Preliminary Design Review (PDR)

Team 2 - ARISE

Arcadia Rover for Ice Subsurface Exploration

Neel Shah, Francesca Afruni, Hamdan Almansoori, Wycliffe Acquah, Terence Oscar-Okpala, Andres Oyuela, Matias Campos Tejera, Ana Moats, Nikolaos Tentas, Marcelo Samaan, Gurpreet Singh

Table of Contents

Table of Figures & Tables

1. Mission Overview

1.1 Mission Statement

The primary aim of this mission is to explore Mars to identify and characterize potential energy sources and essential resources that could support human exploration and future missions. The mission focuses on identifying chemical energy sources such as methane and hydrogen, studying the decomposition of perchlorates, and pinpointing water sources within Martian ice formations. This research aims to assess the feasibility of utilizing these resources for human activities and future missions, enhance understanding of Martian soil chemistry, and develop necessary infrastructure for sustained human presence and agriculture on Mars, aligning closely with the mission's goals of sustaining human exploration and establishing a long-term human presence.

Using a small, cost-effective robotic reconnaissance technology(rover), the mission aims to use innovative science instruments[Planetary Instrument for X-ray Lithochemistry (PIXL) & Radar Imager for Mars' Subsurface Experiment (RIMFAX)] within stringent constraints of mass(45kg), volume, and cost. The mission is dedicated to gathering essential data on identifying human mission zones and water resource characterization by using radar imaging, sending radio waves to the region of interest, and detecting deflected and scattered waves, which would help determine the type of materials within the area. The mission aims to find Mars' mysteries, specifically in regions exhibiting evidence of water ice through strategic site selection around the Arcadia Planitia, which has a shallow ice presence at relatively low altitudes. This mission's success can shape the future of Mars exploration and influence scientific understanding and human habitation's feasibility on the red planet.

1.2 Science Traceability Matrix

Table 1 : STM

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
Q10.6a What Are the Available Energy Sources for Life that may sustain human exploration and be used as resources for future human missions? [National Academies of Sciences, Engineering, and Medicine. 2023. Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. Washington, DC: The National Academies Press. https://doi.org/10.17226/26522.]	Determine possible sources of chemical energy on Mars.	Determine the abundance of Calcium Oxide within possible habitation sites.	Collect and compare the absorbance spectra of samples to the library of spectra for calcium over a 5 km^2 area	Wavelength range :	Instrument Performance Req. Value 1	Predicted Instrument Performance 1	Planetary Instrument for X-ray Lithochemistry (PIXL)	Mission Req. 1
				Instrument Performance Req. Parameter 2	Instrument Performance Req. Value 2	Predicted Instrument Performance 2		
				Instrument Performance Req. Parameter 3	Instrument Performance Req. Value 3	Predicted Instrument Performance 3		
				Instrument Performance Req. Parameter 4	Instrument Performance Req. Value 4	Predicted Instrument Performance 4		Mission Req. 2
	Determine the product of the decomposition of perchlorates on the Mars surface	Identify Oxygen gas, Calcium Chloride, Calcium Oxide, and water	Detect mass-to-charge ratio for Oxygen gas, Calcium Oxide, and Water in decomposition samples every 5m	Wavelength range :	Instrument Performance Req. Value 5	Predicted Instrument Performance 5		
				Instrument Performance Req. Parameter 6	Instrument Performance Req. Value 6	Predicted Instrument Performance 6		
				Instrument Performance Req. Parameter 7	Instrument Performance Req. Value 7	Predicted Instrument Performance 7		
				Instrument Performance Req. Parameter 8	Instrument Performance Req. Value 8	Predicted Instrument Performance 8		
Human Exploration Goal:OP-3: Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions. [Exploration Systems Development Mission Directorate: Moon-to-Mars Architecture Definition Document (ESDMD-001)].	Determine locations of Water sources to serve as water feedstock in the Ice formations on Mars.	Identify the presence of liquid water within the subsurface	Measure permittivity values greater than 80 within the subsurface.	Frequency Range :	100-500 MHz	150-1200 MHz	Radar Imager for Mars' subsurFAce eXperiment (RIMFAX)	Mission shall utilize a ground penetrating radar to penetrate greater than 1 m under martian surface. Prioritizing frequencies with deeper penetration capabilities.
				Penetration Depth :	1~2 m	10 m		
				Permittivity Value :	>=80	Predicted Instrument Performance 4		

The goal of this mission is to aid in the human exploration of Mars by determining the abundance of materials vital to chemical energy production on Mars. The science objectives are what are planned to be achieved by this mission. The first goal is to determine the locations of ice formations on the Martian surface, determine the deposition and migration of water ice, and investigate the possibility of finding liquid water beneath and utilizing it as a water feedstock to help future human missions on Mars have access to water, as well as determine the feasibility of extracting resources from water ice and perchlorates such as water, calcium oxides, and oxygen gas.

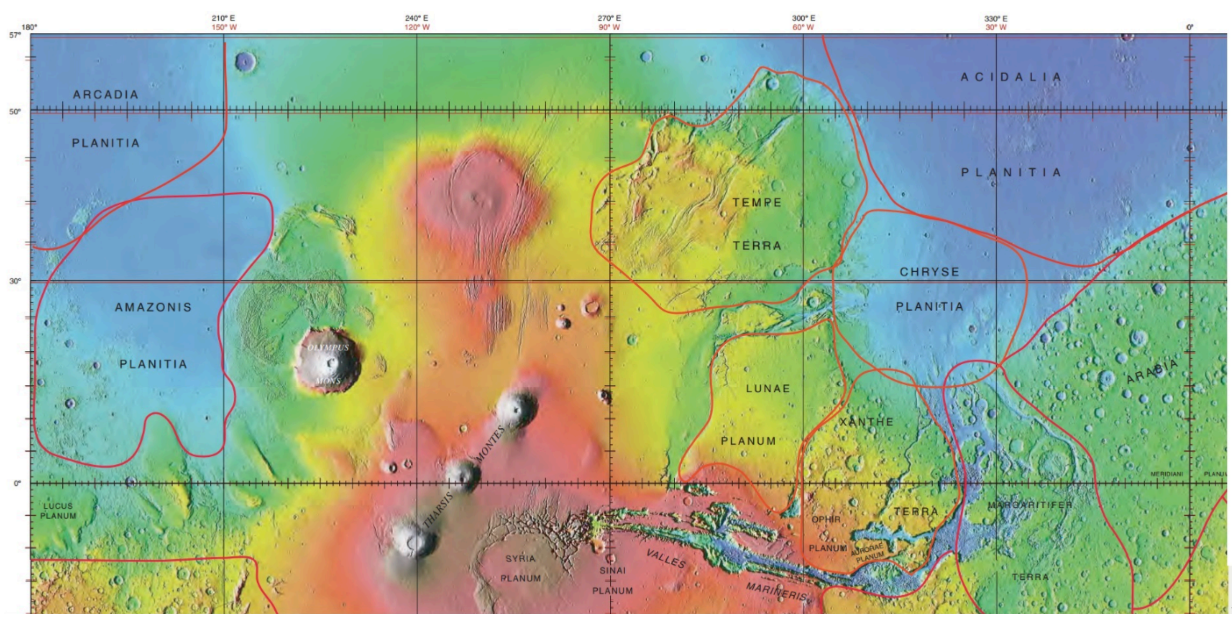
The second goal is to find possible sources of energy on Mars that could be extracted and utilized for future missions, such as determining chemical energy sources by identifying the abundance of calcium oxide within future habitation sites. The products of perchlorate decomposition, calcium chloride, and calcium oxides are considered vital reagents in the production of Calcium Carbonate and heat which can siphoned for maintaining the internal temperature of the spacecraft or certain sections during a manned mission specifically keeping water liquid during the night. The water obtained from the decomposition of perchlorates could be extracted and purified for various purposes within the manned mission with water a vital commodity in manned space missions.

1.3 Summary of Mission Location

Arcadia Planitia's flat topography, possible water ice deposits, and equatorial climate make it a good site for a surface mission on Mars. Since Arcadia Planitia is one of the few places with significant shallow ice present at a relatively low latitude, the mission's location is ideal for achieving OP-3's principal science goal, emphasizing resource availability. Arcadia Planitia is found no more than three meters below the surface and may contain silicon metal, which can be mined by highly automated methods.

According to Dr. Viola, Graduate Research Associate at University of Arizona, Arcadia's surface is covered in dark, minimally altered basaltic sand. It provides chances to use resources for building and manufacturing, backs geological research to learn about the history of Mars, helps with the search for life, shields habitats from radiation, provides stable landing grounds, and makes exploration operations more effective. There are high chances of finding active traces of gas sources, which could aid in investigating and discovering Mars' chemical energy sources.

Additionally, the surface features a regolith mix that may contain perchlorates. Perchlorates are valuable because they can produce oxygen and fuel, can be used as a resource for microbial life support, and are vital for understanding planetary geology and environmental history.



1.4 Mission Requirements

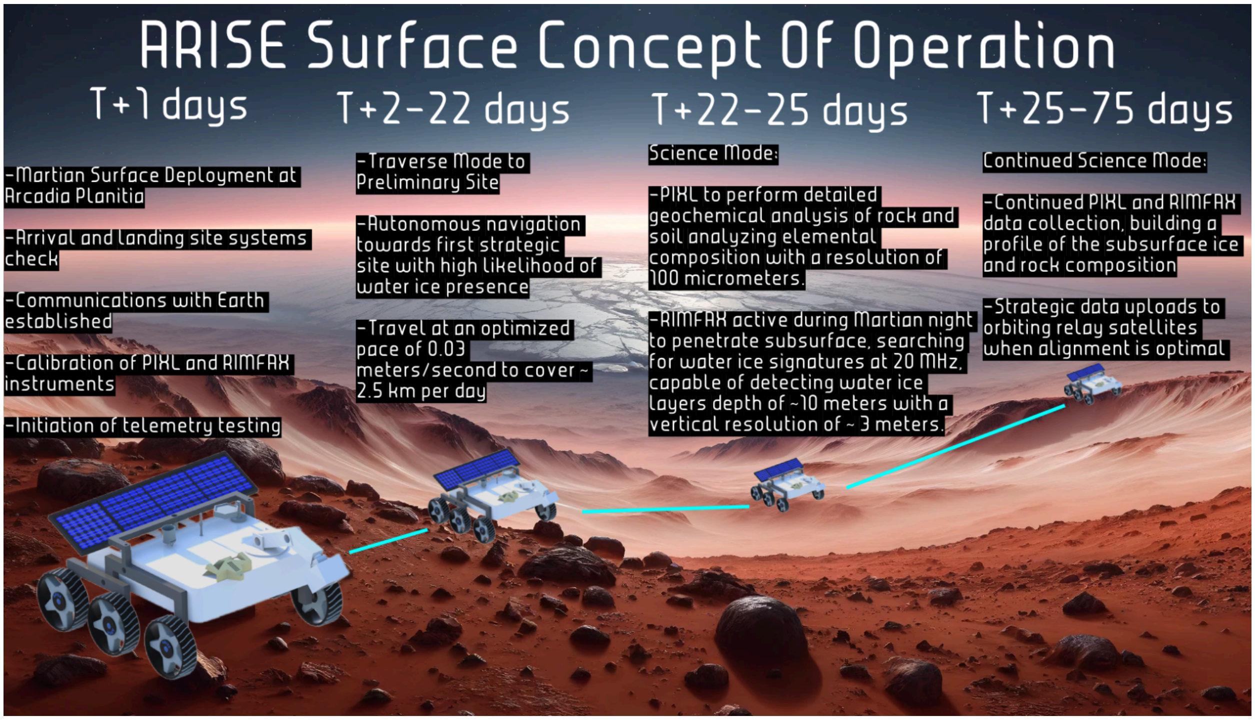
The table below illustrates the requirements for a Mars exploration development; each requirement meets the criteria outlined in the Mission Concept Task Document, ensuring the mission's success while sticking to constraints. These requirements focus on crucial sections, like navigation for terrain exploration, subsurface sampling with a mechanism for water analysis, communication between Mars and Earth, and compliance with mass and volume measures set by L'SPACE. The verification methods and plans are written to validate each requirement, ranging from simulated missions for navigation to laboratory testing for subsurface sampling mechanisms. These requirements and their verification strategies form the basis for a robust and scientifically sound Mars exploration mission concept.

Table 2: Summary of Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
SYS-01	The spacecraft shall not exceed a total mass of 45 kg.	To adhere to mass constraints specified by the customer	-	SYS-1.1, SYS-1.2	Analysis	Mechanical Subsystem	Met
SYS-1.1	The spacecraft shall not exceed a volume of Length 100 cm x Width 100 cm x Height 100 cm.	To adhere to volume constraints specified by the customer.	SYS-1	-	Inspection	Mechanical Subsystem	Met
SYS-1.2	The mission cost shall not exceed $300M (excluding launch and cruise costs).	To adhere to budget constraints specified by the customer.	SYS-1	SYS-4.4	Demonstration	Command and Data Handling Subsystem	Met
SYS-02	The launch date shall be December 31st, 2028, with a cruise time of 240 days to Mars for an	To meet the specified launch and arrival schedule.	-	-	Test	Mechanical Subsystem	Met

	arrival date of August 28th, 2029.						
SYS-03	The spacecraft shall have no more than two science instruments.	To meet the science instrumentation constraint.	-	SYS-3.1	Analysis	Payload Subsystem	Met
SYS-3.1	Prohibited materials: The rover shall not have a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof. Any radioactive material used for other spacecraft systems shall not exceed a cumulative mass of 5g.	To adhere to safety regulations and constraints.	SYS-03	-	Inspection	Mechanical Subsystem	Met
SYS-04	Transportation Parameter: The mission concept will be transported to Mars on a separate, primary launch vehicle equipped with a power supply sufficient for transit.	To meet transportation requirements.	-	SYS-4.1,SYS-4.2,SYS-4.3	Demonstration	Power Subsystems	Met
SYS-4.1	Site Selection and Landing Parameter: The landing site must be at any longitude and no greater than 60 degrees latitude, within a Potential High Priority Radar Targeting Zone, and	To meet landing site selection criteria.	SYS-04	-	Test	Guidance, Navigation & Control Subsystem	Met

1.5 Concept of Operations (ConOps)



1.6 Vehicle Design Summary

The following image shows the final design of the rover in its deployed configuration. Detailed explanations of each subsystem can be found in their respective sections in this document.

