	$ 405,000.00	$ 405,000.00	$ -	$ -	**$ 810,000.00**
Total Vehicle Costs	$ -	$ -	$ 508,131.77	$ 508,131.77	$ -	$ -	**$ 1,016,263.54**
|> Manufacturing Facility Cost	$ 3,000,000.00	$ 3,000,000.00	$ 10,200,000.00	$ 10,200,000.00	$ 3,000,000.00	$ 3,000,000.00	**$ 32,400,000.00**
|> Test Facility Cost	$ 1,000,000.00	$ 1,000,000.00	$ 3,000,000.00	$ 1,000,000.00	$ 1,000,000.00	$ 1,000,000.00	**$ 8,000,000.00**
Total Facilities Costs	$ 4,000,000.00	$ 4,000,000.00	$ 13,200,000.00	$ 11,200,000.00	$ 4,000,000.00	$ 4,000,000.00	**$ 40,400,000.00**
Manufacturing Margin	$ 2,000,000.00	$ 2,000,000.00	$ 11,859,815.89	$ 10,859,815.89	$ 2,000,000.00	$ 2,000,000.00	**$ 30,719,631.77**
Total Direct Costs	$ 6,000,000.00	$ 6,000,000.00	$ 35,579,447.66	$ 32,579,447.66	$ 6,000,000.00	$ 6,000,000.00	**$ 92,158,895.31**

Total MTDC	$ -	$ -	$ 5,259,815.89	$ 5,259,815.89	$ -	$ -	**$ 10,519,631.77**
FINAL COST CALCULATIONS							
Total F&A	$ -	$ -	$ 525,981.59	$ 525,981.59	$ -	$ -	**$ 1,051,963.18**
Total Projected Cost	$ 8,991,557.00	$ 8,991,557.00	$ 39,199,314.24	$ 36,199,314.24	$ 8,786,901.00	$ 8,814,901.00	**$ 110,983,544.49**
Total Cost Margin	$ 2,697,467.10	$ 2,697,467.10	$ 11,759,794.27	$ 10,859,794.27	$ 2,636,070.30	$ 2,644,470.30	**$ 33,295,063.35**
Total Project Cost	$ 11,689,024.10	$ 11,689,024.10	$ 50,959,108.52	$ 47,059,108.52	$ 11,422,971.30	$ 11,459,371.30	**$ 144,278,607.83**

Do not change percentages in the boxes below unless mission concept instructions specify otherwise.						
F&A %	10%	10%	10%	10%	10%	10%
Manufacturing Margin	50%	50%	50%	50%	50%	50%
Total Cost Margin	30%	30%	30%	30%	30%	30%
ERE - Staff	28%	28%	28%	28%	28%	28%

6.1.1. Personnel

Year 1 and Year 2 will require the most research to be done and science personnel, allowing for a budget of $2,903,557.00 each year. During Year 3 and Year 4, more engineers will be required as the project progresses to final fabrication and system assembly. This has a budget of $3,005,855.00 each year. Year 5 and Year 6 will move into integration, testing, and launch. Less personnel will be needed at this stage, allowing for a budget of $2,698,901.00 each year. This makes a total of $17,216,686.00 budgeted for personnel.

6.1.2. Travel

Based on the average costs of roundtrip flights to Cape Canaveral, FL; transportation; and per diem costs, a budget of $43,000 for each year in a span of 5 years of the project was set. During year 6 when the launch is set to occur, more personnel are scheduled to travel. This allows for a budget of $71,000 for year 6. This makes a total of $286,000 budgeted for travel.

6.1.3. Outreach

Outreach is to bring support and knowledge of the SoCoLD mission out to the budget. To do so costs for materials was estimated to be $10,000 each year giving access to supply. For finding and renting venues to take part in, a budget of $35,000 was given for each year.

6.1.4. Direct Costs

Total payload costs are budgeted for $20,023,000.00 in total, split between Year 3 and Year 4. This is broken down into science instruments and additional payload costs. The science instruments are budgeted as follows: $10,000,000 for SuperCam; and $1,500 for the Innoviz360. Additional payload is budgeted for $10,000.