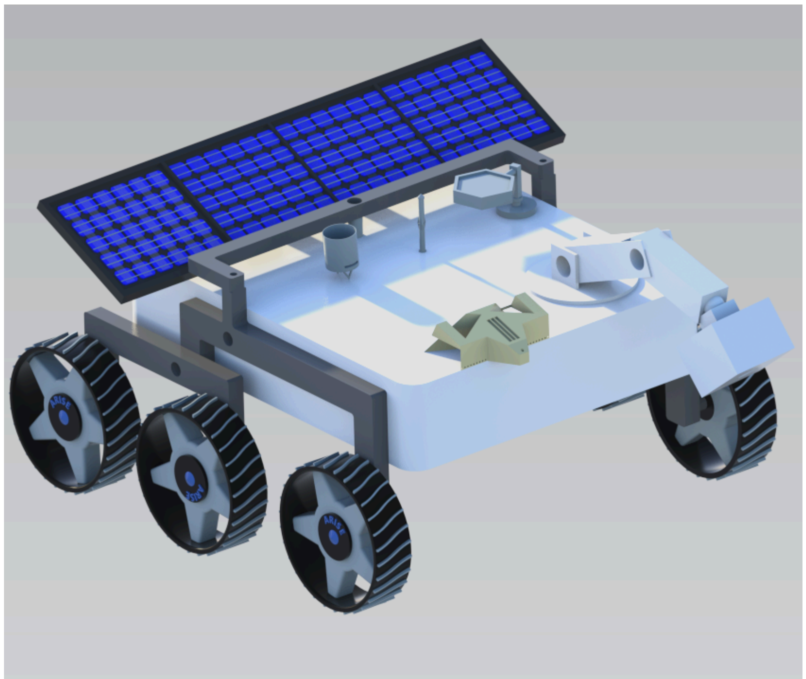


Figure 1: Vehicle Design

The following table contains general information about the mass, volume and total power output of the rover.

Measurement	Value
Mass (kg)	44.5
Volume (m^3)	0.305
Power(Watts)	200

1.7 Science Instrumentation Summary

The two instruments that shall be on the payload subsystem are the Planetary Instrument for X-ray Lithochemistry (PIXL) and the RIMFAX (Radar Imager or Mars Subsurface Experiment). The PIXL can define the chemical and elemental composition of minute samples accurately. The PIXL is equipped with an X-ray spectrophotometer that will determine the presence and abundance of Calcium Oxide and other elements and compounds within possible zones of interest. Its function will intersect with the search for water, calcium oxide, and perchlorates. The instrument will record absorbance spectral data generated from the sample within a small sample within the region of interest by transmitting X-ray radiation to vaporize the samples from various unique areas within the chosen region of interest and analyze the X-ray fluorescence detected. Calcium is expected to produce bluish fluorescence. The expected data return is about 2 megabytes per day. The PIXL is also equipped with a nightlight as it requires pictures of the rock samples for autonomous positioning. The PIXL instrument is vital to the mission objectives. By determining the abundance of Calcium Oxide and Calcium Perchlorate, we can determine the approximate amount of energy that can be generated from reactions of Calcium and Carbon Dioxide. This energy will be geared towards warming liquids utilized during manned missions at night time because the temperature at night drops below the freezing point of vital liquids in the spacecraft. The abundance can determine how readily available these starting materials are and the sustainability of this chemical system.

The RIMFAX will be utilized to map and analyze the geology and geography of regolith on the Martian subsurface. This will be essential in determining possible locations of liquid water or ice within the regions of interest. The RIMFAX is a ground penetrating radar instrument that transmits radio waves through the marian surface into the various layers of the subsurface and detects and records the deflected and scattered radio waves from each layer which can be used to determine the composition and texture of the layers within that region. RIMFAX will be able to detect different subsurface layers and assess the depth and extent of the regolith. This will aid in determining the nature of the material under the landing site and expected observation zones through the propagation of radar waves sensitive to certain properties of the materials that make up the strata. These instruments will be housed on the rover and shall remotely transmit data obtained via X-band radio waves to the NASA Mars' Odyssey and Mars Reconnaissance Orbiter.

1.8 Programmatic Summary

1.8.1 Team Introduction

Table 3: Team Introduction

Name	Primary Role	University	Major	Experience
Neel Shah	Project Manager	Rutgers University	Computer Engineering	Sophomore Undergraduate student with experience in : Java, C/C++, Python, MATLAB, PSpice, and Program Management.
Francesca Afruni	Deputy Project Manager of Resources	Florida Institute of Technology	Aerospace Engineering	Junior Undergraduate student with experience in CAD modeling, coding, 3D printing, and teamwork skills.
Ana Koyasha Moats	GNC Engineer	Montgomery College Maryland	Aerospace Engineering	Freshman Undergraduate with experience in computer, marketing and teaching
Gurpreet Singh	Computer Hardware Engineer	New york city College of technology	Computer Engineering Technology	Senior Undergraduate with experience in Computer design and programming Languages
Marcelo Samaan	Mechanical Engineer	Florida Institute of Technology	Aerospace Engineering	Junior undergraduate student with experience in

				CAD and time management skills.
Hamdan Almansoori	Chief Scientist	Trinity college	Physics, Applied Math	Senior undergraduate with experience in applied research.
Terence Oscar-Okpala	Scientist	Bethune-Cookman University	Chemistry, Mathematics	Junior Undergraduate with experience in experimental design and computational chemistry.
Matias Campos	Thermal P. Engineer	University of Central Florida	Aerospace Engineering	Freshman Undergraduate student experienced in JavaScript, C, CAD modeling, and rocket simulations with aerodynamic structures.
Andres Oyuela	Mission Assurance Specialist	University of Central Florida	Aerospace Engineering	Junior Undergraduate student with experience in CAD, rockets, and coding.

1.8.2 Team Management Overview

Before the first team meeting, the members filled out a role interest form in which they answered what roles they were interested in. With this information, Michael Fogg (the team's mentor) assigned each person a primary and secondary role. As Fabian Gander argues, "Teams in which more team roles are represented report higher team performance and teamwork quality, both on the levels of individual and aggregated ratings".[8] This role-based team has three main sub-teams: Engineering, Programmatics, and Science, each with a leader. Additionally, there is the Project Manager, who, like all the roles, was decided democratically by the whole team.

With this organization, the team delegated the workload based on what duty is about. For instance, the STM will primarily be made by the Science Sub-Team. However, certain tasks are hard to do by one sub-team; in this scenario, the secondary roles would come and support. Thus, each sub-team is equipped enough to handle its tasks. In the event they are missing people for an assigned duty due to external causes, the PM will take charge of the matter and assign more members to the task.

In case there is a big thing to be decided, each member should research the things they support and bring arguments to a team meeting to discuss all trade studies. Hence, each member's vote would be considered, and in the end, it would be decided by a poll made by all the groups. In case of a draw or there is a significant disagreement between member's ideas, the mentor will give an opinion of what is best depending on the team's goals.

Each member is encouraged to spend a couple of hours per week doing their tasks and attending weekly meetings. These meetings will be held mainly on Sunday at 11:00 am ET time, a day where most of the team can attend. Additionally, there are other team and subsystem meetings in order to talk about the progress. In the scenario that a problem arises, another weekly meeting could be held to overcome the difficulty on time.

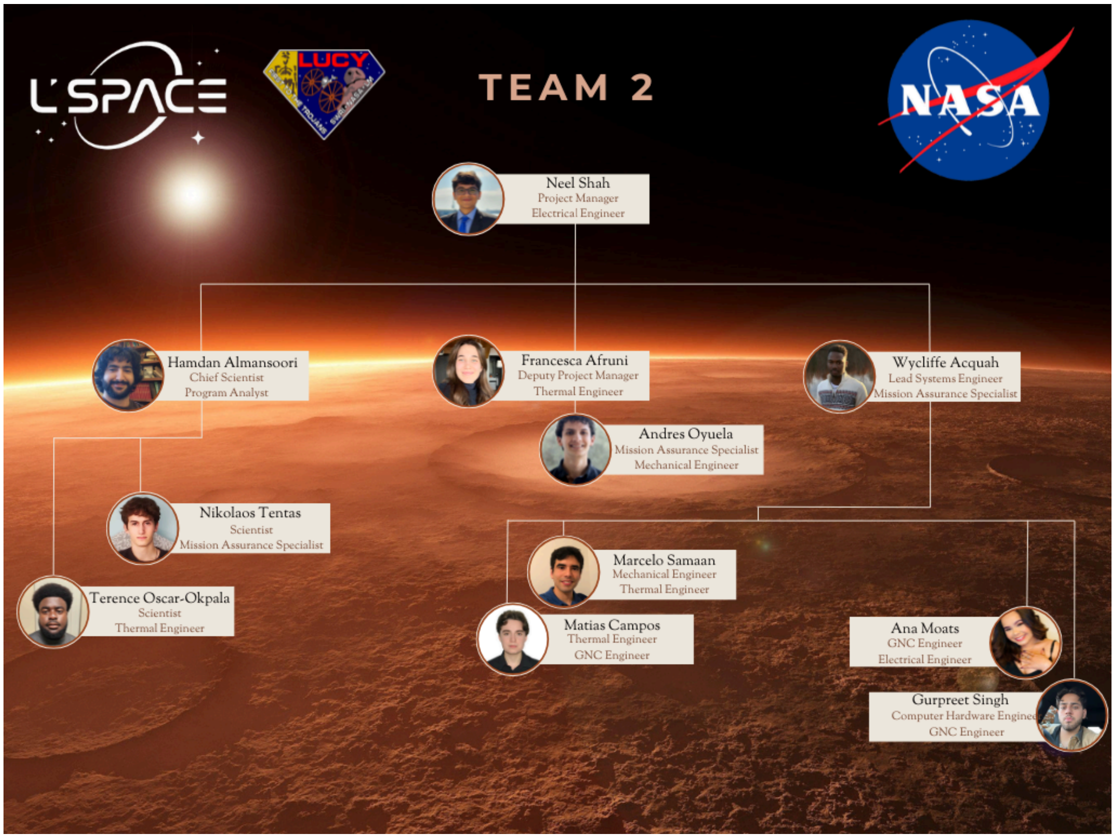


Figure 2: Team Org Chart

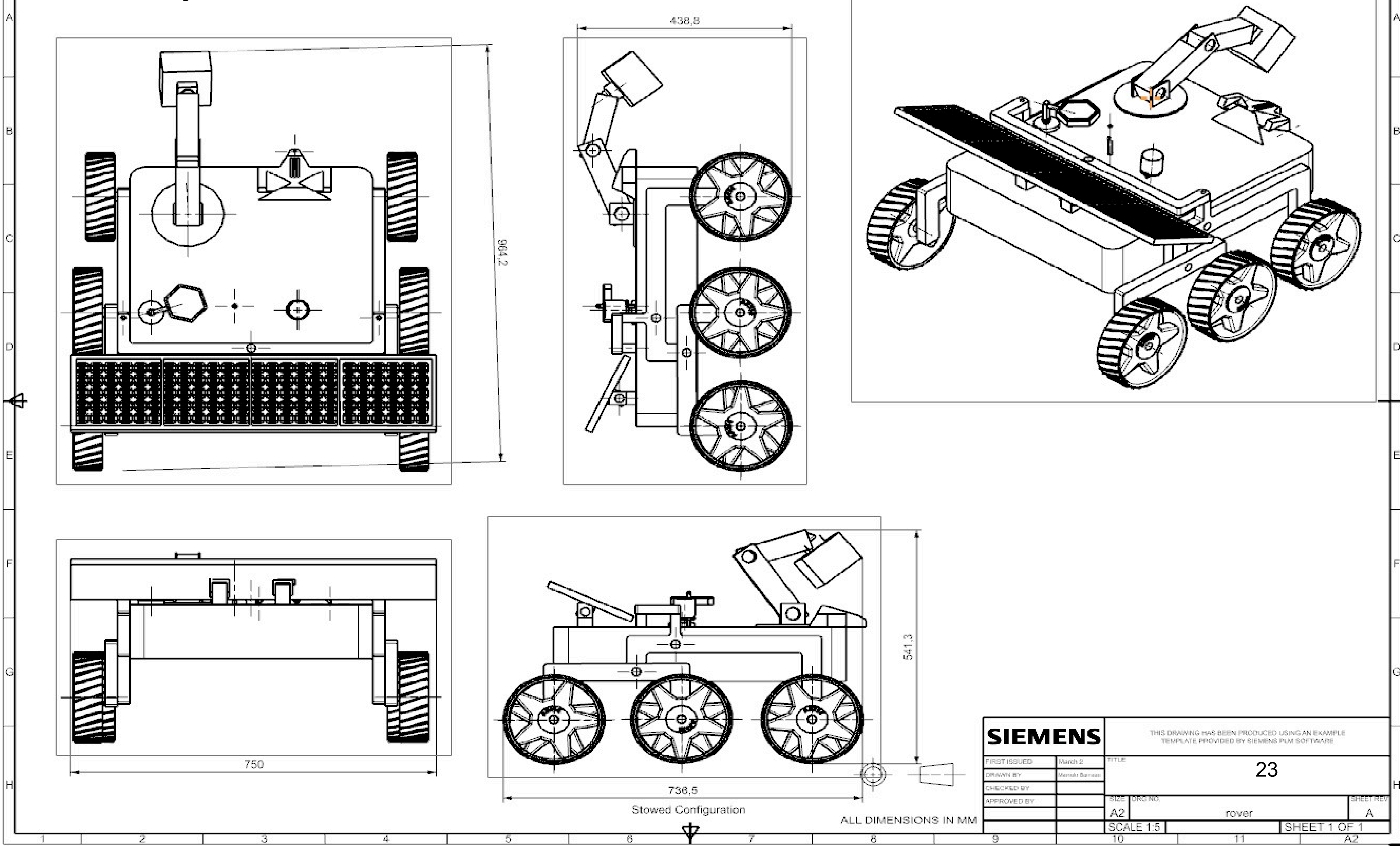
1.8.3 Major Milestones Schedule

1.8.4 Budget Overview

This Mars rover mission was initially allocated $300,000,000, but a budget cut of $50,000,000 was applied, reducing the total budget to $250,000,000 to ensure mission success. All the financial projections are calculated in U.S. dollars, assuming economic stability during the project's duration. The project timeline, closely intertwined with its budget, is delineated into key phases from launch to closeout, each with allocated funds and personnel requirements. Personnel costs, over seven fiscal years, are of a total of $21,872,610. The total estimated travel budget is $2,985,705, factoring in a 30% margin and inflation. Outreach, crucial for broadening mission engagement, presents a total of $2,270,000 for social media campaigns, expert talks, educational partnerships, and exhibits. Direct costs, analyzed with tools such as the Mission Concept Estimate Tool (MCCET), include the science instruments (RIMFAX and PIXL), the mechanical, thermal, guidance navigation and control, power, and communication/data handling subsystems. Finally, the total cost for the mission is of $ 214,767,927.

2. Overall Vehicle and System Design

2.1 Spacecraft Overview



The rover has been designed to accurately achieve all the science objectives within all mission parameters and constraints. This rover consists of several subassemblies that work together to ensure the proper performance of the spacecraft. The mechanical subsystem consists mainly of a rocker-bogie suspension system, which will guarantee the rover's stability while traversing Mars' surface. Furthermore, the arm structure is designed specifically to help the instrument PIXL achieve the science goals.

The rover's power subsystem comprises a robust solar array, consisting of 13 parallel strings with 18 series cells each, generating 16.5 watts on Mars at noon. GomSpace's NanoPower Battery 3000 mAh is chosen for night-time power, offering reliability and adaptability to Mars conditions. The power management and distribution system, utilizing the P31u, efficiently conditions solar output, charges the battery, and distributes power to various components. Key features include adjustable output switches, overcurrent protection, and successful space-tested performance. Trade studies led to the selection of the Nanopower BPX 3000mAh battery for its high specific energy and the GomSpace P31U for its compact design and efficient power distribution, ensuring a reliable and adaptable power subsystem for the rover's Mars mission.

The Command and Data Handling (CDH) subsystem in the rover is essential for managing and processing data onboard. It includes a transmitter for efficient data transmission, antennas for communication, a GPS receiver for precise location tracking, and solid-state recorders for data storage. These components enable the rover to send scientific data back to Earth or relay it to other spacecraft or ground stations in real-time. The antennas facilitate communication with mission control, allowing for timely command execution and data exchange. The GPS receiver ensures accurate navigation, enabling the rover to traverse Martian terrain confidently. Solid-state recorders provide ample storage for storing scientific data and telemetry, supporting extensive data analysis. The power amplifier strengthens signals for robust communication, even in challenging deep space environments. Transponders establish reliable communication links with deep space probes, enhancing mission success. Together, these CDH subsystem components play crucial roles in achieving the rover's scientific objectives within mission constraints.
The two science instruments that have been chosen to complete the science mission are the Planetary Instrument for X-ray Lithochemistry and the RIMFAX (Radar Imager for Mars' Subsurface Exploration. The PIXL will be used to determine the presence and abundance of Calcium Oxide within possible habitation zones. The instrument will provide spectral data by transmitting X-ray

electromagnetic waves through the sample or chosen region of interest and analyze the X-ray fluorescence detected. Calcium is expected to produce bluish fluorescence. The RIMFAX will be utilized to map and analyze the geology and geography of regolith on the Martian subsurface. This will be essential in mapping and detecting possible locations of liquid water or ice within the regions of interest. The RIMFAX works by ground penetrating radar and detecting and analyzing the reflected and scattered radio waves which can be used to determine the composition and texture of the layers within that region. These instruments will be housed on the rover and shall remotely transmit data obtained via X-band radio waves to the NASA Mars' Odyssey and Mars' Reconnaissance Orbiter.

2.1.1 Mechanical Subsystem Overview

The mechanical subsystem has been designed with the purpose of helping achieve all the mission objectives presented in this project. Accordingly, the mechanical subsystem has the task of providing the instruments all the capabilities they require in order to perform properly. Another crucial task that the mechanical subsystem must achieve is the capacity of sustaining the overall rover and all its components in an efficient and proper manner in the environmental conditions that Mars imposes. These tasks, which are concisely presented as the mechanical subsystem requirements in the following section, guided this mechanical design. Furthermore, all components have been designed to fall within the customer's constraints.

Therefore, the mechanical subsystem consists of an aluminum chassis from where the other mechanical structures are sustained. This chassis design guarantees that it is strong enough to carry other engineering components and structures, and to withstand launch loads and any type of fatigue incurred during rover operations. The suspension system chosen is a titanium rocker bogie suspension system. This suspension system used commonly in multiple other successful rovers like Perseverance, ensures the rover's stability and effective mobility while traversing a harsh terrain like Mars' regolith. It is also important to mention that due to the inner characteristics of the metals chosen for this mechanical design, like their CTE for example, that the mechanical subsystem will be capable of handling the temperature fluctuations that our deployment location on Mars imposes.

Accompanying the suspension system are a set of six robust wheels that guarantee endurance, friction, and strength. Mars' surface is a rough terrain full of rocks and ventifacts which can easily render useless unprepared wheels. Therefore, the wheels used in this rover are made of a strong aluminum alloy (Aluminum 6061) capable of effectively resisting this terrain conditions. Another important detail when designing these wheels was the tread pattern which was decided to follow Perseverance's tread pattern to increase its TRL and thus effectiveness. Moreover, electrical motors are present in all wheels. The type of motor has been accurately chosen to provide the necessary amount of torque so that the rover can achieve its desired cruise speed of 0.03 meters per second as demanded by time and science constraints.

The mechanical subsystem also consists of a mechanical arm. This arm has the capacity of 360 degrees mobility, and to extend and contract itself as necessary for the successful performance of the PIXL instrument that it will be carrying. This arm, through a ball and socket mechanism, is capable of allowing the PIXL instrument to have the required degrees of freedom to achieve the science objectives effectively. It is important to mention that the arm contracts in stowed configuration with the intent of reducing the area covered to avoid unnecessary moments during launch operations, and to avoid surpassing the volume envelope required.

A complete description of the mechanical subsystem and all its components is explained in the following section. To conclude this overview, it is possible to affirm that the mechanical subsystem fulfills all the requirements to effectively perform on Mars' terrain and help the instruments achieve the science objectives presented in this project.

Table 4: Mass of mechanical components

Part	Quantity	Mass (kg) of unit	Total Mass (kg)
Box	1	9.68	9.68
Rocker	2	2.7	5.4
Bogie	2	1.37	2.74
Differential Bar	1	1.1	1.1
Spokes	6	0.45	2.7
Aluminum Tires	6	0.7	4.2
Arm Assembly	1	2.28	2.28
Solar Panel actuators	1	0.26	0.26
Sockets head cap screws	14	0.004	0.056
Motors	6	0.26	1.56
Total Mass (kg)			**29.976**

The following table describes the volume of the rover.

Table 5: Volume of mechanical subsystem

Measurement	Volume (m3)
CAD volume	0.0137
Volume of envelope (stowed configuration)	0.305
Volume of envelope (operating configuration)	0.342

This CAD volume refers to the total space occupied by the mechanical components, and thus considers the hollow spaces of each part. The volume of the envelope is more useful for the mission concept. This volume was calculated by enclosing the overall mechanical components (in stowed configuration) in a square envelope, and thus multiplying width*length and height. As we can observe it is less than a third of the available volume. In normal operating conditions, the arm is extended and thus has an average higher volume of 0.342.

.

Table 6: TRL of each mechanical subassembly

Mechanical Subassembly	**TRL**
Chassis	5
Rocker-Bogie suspension system	6
Wheels	6
Motors	5
Arm	5
TRL	**5**

As observed from this table, the mechanical subassembly will have a TRL of five. More details of the TRL of every mechanical component can be found in the sections below.

2.1.1.1 Mechanical Subsystem Requirements

Table 7: Mechanical Subsystem Requirements

WBS Level	Requirement ID	Requirement	Notes	Parent Requirement	Verification Method
Level 2	MEC-1	Rover in stowed configuration shall fit within the 1m x 1m x 1m envelope.	Provided by mission document	SYS-05	Inspection
Level 2	MEC-2	Rover shall effectively navigate through Mars' surface	Rover shall transverse to different areas of interest to satisfy science objectives	SYS-01 SYS-02	Test
Level 2	MEC-3	Mechanical systems shall guarantee the effectiveness of science instruments.	Science Instruments require mechanical assemblies to operate.	SYS-02	Test
Level 2	MEC-4	Mechanical Subsystem shall endure loads during launch without harmful structural damages.	Loads and vibrations during launch operations can damage rover's structures if materials chosen are not strong enough.	SYS-01	Test
Level 3	MEC-2.1	Rover's suspension system shall ensure stability and maneuverability.	Mars' irregular surface demands a rover equipped with an effective stability system.	MEC-2	Test

Level 3	MEC-2.2	Rover's wheels shall be robust, fatigue resistant, and ensure traction.	Mars' regolith presents ventifacts that can harshly damage wheel structures and traction.	MEC-2	Test
Level 3	MEC-2.3	Rover shall be able to complete turns effectively.	Rover's path to areas of interest will not always be straight lines. Also, it is convenient for maneuverability.	MEC-2	Inspection
Level 3	MEC-2.4	Rover shall achieve a cruise speed of 0.03 meters per second	Based on the distances to the zones of interest, this speed allows the rover to have a proper traveling time, and effective maneuverability.	MEC-2	Inspection
Level 3	MEC-3.1	Arms carrying science instruments shall have the necessary mobility to ensure their performance.	Instruments will have their respective rotating arms.	MEC-3	Inspection
Level 3	MEC-4.1	All materials used in mechanical subsystems shall have a yield strength above 250 MPa.	This will ensure that materials used do not suffer relevant damages during load operations.	MEC-4	Inspection

Level 4	MEC-2.1.1	Rover's suspension system shall not exceed 15 kilograms.	A total weight of 45 kilograms is an important constraint.	SYS-01 MEC-2.1	Inspection
Level 4	MEC-2.1.2	Suspension system shall be able to climb obstacles of 15 centimeters	Mars' surface presents many rocks of different sizes. Suspension system will have to climb some rocks found on its path.	MEC-2.1	Test
Level 4	MEC-2.2.1	Wheel's material shall possess a yield strength greater than 400 MPa and a stiffness above 60 GPa.	Ventifacts cannot penetrate or damage outer wheel structure.	MEC-2.2	Inspection.
Level 4	MEC-2.2.2	Wheel's tread patterns shall ensure effective traction through Mars surface	Tread patterns can maximize friction to guarantee better traction in rough surfaces.	MEC-2-2	Test
Level 4	MEC-2.3.1	Front wheels shall have an angle of rotation of 40 degrees.	This will ensure turn effectiveness	MEC-2.3	Inspection
Level 4	MEC-2.4.1	Rover's motor shall generate a power output higher than 15 W	Motors with these power outputs will generate torque values that will allow the rover to reach the desired speeds.	MEC-2.4	Test

2.1.1.2 Mechanical Sub-Assembly Overview

<u>Chassis:</u>

The chassis of the rover is made of the aluminum alloy 6061, which possesses a high tensile yield strength of 276 MPa [9], thus satisfying requirement MEC-4.1. This chassis presents the corresponding connections to the other mechanical components. The top surface connects the arm holding the PIXL instrument and the RIMFAX instrument. Moreover, the top surface connects the solar panel to its actuators. Finally, the top surface connects the differential bar to the rover's body. It is relevant to mention that on top of the box, other engineering components are present like the CDH high gain antenna, for example. On the other hand, the side of this chassis presents connections to the rocker-bogie suspension system (Figure 8).