Total vehicle costs are budgeted for $508,131.77 in Year 3 and Year 4, for a total of $1,016,263.54. This is broken down and budgeted as follows: $28,131.77 for the mechanical subsystem; $70,000 for the power subsystem; $5,000 for the thermal control subsystem; and $405,000 for the communications/data handling subsystem.

Total facilities costs are budgeted for $40,400,000 in total. The manufacturing costs are budgeted for $30,719,631.77, and the test facility costs are budgeted for $8,000,000.

6.2. Schedule

Pre-Phase A:

The Concept Studies will be conducted primarily by the science and engineering teams. Throughout this phase, these teams will focus on analyzing the customer's needs, the conditions of the mission environment, and given constraints in order to draft top-level system requirements and science goals/objectives. Alongside the development of these requirements, the teams will begin development on V&V procedures for each system requirement.

Studies began on 5/31/22 and concluded on 6/13/22 with the formation of a general mission concept.

Table 44: *Mission Schedule, Pre Phase A*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2022	
							M	J
1	**Concept Studies (Pre-Phase A)**		5/31/22	6/13/22	14	1		
1.1	Identification of top-level system and customer requirements	All	5/31/22	6/6/22	7			
1.2	Broad research into science goals and objectives	Science	6/6/22	6/11/22	6			
1.3	Early development of V&V approaches	Engineering	6/11/22	6/12/22	2			
1.4	Formation of general mission concept	Science, Engineering	6/11/22	6/12/22	2			
1.5	Schedule Margin		6/12/22	6/12/22	1			
1.6	◆ Completion of mission concept and MCR		6/13/22	6/13/22	1			◆

Phase A:

Concept and Tech Development will be held by the science and engineering teams immediately following the conclusion of the Concept Studies. The science team will work to clearly define the mission's science goals and objectives, summarized in a Science Traceability Matrix. The engineering team will further review system requirements in order to develop further requirements on a subsystem level. Following this, the team will identify risks to the mission and establish mitigation plans/research.

Development lasted a week and concluded on 6/20/22 with the finalization of the Mission Concept Readiness Review (MCRR).

Table 45: *Mission Schedule, Phase A*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2022
							J
2	**Concept and Tech Development (Phase A)**		6/13/22	6/20/22	8	3	
2.1	Defining strict science goals and objectives and form an STM	Science	6/13/22	6/14/22	2		
2.2	Further development of top level system and subsystem requirements	Engineering	6/14/22	6/16/22	3		
2.3	Drafting of V&V plans for system and subsystems	Engineering	6/14/22	6/16/22	3		
2.4	Identification of risks in detail and develop mitigation plans	Engineering	6/16/22	6/18/22	3		
2.5	Schedule Margin		6/18/22	6/20/22	3		
2.6	◆ Completion of SRR and MDR (or MCRR)		6/20/22	6/20/22	1		◆

Phase B:

The Preliminary Design and Tech Completion will be conducted by all teams immediately after the Concept and Tech Development. The team will assign key officers/leads in order to develop a program management plan. These officers, along with the help of others, will work to develop safety policies, outreach plans, a preliminary schedule, and a budget. The science and engineering teams will conduct research on instrumentation and subsystem components in order to make preliminary selections. These teams will also work to further refine established mission requirements, V&V methods, risk mitigation plans, and to strictly define mission success criteria. The engineering team will also continue development on each major subsystem. Teams will then develop a Concept of Operations and Milestone Schedule. Teams will also begin developing manufacturing plans.

Work on the Preliminary Design Review (PDR) began on 6/21/22 and will conclude on 8/15/22. The PDR will be presented no later than 9/2/22.