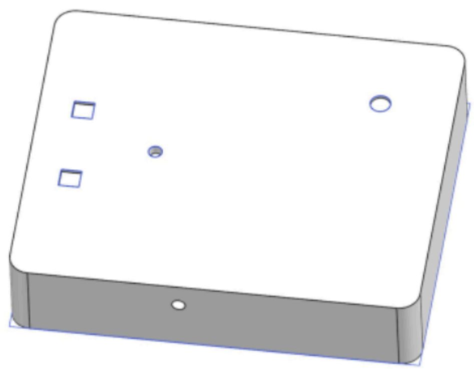


Figure 8: Rover's chassis

The dimensions of this chassis are 500x600x125 millimeters (Figure 9). In order to have enough space for the different components that have to be within the chassis, it is hollow with a thickness of 5 mm. This also reduces its total weight.

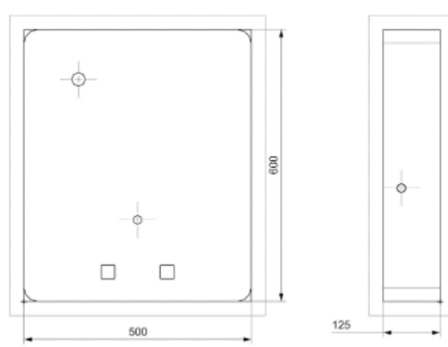


Figure 9: Chassis' Dimensions

It is crucial to mention that this chassis will have a complete and effective insulation to external environmental factors. As identified in the MCR, dust is an important harmful risk because it can damage mechanisms if it accumulates. Consequently, the connections and joints, which are the only possible entrances for dust, will be effectively sealed with, for example, silicon rubber.

This chassis has not been validated in a space environment; however, it has been validated through testing in relevant environments and thus a TRL of 5 has been given to it.

Wheels:

Because the wheels are in direct contact with the rough regolith of Mars, it was crucial to select robust materials. Consequently, and following the characteristics of the successful rover Perseverance, the tires of this rover are also made of aluminum. The specific alloy is Aluminum 7075 which is an alloy that possesses a very high stiffness value, and it is used in other common aerospace applications like in the primary structures of CubeSats [10]. This alloy has a modulus of elasticity (stiffness) of approximate 71.7 GPa and a tensile yield strength of 503 MPa [11]. Consequently, this metal will be strong enough to navigate through Mars' regolith, and thus satisfying the requirement MEC-2.2.1. On the other hand, the tire tread pattern design follows the Perseverance design of aluminum cleats for enhanced traction [12]., thus satisfying MEC-2.2.2 (Figure 10).

Figure 10: Tire design and tread pattern

The wheels' tire has a radius of 20 centimeters and a thickness of 2 centimeters (Figure 11). This high value of thickness was given to prevent problems like the one Curiosity encountered. As described in our physical environmental hazards of the MDR: the rocky terrain generates specific challenges for the rover's wheels. For example, this problem was encountered by the "Curiosity" rover, whose wheels were proven to be very susceptible to puncture [13]. This was due to immobile, wind-eroded pyramidal rocks embedded in bedrock, also called ventifacts [13].

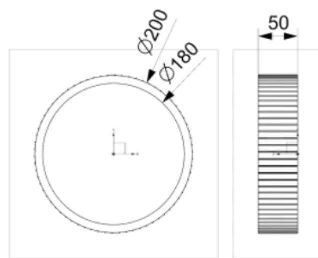


Figure 11: Wheel dimensions

This wheel design with the characteristics mentioned above should be able to traverse Mars' surface safely and effectively by providing enhanced traction and by being strong enough to resist the fatigue created by the rough regolith. Consequently, this wheel design ensures that the requirement MEC-2.2 will be effectively achieved.

As described in the requirements section, our rover necessitates for maneuverability to be able to perform effective turns. Consequently, the front wheels will be able to rotate 40 degrees left and right as shown in figures 12 and 13, thus satisfying requirement MEC-2.3.1.

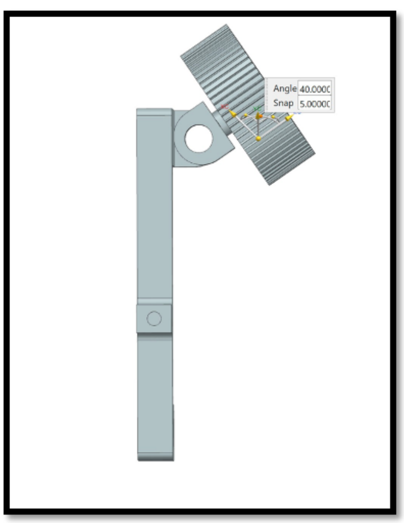


Figure 12: Wheel rotation for left turn

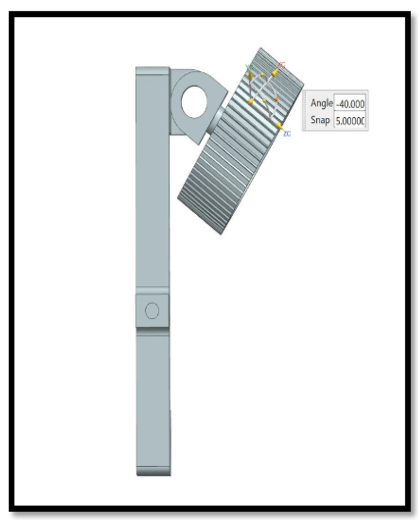


Figure 13: Wheel rotation for right turn

Although other rovers like Perseverance have steering motors for the front and back wheels, the rover presented in this PDR will only have operating steering motors for the front wheels. For the characteristics of this mission, maneuverability shall be enough to achieve the science objectives. Furthermore, as demonstrated in the SRR trade studies, this decision saves costs, weight, and complexity.

As mentioned, this wheel design mainly follows the wheel design of the Perseverance Rover. Nevertheless, the wheel design has been adapted to fit into the mission requirements of this project. Consequently, the TRL of the wheels is a 6.

Suspension System:

There is a crucial importance in a rover's suspension system when traversing Mars' surface. This is due to the irregularities that it presents, which can destabilize the rover and, in a worst-case scenario, make the rover fall over. Consequently, the rover suspension system designed for this rover is a rocker-bogie suspension system with a differential bar above the chassis. This design was successfully implemented and tested in the 2020 Perseverance rover. This suspension system consists of three main components: the rocker, the bogie, and the differential bar. As defined by NASA, the differential connects the left and right rockers and to the rover body in the center of the rover's top deck [12]. The differential bar is what ensures stability by lowering one rocker when the opposite side rocker moves up. This guarantees that the wheels always touch the ground, and thus provide support to the rover when passing through tilted surfaces. Also, it helps to maintain a relatively constant weight on each of the rover's wheels [12]. Lastly, the rocker connects the front wheel to the differential and the bogie in the rear, whereas the bogie Connects the middle and rear wheels to the rocker [12].

In this design, the rocker-bogie suspension system has been adapted to the mission requirements, and its complexity has been reduced in comparison to Perseverance to improve manufacturability, as observed in Figure 14.

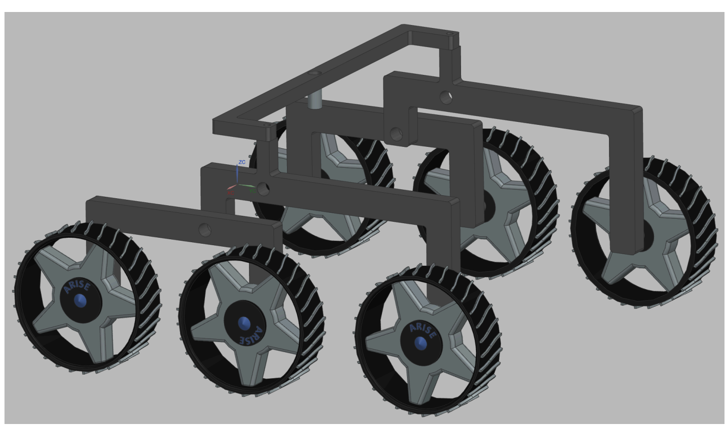


Figure 14: Rocker Bogie Suspension system of the rover

The material chosen for the components of the suspension system is titanium, the same material used in the Perseverance suspension system. The specific alloy of Titanium is TI-6AI-4V, which is a very strong material with a tensile yield strength of 880 MPa, thus guaranteeing the durability of these crucial mechanical components. Figure 9 also shows the spacing between the rockers and the length of the differential bar which is approximately 55 centimeters. The dimensions of the rocker and bogie are shown in figure 15 and 16.

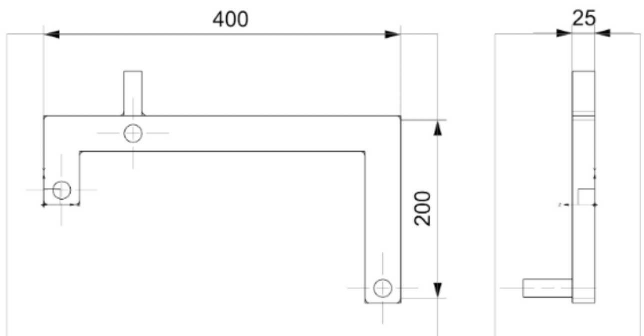


Figure 15: Rocker Dimensions

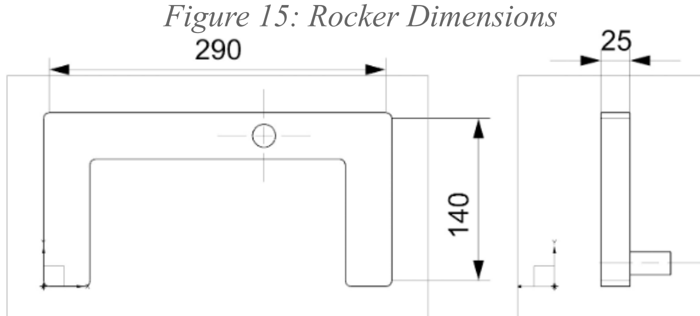
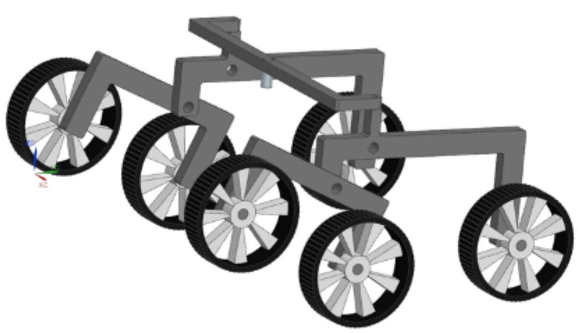


Figure 16: Bogie Dimensions

It is important to mention that the rockers and bogies are hollow. This is crucial because of the need to place all mechanisms and electronics within the protection of the titanium bars. This will prevent dust from clogging gears and damaging structures. Figures 17 and 18 demonstrate the underlying principles of the rocker-bogie suspension system for the designed rover.



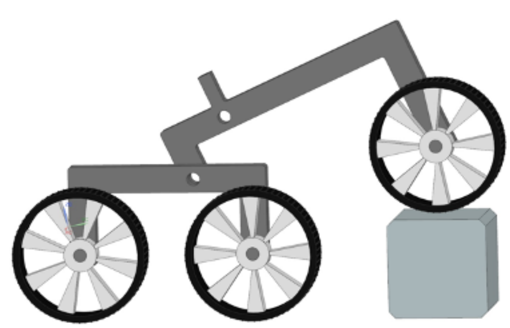


Figure 17: Upward movement of both Bogies. *Figure 18: Rocker climbing obstacle*

In these figures it can be observed some of the movements that the rocker-bogie suspension system provides. In figure 17, the bogies move upwards while the other wheels remain in their positions. This would correspond to the rover reversing for example. On the other hand, figure 18 demonstrates what would happen if the rover encountered an obstacle in its path, here the rocker's wheel would move upwards through the obstacle while the two rocker wheels would remain touching ground, ensuring stability and traction. The obstacle presented in the image has a height of 15 centimeters with the purpose of demonstrating that the requirement MEC-2.1.2 can be satisfied with this suspension system. Consequently, it is possible to affirm that the suspension system chosen for this rover satisfies completely MEC-2.1.

Similar to the wheel design, the suspension system closely follows Perseverance, but it has been modified to the mission constraints, and thus the TRL is a 6.

<u>Motors:</u>
The type of electrical motor chosen for this rover is based on the requirements. MEC-2.4 requires a rover cruise speed of 0.03 meters per second. This speed was estimated to be the ideal based on the distances that the rover will travel, and the time constraints of the rover's battery lifetime and mission schedule. Analysis performed with this speed and the wheel radius of the rover showed that the minimum required torque to achieve this speed was 1.6324 Newtons*meter or 1632 millinewtons*meter. The following figure shows all calculations and analysis performed.

Torque and Power Calculations

```
Radius=0.1;%m
Mass_Earth=44;
Mars_gravity=3.71; %m/s^2
Torque_required_total= Mass_Earth*Mars_gravity*Radius*0.6
```

```
Torque_required_total = 9.7944
```

```
Torque_required_per_wheel=Torque_required_total/6 %Nm
```

```
Torque_required_per_wheel = 1.6324
```

```
Velocity_required=0.05; %ms^-1
Power_per_wheel=Torque_required_per_wheel*Velocity_required/Radius
```

```
Power_per_wheel = 0.8162
```

```
Total_Power=Power_per_wheel*6
```

```
Total_Power = 4.8972
```

Motor Specifications and Gear Ratio Calculation

```
%Motor chosen RE 30 Ø30 mm, Precious Metal Brushes, 15 Watt

Nominal_torque=51.3; %mNm
Mass_motor=260; %grams

Gear_Ratio=Torque_required_per_wheel*10^3/Nominal_torque
```

```
Gear_Ratio = 31.8207
```

```
Total_mass=6*Mass %grams
```

```
Total_mass = 1560
```

Figure 19: Analysis and Calculations

Due to the high torque required, no common DC motor can achieve this nominal torque value with a low to medium power output by itself, and thus there is the need of applying gearings to increase the torque output of the motor. Low power motors like the Maxon's A-max 26 Ø26 mm, Precious Metal Brushes CLL (figure 20), with a 7-Watt power output and a nominal torque of 15.2 mNm would require a gear ratio of over a 100. Consequently, it was decided to choose a motor with a higher power output and thus higher nominal torque. Therefore, the motor chosen is Maxon's RE 30 Ø30 mm, Precious Metal Brushes, with a power output of 15 Watt and a higher nominal torque of 51.4 mNm [14]. The gear ratio needed for this power to satisfy the torque required per wheel is 31.8:1.

Figure 20: Maxon's A-max 26 Ø26 mm motor [14]

The RPM of the wheels at the required speed is of 2.87 revolutions per minute, which would correspond to an RPM of the motor of 91.1 revolutions per minute at the nominal torque. The following graph modified from Maxon's official web page shows the operating range of the motor.

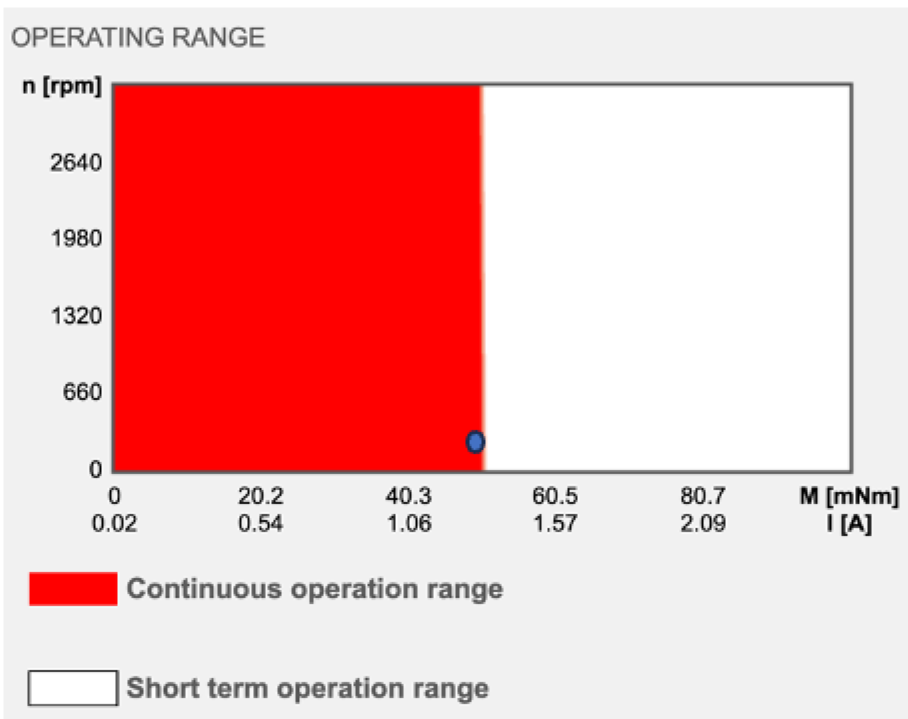


Figure 21: Operating range of motor. Blue dot represents operating condition for the rover [14].

It is important to mention that the operating temperature range of this motor is from -20...+85 °C [14], and thus heating is needed due to the low temperatures that the rover will experience due to Mars' climate.

This motor has not been tested in space. However, it can be tested in relevant environments on Earth to observe its performance. After testing, a TRL between 6 or 5 can be given.

Arm:

The arm (figure 22) has been designed to perform all movements necessary for the effective use of the PIXL instrument.

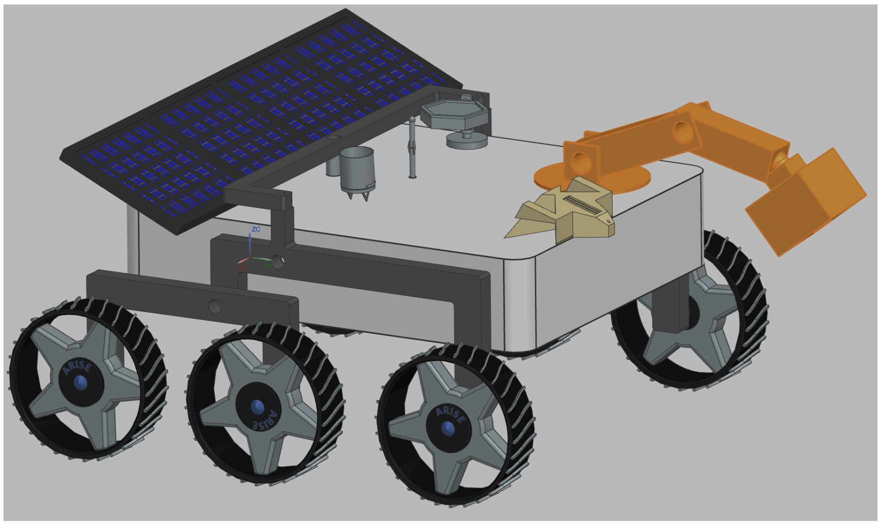


Figure 22: Rover's arm and PIXL instrument (yellow)

Accordingly, the arm is able to rotate, expand and contract (Figure 23). Furthermore, with the use of a ball and socket joint, the box containing the instrument can rotate and move in multiple directions (Figure 24). Consequently, this arm ensures the proper placement of the PIXL instrument to guarantee the achievement of the science objectives, therefore achieving requirement MEC-3.1.

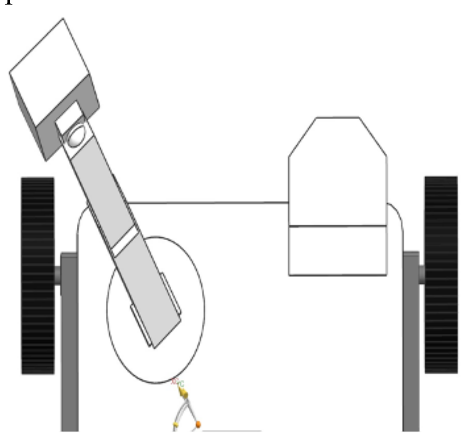


Figure 23: Arm extended and rotated to the left

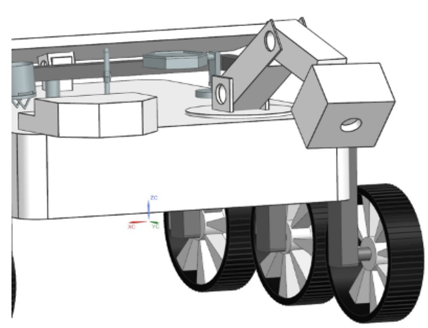


Figure 24: PIXL instrument facing towards the ground

The arm is made of aluminum 6061 and weighs 2.3 kilograms (without considering the instrument). Some of the important dimensions of the arm are shown in the following figure.

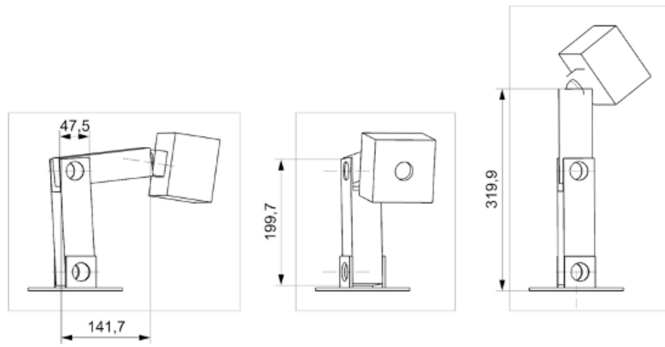


Figure 25: Important arm dimensions in mm.

The arm design is a modification of the arms designed to hold instruments in other deployed rovers like Perseverance. However, this arm can only be validated in a relevant ground environment before launch, and thus a TRL of 6 has been given to it.

<u>Solar Panel actuators:</u>

Due to the importance of energy efficiency in the design of our mission, the solar panel has been given the capability to tilt itself and rotate (Figure 26). This presents two crucial benefits, the first one being that the solar panel can adjust itself to maximize its exposure to sunlight; and the second benefit being that letting the solar panel rotate can disperse the accumulated dust. Consequently, this mechanism will maximize the effectiveness and efficiency of the solar panel.

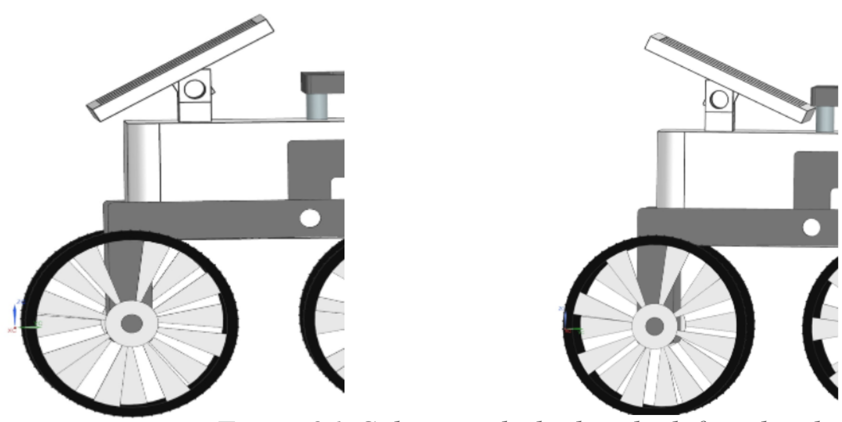


Figure 26: Solar panel tilted to the left and right.

The mechanism is made of aluminum 6061 and it has a low total weight of approximately 0.26 kilograms.

2.1.1.3 Mechanical Subsystem Recovery and Redundancy Plans

Redundancy measures have been taken to prevent some of the possible failures regarding the mechanical subsystem. The front wheels have steering motors and thus they allow the rover to perform turns. Nevertheless, the consequences of a problem occurring to the steering capabilities of the front wheels would render the rover incapable of turning, and thus completely harming the success of our science goals. Consequently, steering capabilities have also been added to the rear wheels. This measure mitigates the harmful consequences of the risk of malfunction in the front wheels, because even if something like that would happen, the rover would still be able to turn effectively. On the other hand, structures like the arms and the rocker-bogie suspension system do not have redundancy precautions. This is because of several factors. For example, the cost of implementing redundancy to these systems would vastly increase costs and the total weight of the rover. Nevertheless, the robust design of these assemblies plus the fact that they are mainly flight-tested heritage (Mechanical Sub Assembly has a TRL of 5), ensure the effectiveness and low risk using these structures. Therefore, there is no need for redundancy procedures for these mechanical components.

2.1.1.4 Mechanical Subsystem Manufacturing and Procurement Plans

The contractor chosen to manufacture the mechanical subsystem of the rover is California Institute of Technology, which operates the Jet Propulsion Laboratory (JPL). The reason this contractor has been chosen is because of its continuous successes in developing spacecrafts and especially Mars rovers. JPL is the only contractor that has designed, built, and operated all five of the successful rovers sent to the surface of Mars [15]. Furthermore, it is important to mention that California Institute of Technology is the contractor with the greatest number of actions related to NASA.

Consequently, the renown and experience that this contractor has will ensure the effectiveness of the design and manufacturing process of the rover. The estimated time that it will take to manufacture the complete mechanical subsystem is 2 years and at the end of the complete manufacturing process. This is because the mechanical subsystem must guarantee the proper positioning and performance of the other subsystems that the rover presents. For example, the mechanical subsystem must ensure that the instruments are accurately located in the rover, and that they have all the requirements to perform properly.

As specified previously the motors will be acquired from MAXON. The motor chosen is the RE 30 Ø30 mm, Precious Metal Brushes, 15 Watt. This motor is a standard motor manufactured by MAXON, and thus there is no need to design or redesign the motor. Consequently, the lead time to acquire these motors should be quickly and only depending on distribution times which has been estimated to take a maximum of 2 weeks.

2.1.1.5 Mechanical Subsystem Verification Plans

Table 8: Mechanical Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MEC-1	Rover in stowed configuration shall fit within the 1m x 1m x 1m envelope.	Inspection	Volume can be accurately measured by standard procedures.	Tape measurements and laser distance meters will be used to accurately measure the width, length, and height of the rover in stowed configuration to ensure that it fits within 1 m^3 of volume.
MEC-2	Rover shall effectively navigate through Mars' surface	Test	A physical test of the rover capabilities will be necessary to determine its performance under certain predefined conditions.	An environment and terrain which resembles Mars' regolith will be developed in order to test the rover's performance.
MEC-3	Mechanical subsystems shall guarantee the effectiveness of science instruments.	Test	A testing of the mechanical subsystems will be required to ensure that they allow the instruments to perform properly.	A test of the rover's mechanical subsystem in conjunction with the instruments will be performed. This test will involve the operation of the mechanical subsystem while the instruments are active to guarantee that they interact effectively with each other.