Table 46: *Mission Schedule, Phase B*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2022			
							J	J	A	S
3	**Preliminary Design and Tech Completion (Phase B)**		6/20/22	9/2/22	75	19				
3.1	Identifying officers & leads and development of program management	All	6/20/22	6/21/22	2					
3.2	Development of safety policy and outreach plans	Admin	6/21/22	6/29/22	9					
3.3	Research instrumentation and components	Science, Engineering	6/20/22	6/30/22	11					
3.4	Preliminary selection of instrumentation	Science, Engineering	6/30/22	6/30/22	1					
3.5	Drafting budget and mission schedule	Admin	6/20/22	7/1/22	12					
3.6	Further research on instrumentation and components	Science, Engineering	7/5/22	7/8/22	4					
3.7	Development of major subsystems design	Engineering	7/6/22	7/9/22	4					
3.8	Refinement of requirements and success criteria	Science, Engineering	7/7/22	7/10/22	4					
3.9	Development of ConOps and Milestone Schedule	Admin	7/8/22	7/11/22	4					
3.10	Drafting of reviews on systems and major subsystems	Engineering	7/12/22	7/14/22	3					
3.11	Refinement of V&V procedures on subsystem level	Engineering	7/13/22	7/15/22	3					

3.12	Development of manufacturing plans	Admin	7/14/22	7/16/22	3					
3.13	Refinement of risk mitigation plans	Admin, Engineering	7/15/22	7/17/22	3					
3.14	Rigorous outlining of scientific approach and expectations	Science	7/16/22	7/18/22	3					
3.15	Development of conclusion of PDR	All	7/19/22	7/31/22	13					
3.16	Review and finalization of PDR	All	7/20/22	8/15/22	27					
3.17	Schedule Margin		8/15/22	9/2/22	19					
3.18	◆ Completion/Presentation of PDR		9/2/22	9/2/22	1					◆

Phase C:

Final Design and Fabrication will be conducted by all teams some time after the PDR presentation. Teams will continue further research into instrumentation and other hardware to make a final selection. Following this, the update and mission schedule will be updated, along with V&V methods, risk mitigation plans, assembly plans, and the overall system design. This phase focuses on maturing the design from the previous phase.

The “Final Design” portion will occur in the span of a year and will conclude with the completion of the Critical Design Review (CDR) around 9/8/23.

Table 47: *Mission Schedule, Phase C (Design)*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2022				2023								
							S	O	N	D	J	F	M	A	M	J	J	A	S
4	**Final Design (Phase C)**		9/9/22	9/8/23	365	63													
4.1	Continue research on instrumentation and hardware	Science, Engineering	9/9/22	11/9/22	62														
4.2	Finalize selection of instrumentation	Science, Engineering	11/9/22	11/29/22	21														
4.3	Update and refine budget and schedule	Admin	11/30/22	12/15/22	16														
4.4	Refine V&V plans and risk mitigation plans	Engineering, Safety	11/30/22	1/30/23	62														
4.5	Refine manufacturing and assembly/integration plans	Admin, Engineering	11/30/22	3/30/23	121														
4.6	Perform individual components and individual subsystem V&V tests	Science, Engineering	3/25/23	5/25/23	62														
4.7	Finalize system and subsystem designs	Science, Engineering	5/26/23	7/8/23	44														
4.8	Refinement of ConOps	Science, Engineering	5/26/23	7/8/23	44														
4.9	Schedule Margin		7/8/23	9/8/23	63														
4.10	◆ Completion/Presentation of CDR		9/8/23	9/8/23	1														◆

Phase C (cont.)

Following the CDR, the “Final Fabrication” portion will begin and will also occur in the span of a year. Manufacturing of components will begin and teams will conduct V&V tests according to the methods outlined by the CDR. V&V tests will continue in order to demonstrate readiness for integration. Following these V&V tests, the assembly/integration plans will be refined, as well as the budget, schedule, safety policies, and operations procedures. Training requirements will also be established.

This phase will end with the formation of the System Integration Review (SIR) around 10/7/24.

Table 48: *Mission Schedule, Phase C (Fabrication)*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2023			2024									
							O	N	D	J	F	M	A	M	J	J	A	S	O
5	**Final Fabrication (Phase C)**		10/7/23	10/7/24	367	61													
5.1	Manufacture/outsource components	Admin, Engineering	10/7/23	4/3/24	180														
5.2	Perform V&V tests on individual components	Science, Engineering	1/3/24	4/3/24	92														
5.3	Refining of assembly/integration plans	Science, Engineering	3/14/24	5/14/24	62														
5.4	Updating budget and schedule	Admin	5/14/24	6/3/24	21														
5.5	Development of training requirements	Admin	6/4/24	6/24/24	21														
5.6	Further development of mission operations procedures	Admin, Science	6/24/24	7/24/24	31														
5.7	Refinement of safety policies and procedures	Admin	7/25/24	8/8/24	15														
5.8	Schedule Margin		8/8/24	10/7/24	61														
5.9	◆ Completion/Presentation of SIR		10/7/24	10/7/24	1														◆