MEC-4	Mechanical Subsystem shall endure loads during launch without harmful structural damages.	Test	Testing of the materials chosen for the rover's structure will be necessary to ensure that the rover can survive launch loads	A vibration and shock test will be conducted with 3-axis testing and acoustic chamber while the rove is in stowed configuration. Based on the results, it will be known the capacity of the rover's structure to endure the launch loads.
MEC-2.1	Rover's suspension system shall ensure stability and maneuverability.	Test	Testing of the suspension system in a relevant terrain will be crucial to analyze its stability and maneuverability performance	In a terrain that resembles Mars' regolith, the suspension system will be tested. The test will consist of the suspension system traveling through certain obstacles in a terrain similar to Mars' terrain to perform an analysis of its stability and maneuverability.
MEC-2.2	Rover's wheels shall be robust, fatigue resistant, and ensure traction.	Test	Roughness of Mars' regolith must be replicated in order to test how the rover wheels perform in those conditions	During the same test for MEC-2.1, the wheels will be tested on terrain which resembles Mars'. This will allow us to analyze the endurance and effectiveness that the wheels will have on Mars and perform

				design changes accordingly if needed.
MEC-2.3	Rover shall be able to complete turns effectively.	Inspection	The capacity of the rover to perform turns can be observed directly.	The rover will be commanded to perform turns of different radii, and its performance will be visually inspected and analyzed.
MEC-2.4	Rover shall achieve a cruise speed of 0.03 meters per second	Test	A test to correctly measure the velocity is needed because it is necessary to replicate the condition on Mars' surface.	A test of the rover's speed will be conducted on terrain resembling Mars' regolith.
MEC-3.1	Arms carrying science instruments shall have the necessary mobility to ensure their performance.	Inspection	The mobility of an arm carrying a science instrument can be accurately inspected visually	The arm, while holding the science instrument, will be commanded to perform several movements: extension, rotation, and both movements at the same time.
MEC-4.1	All materials used in mechanical subsystems shall have a yield strength above 250 MPa.	Analysis	Data of materials properties can be determined analytically.	Data like strength of a material is common knowledge for the typical metals expected to be used in the rover's mechanical subsystem. When using two different materials, analytical methods can be used to determine the overall strength.

MEC-2.1.1	Rover's suspension system shall not exceed 15 kilograms.	Inspection	Mass can be accurately measured by standard procedures.	The mass of individual parts will be gathered with standard weight scales and then added together to get the total mass. As verification, once the suspension system is assembled, its mass will be measured again.
MEC-2.1.2	Suspension system shall be able to climb obstacles of 15 centimeters	Test	A test must be conducted to analyze the performance of the suspension system when trying to climb objects of 15 centimeters	In a terrain resembling Mars' regolith, several obstacles with different heights up to 15 centimeters will be placed. The rover will have to climb those obstacles effectively while continuing to traverse in the same initial direction.
MEC-2.2.1	Wheel's material shall possess a yield strength greater than 400 MPa and a stiffness above 60 GPa.	Analysis	Data of materials properties can be determined analytically.	Data like yield strength and stiffness of a material are common knowledge for the typical metals expected to be used in the rover's mechanical subsystem. When using two different materials, analytical methods can be used to determine the overall strength.

MEC-2.2.2	Wheel's tread patterns shall ensure effective traction and friction through Mars surface	Test	Tread patterns must be tested in the exact surface conditions to measure its performance.	During the same test for MEC-2.1, in which the wheels will be tested, the performance of the tread pattern will be analyzed to ensure that correct traction and friction are present in the wheels.
MEC-2.3.1	Front and back wheels shall have an angle of rotation of 40 degrees.	Inspection	Angle of rotation can be measured precisely with standard procedures.	Angle of rotation of the front and back wheels will be measured with standard geometric tools.
MEC-2.4.1	Rover's motors shall generate a total power output higher than 5 W	Inspection	Motor's power data is accurately provided by vendors.	The motors bought and used for the wheels will be inspected so that all of them have the desired output power.

The verification table above shows all the mechanical subsystem requirements, their verification method, and a preliminary verification plan for each of them. As we can observe, inspection methods will be applied to measure properties like volume and mass, whereas other properties like yield strength and stiffness can be obtained through material analysis. Nevertheless, the main verification method for the mechanical subsystem requirements is testing. This is because of the need to accurately analyze the performance of the mechanical components in the rover as if it was traveling on Mars' surface.

Consequently, it will be crucial for the proper testing of the rover to have a facility which can effectively replicate the characteristics of Mars' environment and regolith. This is extremely important because of the need to test critical mechanical subsystems like the wheels and the suspension system. On the other hand, another relevant test environment that has to be precisely replicated is the rocket launch. This is because during launch, the rover will suffer from different harmful loading conditions and vibrations which could damage the rover's mechanical structures. Therefore, a vibration and shock test will be needed in order to guarantee that the rover in stowed configuration can effectively survive launch operations without any type of critical damage.

2.1.2 Power Subsystem Overview

Power Subsystem integration with other subsystems

Communication and Data Handling (CDH):

During data transmission phases, power is sent to communication antennas, transmitters, and receivers to maintain a dependable connection with mission control.In order to minimize computing load and preserve battery life during data analysis, power-efficient data processing algorithms are used.

Mechanical Systems:

In order to move, manipulate, and deploy the rover over a variety of terrains and engage with its environment, power is provided to motor controllers and actuators. Power management strategies vary power distribution according to the difficulty of the terrain and operational requirements, giving priority to energy allocation for locomotion and manipulation tasks.

Science Instruments:

During the data collecting stages, power is provided to science instruments, triggering sensors and cameras to record scientific observations. In order to extend battery life, power-efficient instrument operation modes are used, balancing the need for continuous data acquisition with energy conservation during idle periods.

Science Instruments:

During the data collecting stages, power is provided to science instruments, triggering sensors and cameras to record scientific observations.
In order to optimize battery life, power-efficient instrument operation modes are used to strike a balance between the requirement for continuous data collecting and energy conservation during idle times.

Guidance, Navigation, and Control (GNC):

The GNC system provides navigation algorithms and control mechanisms by allocating power to sensors, computers, and actuators.

Power management techniques give navigation duties first priority when it comes to energy usage, guaranteeing precise positioning and trajectory control while lowering power usage.

Thermal Management:

To maintain ideal thermal conditions, power is provided to temperature sensors, thermal insulation systems, and heating and cooling elements.

In order to control thermal loads during severe temperature swings, power distribution is dynamically altered, safeguarding delicate electronics and guaranteeing mission success.

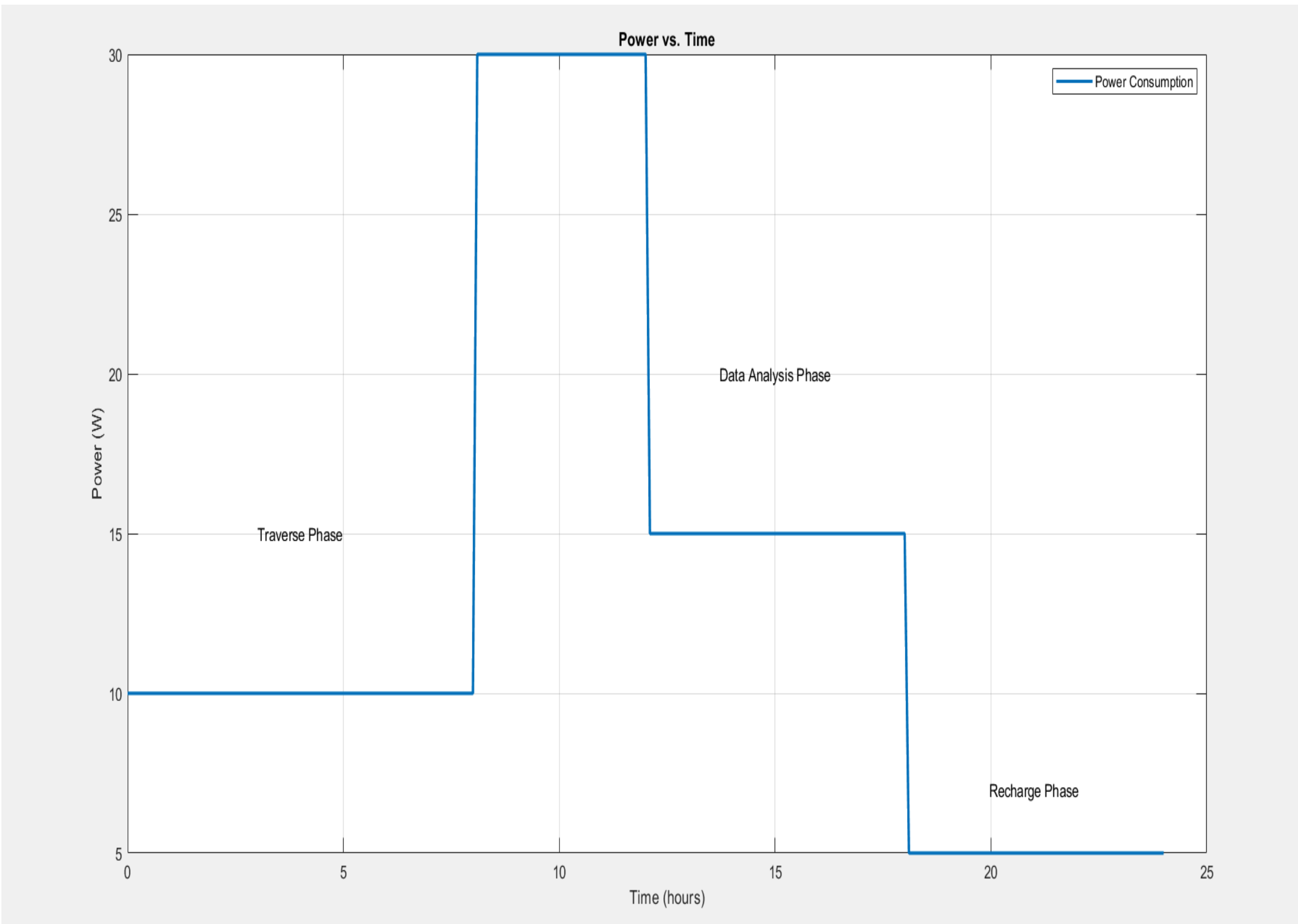


Figure 27: Power vs. Time graph

2.1.2.1 Power Subsystem Requirements

Table 9: Power Subsystem Requirements

#Req	Requirement Description	Verification method	Priority
1	The power subsystem must generate power using the solar panel at least 16 watts of power at noon on Mars.	Under simulated Martian conditions the solar panel should be tested.	High
2	The solar array should be made up of 200 photovoltaic solar cells. The length of the solar cell is 5 cm and has a width of 1 cm.	Physical inspection of the actual solar array components by counting the number of photovoltaic solar cells.	Medium
3	The power system should be able to switch between the batteries and solar panel to ensure continuous rover operation.	Simulate and oversee the power source transition and monitor for any discrepancies.	High
4	The power subsystem should output at least ten different voltages to various rover hardware components	Multimeter should be used to verify the voltage output.	High
5	Batteries will be utilized to create power at night and a solar array will be used to generate power during the day.	The battery usage patterns should be monitored and noted.	High

2.1.2.2 Power Sub-Assembly Overview

Solar Array

13 parallel strings, each with 18 series cells, make up the solar array structure. It was utilized to power the rover during NASA's Pathfinder mission in 1997. The proven reliability and performance of the solar array make it an effective option for powering the rover during the space exploration mission.

Table 10: Solar Array

Solar Array Specs	Details
Configuration	13 parallel strings, 18 series cells per string
Power	16.5 watts on Mars at noon, 45 watts at 1 sun/AMO (Earth)
Operating Voltage	14-18 volts
Weight	0.340 kg
Size	0.22 m^2
Survival Temperature	-140 to 110°C
Substrate	Nomex honeycomb
TRL	9

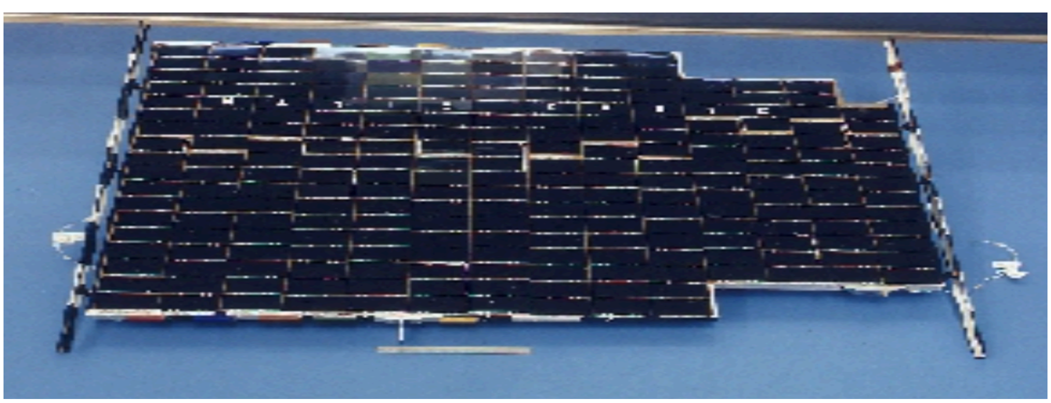


Figure 28

Batteries

GomSpace's NanoPower Battery 3000 mAh, with its proven 18650 form size and lithium-ion construction, is a good choice for a Mars mission. The battery is a reliable power source with a nominal capacity that ranges from 2050 mAh to 3000 mAh and recommended voltage levels. Its wide temperature range for both charging and discharging is a result of its electrical and thermal properties, which greatly increase its adaptability to the various mission conditions. The cycle life statistics of the battery, which includes estimates for a five-year low-Earth orbit mission, highlights its robustness. A suggested state of charge (SOC) and temperature range for storage maximize durability. It has safety features like a current-interrupt device (CID) and vent, and quality control procedures adhere to strict industry requirements.

Batteries electrical and thermal characteristics

Table 11: Batteries electrical and thermal characteristics

Parameter	Condition	Min.	Typ.	Max	Unit
Nominal Capacity, for 1500mA discharge	@ 2.0 V cut-off @ 2.95 V cut-off @ 2.95 V cut-off, and charging to 4.0 V	 2700 2050	3000 2750 2100	 2800 2150	mAh mAh mAh
Voltage	Safe Recommended	2.0 2.95	3.6	4.2 4.0	V
Current - Charge	0 to +50 °C		1500	4000	mA
Current - Discharge	-20 to +75 °C		1500	6000	mA
Temperature – Storage (recommended)	3 months 12 months	-20 -20		45 20	°C °C
Temperature - Operating	Charge Discharge	0 -20		50 75	°C °C
Internal impedance	1 s, 3000 mA, 60% SOC 20 s, 3000 mA, 60% SOC 1 Hz		21 36 <= 20		mΩ mΩ mΩ

Battery Cycle life

- The lower the DOD, the better the cycle life.
- The lower the temperature, the better the cycle life (unless too low for charging).
- The lower the charge/discharge current, the better the cycle life.

- The lower the EOCV, the better the cycle life.

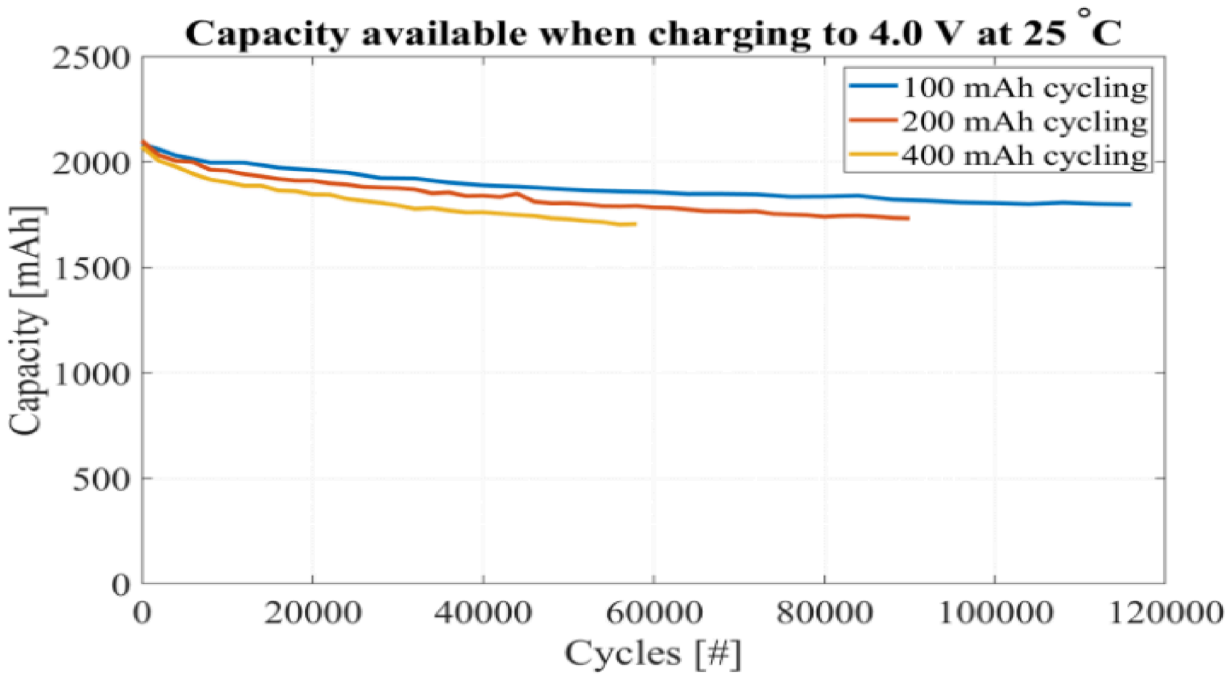


Figure 29

Power management and Distribution

Figure 30

The P31u power supplies are intended for small, inexpensive satellites with power requirements ranging from 1 to 30 W. Following the KISS design principle, the P31u connects to triple junction solar cells and conditions their output power to charge the attached lithium-ion battery through the use of an incredibly effective boost-converter. Two buck-converters that provide a 3.3 V @ 5 A and a 5 V @ 4 A (configurable) output bus are fed by the incoming power and the energy stored in the batteries. Six separately adjustable output switches, each having a distinct 3.3 V or 5.0 V output and overcurrent shut-down and latch-up protection.

Block diagram

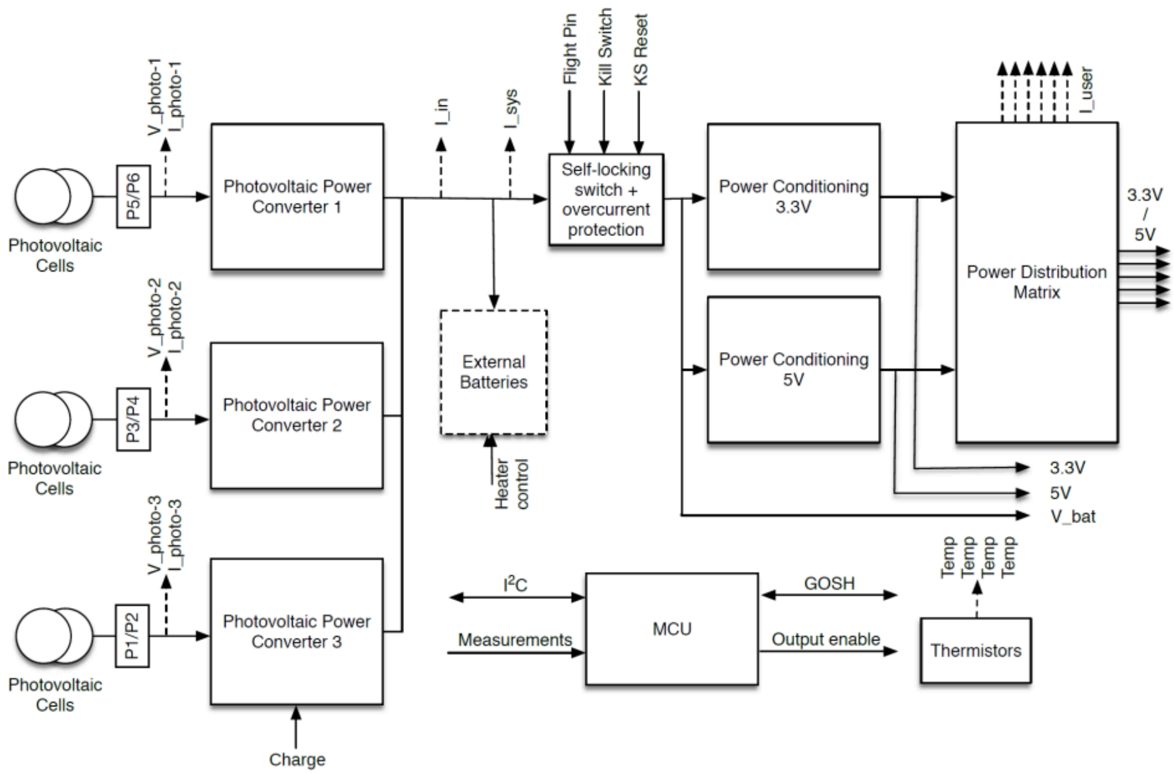


Figure 31: Block Diagram

1. Overcurrent Detector (OCD) and Power Distribution Switches:**

- Time before latch-off varies based on normal current usage.

- For 50% load, latch-off time is 580 µs.

- Fault condition defined if output current exceeds limit for >28 ms.

- Output switch shuts off power to load, remains off until fault load is removed or auto-cycles after 500 ms.

- Repeat fault leads to power shut-off after 28 ms.

2. Heater and Temperature Sensor:

- Lithium-ion batteries require temperature maintenance for charging.

- Heater on the BP4 maintains temperature above the charging threshold.

- Default mode: Manual.

- Heater elements:

- Resistance: 2x22 Ω (8V), 2x82 Ω (16V).

- Power: 6W for both.

3. Batteries:

- Connect to circuit via jumpers on battery ARM connector (P7).

- Operating without batteries is possible for testing, using a power supply and resistor.

- Operating without batteries only as a failure backup mode.

4. Physical Characteristics

- Mass: 100g.

- Size: 89.3 x 92.9 x 15.3 mm.

5. Performance:

- Designed for efficiency and reliability.

- Photovoltaic converter efficiency graph for different input voltages.

- Power-conditioning converter efficiency graph.

- Line loss/voltage drop: Total resistance typically <50 mΩ.

6. Environment Testing:

- P31u subjected to rigorous environment tests simulating launch and space conditions.

- Successful flights on several satellites.

2.1.2.3 Power Subsystem Recovery and Redundancy Plans

Redundant power supplies: Backup power supplies, such as redundant P31u units, are installed for critical components to ensure uninterrupted operation in case of primary supply failure. These redundant units are automatically switched to in the event of a failure in the primary power supply, maintaining continuous power flow to essential systems without disruption.

Multiple NanoPower Batteries: Multiple NanoPower Batteries are employed in parallel to ensure a continuous power supply, even in the event of a battery failure. This redundant configuration allows the system to draw power from multiple batteries simultaneously, distributing the load evenly and enhancing overall system reliability.

Fault detection and isolation mechanisms: Sophisticated fault detection and isolation mechanisms are integrated into the power management system. These mechanisms continuously monitor various parameters such as voltage, current, and temperature, detecting any anomalies indicative of a fault. Once a fault is detected, the system isolates the affected component or subsystem to prevent the spread of the fault to other parts of the system.

Emergency power generation: In addition to primary power sources, backup emergency power generation capabilities are incorporated into the system. This may include backup solar panels or alternative power sources such as fuel cells or RTGs (Radioisotope Thermoelectric Generators). These backup power sources are designed to provide emergency power in situations where primary power sources are unavailable or insufficient.

Load shedding mechanisms: Load shedding mechanisms are implemented to prioritize power distribution to essential systems during power shortages. These mechanisms automatically identify non-essential or lower-priority loads and temporarily deactivate or reduce power to these loads, ensuring that critical systems receive sufficient power to maintain operation.

Manual override capabilities: The power management system is equipped with manual override capabilities that allow operators to intervene and manually control key functions in case of automated system failures or emergencies. This includes manual control over power distribution, voltage regulation, and other critical parameters, providing operators with the flexibility to react quickly to unexpected situations.

Real-time monitoring and telemetry systems: Real-time monitoring and telemetry systems continuously track the performance and health of the power subsystem. These systems collect data on various parameters such as voltage, current, temperature, and system status, providing mission operators with real-time insights into the condition of the power system and enabling early detection of potential issues.

Detailed recovery procedures: Comprehensive recovery procedures are developed to guide response to various power subsystem failure scenarios. These procedures outline step-by-step instructions for diagnosing the cause of the failure, implementing corrective actions, and restoring normal operation.

2.1.2.4 Power Subsystem Manufacturing and Procurement Plans

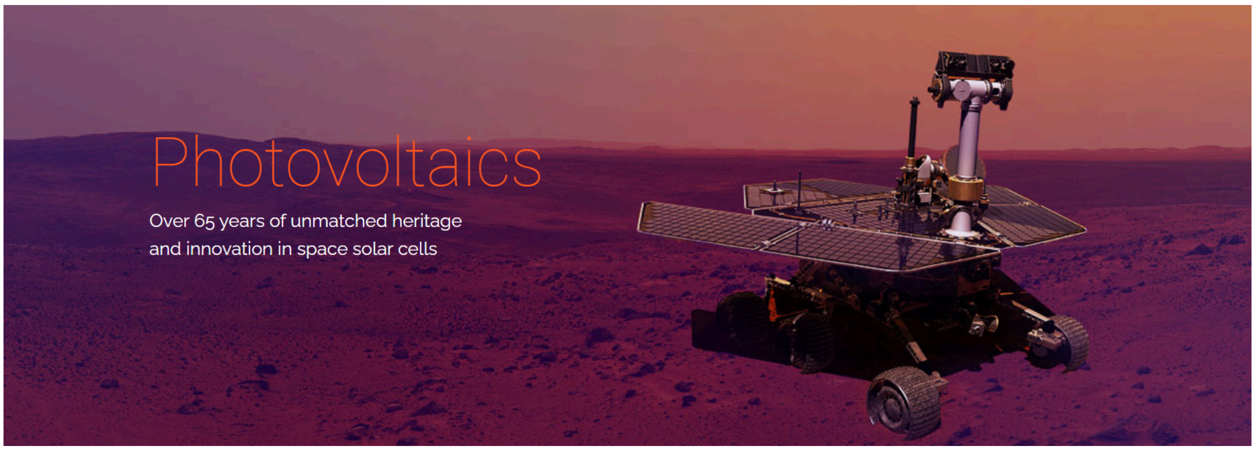


Figure 32

Spectrolab, a Boeing company, is well-known for producing solar panels fit for space missions. Given that it has created solar panels for multiple space missions, including NASA programs for Mars rovers, Spectrolab has an extensive amount of expertise in the industry. The contractor provides customization options that enable the solar panel to be designed and manufactured in accordance with the rover's specifications. Solar panels made by Spectrolab are renowned for their dependability and performance in challenging space conditions. Custom space-grade solar panels are expected to take 10 to 12 months to manufacture and supply, taking into account the time needed for design, production, testing, and delivery.