Phase D:

The System Assembly, Integration & Test, Launch & Checkout will be conducted by all teams some time after the SIR finalization. Teams will begin integrating the components and subsystems. During integration, work on the Operational Readiness Review (ORR) will begin. Following this, V&V procedures will be performed on components and subsystems. The assembling of components and subsystems will begin during ORR development. After the ORR is finalized, the work Mission Readiness Review (MRR) will begin alongside further V&V tests. Following this round of V&V, the complete system will be assembled. A third round of V&V procedures will be held and will end alongside the development of the MRR. This mission will launch on 11/24/26. After launch, work on the Post-Launch Assessment Review (PLAR) will begin as teams collect data on the system during early flight operations.
This phase will end by 1/30/27 with the finalization of the PLAR.

Table 49: *Mission Schedule, Phase D*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2024		2025												2026												2027
							N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J
6	**System Assembly, Integration & Test, Launch & Checkout (Phase D)**		11/6/24	1/30/27	816	48																											
6.1	Integration of components and subsystems	Engineering	11/6/24	1/11/25	67																												
6.2	Beginning ORR by updating documents and performing V&V	Engineering	1/11/25	1/24/25	14																												
6.3	Performing V&V procedures on components and subsystems	Science, Engineering	1/11/25	5/11/25	121																												
6.4	Assembly of components and subsystems	Engineering	5/12/25	7/11/25	61																												
6.5	Completion of ORR	Engineering	6/12/25	7/11/25	30																												

6.6	Beginning MRR by refining procedures for mission operations	All	7/11/25	7/12/25	2
6.7	Drafting of Decommissioning and Disposal procedures	Admin	7/11/25	7/25/25	15
6.8	Performing further V&V procedures on subsystems	Science, Engineering	7/12/25	1/11/26	184
6.9	Finalization of assembly of system	Engineering	12/12/25	2/11/26	62
6.10	Performing final V&V procedures and tests on system	Science, Engineering	2/12/26	8/11/26	181
6.12	Completion of MRR	All	7/11/26	8/11/26	32
6.11	Preparing of launch site and post-launch operations	All	8/11/26	11/18/26	100
6.13	Performing mission launch	All	11/24/26	11/24/26	1
6.14	Beginning of early flight operations and collecting post-launch data	Science, Engineering	11/24/26	11/30/26	7
6.15	Beginning PLAR by evaluating system-readiness using post-launch data	All	11/30/26	12/14/26	15
6.16	Schedule Margin		12/14/26	1/30/27	48
6.17	◆ Finalization of PLAR		1/30/27	1/30/27	1

Phase E:

Mission Operations will resume following the PLAR. During flight operations, the team will complete a Critical Events Readiness Review (CERR). On-flight V&V tests will be conducted. The CERR will be finalized by 3/22/27 and flight operations will resume. The primary lander will reach Mars on 7/6/27. The deployment window will span 3 days to wait out any possible dust storms. The system will then be deployed near the skylight and conduct its investigation for at least 3 days. This was assigned a span of 2 weeks on the Gantt Chart to account for any prolongment of the mission. Work on the Decommissioning Review (DR) will begin towards the tail end of the data collection period. Following data collection and transmission, data will be analyzed. The DR will be finalized by 8/20/27. Active mission operations will conclude on 9/20/27.

Table 50: *Mission Schedule, Phase E*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2027							
							F	M	A	M	J	J	A	S
7	**Operations (Phase E)**		2/7/27	9/20/27	226	32								
7.1	Beginning CERR through evaluation of system readiness	All	2/7/27	2/21/27	15									
7.2	Resuming routine flight operations and collecting data on system	Science, Engineering	2/7/27	3/9/27	31									
7.3	Finalization of CERR	All	3/9/27	3/22/27	14									
7.4	Resumption of flight operations in preparation for arrival	Science, Engineering	3/22/27	7/6/27	107									
7.5	Arrival of primary lander	Science, Engineering	7/6/27	7/8/27	3									
7.6	Rover deployment	Science, Engineering	7/8/27	7/10/27	3									
7.7	Collection and transmission of data	Science, Engineering	7/11/27	7/24/27	14									
7.8	Begin DR	All	7/18/27	7/24/27	7									
7.9	Analysis of data	Science	7/25/27	8/7/27	14									
7.10	Finalizing DR	All	8/7/27	8/20/27	14									
7.11	Schedule Margin		8/20/27	9/20/27	32									
7.12	◆ Conclusion of active operations		9/20/27	9/20/27	1									◆

Phase F:

Mission Closeout will commence following the end of Mission Operations and will begin following Mission Operations. Teams will begin by archiving the collected and derived data. Systems and operations will be disposed of and teams will begin developing the Disposal Readiness Review (DRR). During development of the DRR, teams will prepare in advance to dispose of major system assets. The DRR will be finalized by 11/30/27. Disposal will commence shortly after and conclude around 12/8/27. The mission will officially conclude by 12/13/27.

Table 51: *Mission Schedule, Phase F*

ID#	TASK	TEAM	START	END	DAYS	MARGIN	2027		
							O	N	D
8	**Checkout (Phase F)**		10/22/27	12/13/27	53	6			
8.1	Archiving of data	All	10/22/27	11/11/27	21		■	■	
8.2	Decommissioning of systems and operations	All	11/12/27	11/18/27	7			■	
8.3	Beginning of DRR	Science, Engineering	11/18/27	11/24/27	7			■	
8.4	Preparation for disposal of system assets	Engineering	11/18/27	11/24/27				■	
8.5	Finalization of DRR	Science, Engineering	11/24/27	11/30/27				■	
8.6	Disposal of system	All	12/1/27	12/8/27					■
8.7	Schedule Margin		12/8/27	12/13/27	6				■
8.8	◆ Conclusion of mission		12/13/27	12/13/27	1				◆

6.3. Outreach Summary

STEM engagement is important for all ages to participate in, and it is important to cater the materials to different age levels. In all cases, reaching out to underrepresented groups and schools should be a high priority and can be done so with the use of social media. Using social media it is possible to advertise the SoCoLD mission with updates on how the mission is progressing. It would also identify schools that would like to take advantage of the outreach program by advertising and allowing followers to bring the program to school officials. Within the outreach program itself would be an application process for schools to complete to identify what parts of the outreach the schools can take part of.

For students between kindergarten and fourth grade, offering free field trips and events through different NASA centers to families within these age groups creates opportunities to learn about aerospace for the whole community.

For students between fifth and eight grade, doing virtual or in-person presentations is a great way to introduce this age group to SoCoLD. A presentation that explains why Mars is of interest in terms of astrobiology and human exploration, and allows students to develop an understanding of what SoCoLD is trying to achieve.

For students in grades ninth to twelfth grade, presentations provided by NASA scientists about astrobiology on Mars will help students learn more about the field. Meet & Greets with NASA engineers and scientists that are on the SoCoLD team will provide a great way for students to connect on a deeper level with the project, and offer insight on career paths and education pathways to inspire students to pursue STEM careers after high school.

For community college students, an open-ended engineering challenge that includes LiDAR mapping and mineral detection would be a great way to introduce students to STEM fields through SoCoLD. This could be integrated into part 2 or 3 in the

NASA Community College Aerospace Scholars (NCAS) program.

For all university students, webinars or in-person guest lectures about SoCoLD that focus on specific parts of the project would be beneficial. Internship positions within SoCoLD can also be offered as needed for all STEM roles defined in the project.

All schools registered within the outreach program will be entered into a contest in which the winner will decide the name of the Rover. The contest will allow all students who wish to have a chance at naming the Rover to submit possible names and explanations on why it should be named. The submitted documents will be collected and voted against by popularity vote with the highest popular name being choice. The student who created the name will be given credit and given travel to see the launch of the Rover.

6.4. Program Management Approach

6.4.1. Organization Chart

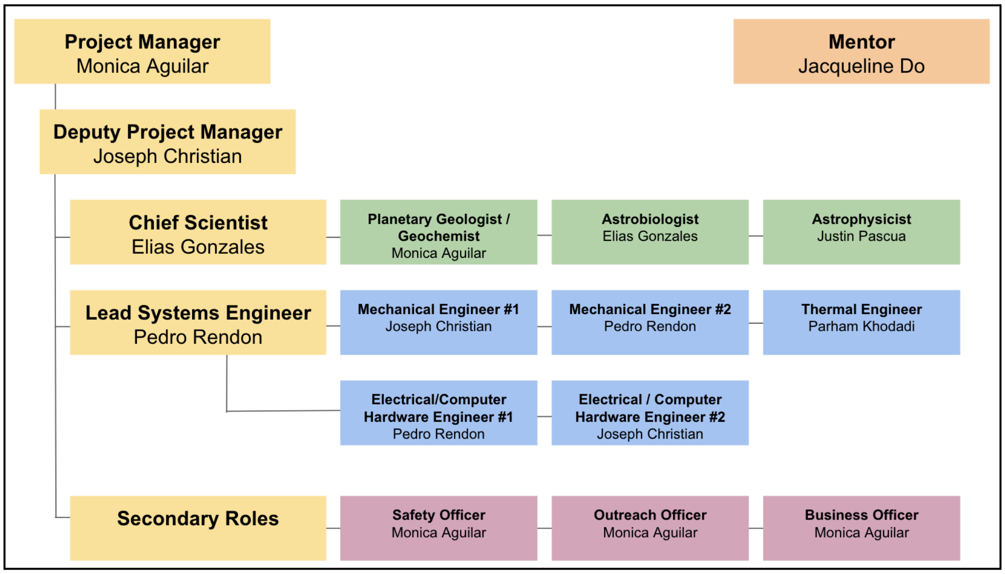

Figure 51: *Organization Chart Breakdown*

Throughout this project, the SoCoLD team worked as individuals as well as a group. All communication and file handling occurred through the use of Google Suite and Discord. Each program has folders and subsections configured to organize documents and files based on information contained. Primary communication and meetings are to take place in Discord allowing for open conversations between the teams. An additional advantage for using Discord is its ability to allow for subsections to grow with the growth of the project. Data and information compiling is collected and stored on Google Suites as a way for all team members to have access to files. Its ability to cloud store all documents and keep edit updates for access limits confusion and possible issues with documentation errors. The engineering and science teams were both encouraged to make their own meetings as needed, outside of the full team meetings. These team meetings would allow each team to discuss their specific challenges, but were still open to the entire team to contribute to the discussion. The full team meetings would be where larger decisions and check-ins were made to ensure the project stayed on track. Decisions were made with majority in favor, and all teams made use of the trade study templates as needed. Meeting notes would be available after almost every meeting.

7. Conclusion

The goal of SoCoLD will be to investigate the subsurface conditions on Mars by exploring the lava tube CC0769. The Rover will enter through CC0769's skylight using an egress system designed with a solar panel and pulley. Upon descending and reaching the subsurface, SoCoLD's science objectives will be to: map the terrain and geography of the skylight and lava tube; determine the abundance of the mineral olivine, within the lava tube; and to determine the mineral composition of the regolith within the subsurface site. Data will be collected using a heritage instrument, SuperCam and a Innoviz360 LiDAR sensor. As the Rover descends into the site and explores under the surface, the LiDAR sensor will collect data to produce a three-dimensional image of its environment. Along with the Rovers exploration, it will also conduct mineral analysis. The data will be sent back to the primary lander with a C/TT-510 UHF transceiver.

The following steps for SoCoLD include preparing for the CDR. This will allow for a final, thorough design review to support full-scale fabrication, assembly, integration, and testing. The SoCoLD team would focus on: further research into instruments and hardware; updating and refining budget and schedule; and refining V&V plans and risk mitigation. Once the Rover finishes its mission, its discoveries will provide great insight into how Martian lava tubes were formed, what resources they provide, and possibly show if life was sustained on Mars.

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