The greatest share of Spectrolab's product deliveries are fully assembled space solar panels. Based on a customer's specifications for maximum area, operating temperature and voltage, and the mission environment and duration, Spectrolab engineers maximize performance for End of Life performance. The panel substrates onto which Spectrolab's multijunction circuits are bonded and wired to terminations, are provided as customer-furnished equipment.

Acquiring the Nanopower BPX 3000mAh batteries and the GomSpace P31U Power Management and Distribution (PMAD) system are essential for ensuring effective power control during the rover expedition to Mars. GomSpace stands out as the manufacturer of both components because of its proven track record of creating dependable systems that are approved for space travel. This procurement strategy ensures a smooth acquisition and integration of the P31U PMAD systems and the Nanopower batteries into the rover by outlining a thorough process that includes requirement definition, contract award, and integration. Working with GomSpace improves the mission's performance and dependability by giving access to cutting-edge technology and committed support. It is projected that the acquisition of the Nanopower BPX 3000mAh batteries will take 8 to 10 months, while the P31U PMAD systems will be acquired in about 8 months. These schedules guarantee on-time rover integration and mission schedule compliance.

2.1.2.5 Power Subsystem Verification Plans

Verification Plan for NASA Rover Power System:

1. Requirements Review
   - Review and validate power system requirements for solar panels, batteries, and overall power management.
   - Ensure alignment with mission objectives, environmental constraints, and operational needs.

2. Solar Panel Verification
   - Conduct solar panel testing under simulated Mars conditions to verify power output.
   - Test solar panel performance across a range of temperatures, irradiance levels, and angles.
   - Verify compatibility with rover's power input requirements and efficiency in converting sunlight into electrical energy.
   - Assess durability and resistance to environmental factors such as dust accumulation and radiation degradation.

3. Battery Verification
   - Perform capacity testing on batteries to verify nominal and maximum capacities.
   - Test battery performance under different charging and discharging rates, temperatures, and cycling conditions.
   - Validate battery voltage regulation and stability over time and under varying loads.
   - Assess battery safety features such as current-interrupt devices (CID), thermal management, and venting mechanisms.
   - Conduct cycle life testing to determine battery longevity and reliability over the mission duration.

4. Power Management System Verification:
   - Verify functionality of power management and distribution systems, including converters, regulators, and distribution switches.
   - Test power conditioning and regulation to ensure compatibility with rover's electrical subsystems and instruments.
   - Validate fault detection and isolation mechanisms to identify and mitigate potential system failures.
   - Assess efficiency and reliability of energy conversion and distribution processes.
   - Conduct testing to evaluate system response to simulated anomalies, such as overcurrent or under-voltage conditions.

5. Integration Testing

- Integrate solar panels, batteries, and power management systems into the rover's electrical architecture.
- Verify compatibility and interoperability between power system components and other subsystems.
- Test power system integration under simulated mission scenarios, including rover movement, instrument operation, and communication activities.
- Assess overall power system performance, efficiency, and reliability in the context of rover operations on Mars.

6. Environmental Testing
- Subject solar panels, batteries, and power management systems to environmental testing to simulate conditions encountered during the mission.
- Conduct thermal cycling tests to assess performance and reliability under temperature extremes on Mars.
- Perform vibration testing to verify structural integrity and resistance to launch and rover movement vibrations.
- Test radiation tolerance of power system components to ensure resilience to cosmic radiation exposure on Mars.

7. Safety and Reliability Testing:
- Verify safety features of batteries and power management systems, including overcurrent protection, thermal shutdown, and fault isolation.
- Assess reliability and robustness of power system components through accelerated life testing and failure mode analysis.
- Conduct risk assessments to identify and mitigate potential hazards associated with power system operation.

8. Documentation and Reporting
- Document all test procedures, results, and observations in comprehensive test reports.
- Provide clear and concise documentation of verification activities and outcomes to support mission certification and approval processes.
- Document any deviations from requirements and proposed corrective actions.

2.1.3 CDH Subsystem Overview

Definition and Purpose:
The Communication and Data Handling (CDH) subsystem is a critical component of spacecraft, responsible for all communication functions between the spacecraft and ground stations, as well as handling the processing, storage, and routing of data within the spacecraft. This subsystem ensures that commands received from the ground station are executed and that data collected by the spacecraft is sent back to Earth.

Onboard Computer (OBC): Acts as the brain of the spacecraft, controlling various functions and processing data from various sensors and instruments.
Data Storage: This includes solid-state recorders or other memory devices that store data collected during the mission for later transmission.
Transponders: Facilitate communication with ground stations, converting received signals into usable formats and vice versa.
Antennas: Critical for maintaining communication links. They can be of various types like high-gain, low-gain, and omni-directional, depending on mission requirements.
Modems: Encode and decode signals for transmission and reception, converting digital data from the spacecraft's instruments into formats suitable for transmission.

Data Handling: Involves the collection, processing, storage, and routing of data. The OBC will often preprocess data to reduce the amount it needs to send back to Earth.
Communication: Maintains constant communication with ground stations. This includes sending spacecraft health data, scientific data, and receiving commands from mission control.
Challenges and Innovations:

Data Volume Management: Modern missions generate large volumes of data. Efficient data compression and selective data transmission are critical.
Fault Tolerance: The CDH subsystem must be highly reliable, often requiring redundancy in critical components like the OBC.
Security: Protecting data and commands from unauthorized access is increasingly important, particularly for sensitive missions.
Relevance to Space Missions:
Every mission, whether it orbits Earth, explores other planets, or observes the universe, relies on a robust CDH subsystem. This subsystem's effectiveness directly impacts the mission's success.

2.1.3.1 CDH Subsystem Requirements

Table 12: CDH Requirements

WBS Level	Requirement ID	Requirement Description	Notes	Parent Requirement	Verification Method
CDH-1	CDH-1	Telecommunications Subsystem Integration	Integrate telecommunications with CDH for seamless operation	SYS-3	Integration testing
CDH-1	CDH-1	Data Computing Subsystem Integration	Integrate data computing functionalities with CDH	SYS-3	Integration testing
CDH-1	CDH-1.1	Software Architecture Design	Design the software architecture for efficient CDH operations	SYS-3	Design review
CDH-2	CDH-1.2	Provide intra- and inter-communication handling	CDH subsystem handles communication between all spacecraft subsystems and instruments, as well as communication between Rover and Earth	CDH-1	System testing, simulation

CDH-2	CDH-2.2	Implement telecommunications functionality	Telecommunications functionality included within CDH subsystem for simplicity	CDH-1	Analysis of system architecture, verification of communication pathways
CDH-3	CDH-3.1	Ensure compatibility with X-Band High-Rate Transmitter	CDH subsystem should support integration and operation of HRT440 X-Band High-Rate Transmitter	CDH-1	Architecture review

2.1.3.2 CDH Sub-Assembly Overview

HRT440 X-Band High-Rate Transmitter: This transmitter facilitates high-rate data transmission in the X-band frequency range. With a maximum mass of 5 lbs (2.3 kg) and input power of 15 Watts maximum, it operates within an operating voltage range of 22.0 – 36.0 VDC and an operating temperature range of -34°C to +71°C (Qualification).

Figure 33

Ultra-High Frequency Antenna: This antenna, with a size of around 30 centimeters in length or diameter and a mass ranging from 0.5 kilograms to 2 kilograms, is crucial for UHF communication.

Sentinel M-Code GPS Receiver: With a size of 180 x 160 x 60 mm and a weight of less than 2.5 kg, this GPS receiver operates at a DC power of less than 9 watts typical in LEO and less than 8 watts typical in GEO, with an operating temperature range of -34°C to +71°C.

X-Band Low-Gain Antenna: This antenna, with a diameter of 10 inches (25 centimeters) and a mass of 1.1 kilograms (2.4 pounds), supports communication at lower transmission/reception rates.

X-Band High-Gain Antenna: With a diameter ranging from 1 to 2 feet (30 to 60 centimeters) and a mass of 3 to 5 kilograms (6.6 to 11 pounds), this antenna supports faster transmission/reception rates, up to 160/500 bits per second or faster to/from the Deep Space Network's 112-foot-diameter antennas or at 800/3000 bits per second or faster to/from the Deep Space Network's 230-foot-diameter antennas.

Low-power Solid-state Recorders: Two solid-state recorders with a storage size of 1 Tb each and power usage ranging from 0.1 watts to 5 watts are included for data storage.

Figure 34

Spaceborne X-Band Solid State Power Amplifier: This amplifier, with maximum dimensions of 6.85"L x 5.275"W x 1.85"H and a mass of 3.02 lbs (1.37 kg), operates within an operating voltage range of 22 to 36 VDC and an operating temperature range of -40°C to +70°C.

Figure 35

Small Deep Space Transponders (SDSTs): These transponders, with a maximum mass of 7.0 lbs (3.2 kg), operate within an input supply voltage range of 22 to 36 VDC or ±11 to ±18 VDC, and an operating temperature range of -40 to +60°C.

VxWorks is a popular choice for many aerospace applications due to its robustness and real-time capabilities, which are essential for the demanding environment of space exploration. This operating system is designed to handle concurrent tasks efficiently, prioritize mission-critical operations, and ensure responsive control and data handling.

VxWorks was also used in previous Mars rovers, including Spirit, Opportunity, and Curiosity, demonstrating its reliability and effectiveness in space missions. The software is customized for each mission, incorporating specific algorithms and functions necessary for the rover's unique instruments and mission objectives.

By using VxWorks, NASA ensures that Perseverance can perform complex, concurrent operations with high reliability, such as navigating the Martian terrain, conducting scientific experiments, and communicating with Earth. This choice reflects the continued trust in VxWorks for critical aerospace applications, highlighting its pivotal role in the success of space exploration missions.

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans

1. Redundancy Implementation: The CDH subsystem typically includes redundancy to prevent failures from jeopardizing a mission. This often involves duplicating critical components such as processors and data storage. For instance, many spacecraft use a dual-string approach, where two separate and identical sets of hardware operate in parallel. One operates as the primary set, while the other serves as a backup. If the primary fails, the system can automatically or manually

switch to the backup, a strategy that significantly enhances mission reliability (Wertz and Larson, "Space Mission Analysis and Design").

2. Fault Detection and Isolation: Critical to recovery and redundancy is the ability to detect and isolate faults effectively. This involves monitoring the system's health data to identify anomalies that may indicate a problem. Advanced diagnostic algorithms can be used to pinpoint the source of a fault, which is crucial for initiating appropriate recovery procedures. The use of FDIR (Fault Detection, Isolation, and Recovery) strategies is standard practice in this context (NASA's "Fault Management Handbook").

3. Software Redundancy: Besides hardware redundancy, software redundancy is also crucial. This includes using error-detecting and error-correcting codes within the data handling systems to ensure data integrity during transmission and storage. Software can also be designed to restart automatically in case of failure, or to switch to a backup mode if errors are detected (ECSS-E-ST-40C, "Space Engineering: Software").

4. Regular Testing and Updates: To ensure the effectiveness of redundancy and recovery plans, regular testing is essential. This includes both hardware and software components under simulated fault conditions to validate the response procedures and backup systems. Updating the software to patch known vulnerabilities and improve fault detection algorithms is also a standard practice (NASA Systems Engineering Handbook).

5. Post-Mission Analysis and Learning: After mission completion, a detailed analysis of any encountered issues and the performance of the redundancy systems is valuable. Lessons learned are documented and used to improve future designs and recovery strategies. This continuous improvement cycle is critical for enhancing the reliability of space missions (NASA's "Lessons Learned Information System").

These practices ensure that the CDH subsystem remains robust against various types of failures, thereby safeguarding mission success.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans

For the Command and Data Handling (CDH) subsystem of a mission, selecting the right suppliers for each component is crucial for ensuring reliability, performance, and schedule adherence. Given the guidelines and the manufacturers listed, here's a detailed overview of supplier decisions for each component, their specialties, and estimated lead times.

Manufacturers:

- *Small Deep Space Transponders (SDSTs)*
    - ☐ Supplier: General Dynamics Mission Systems
    - ☐ Lead Time: 12-18 months
    - ☐ General Dynamics Mission Systems is renowned for their expertise in space communication solutions. Their SDSTs are designed for deep space missions, offering robust communication capabilities. The decision to go with General Dynamics is based on their proven track record in delivering high-quality, reliable transponders suitable for the rigors of deep space communication.

- *HRT440 X-Band High-Rate Transmitter*
    - ☐ Supplier: General Dynamics Mission Systems
    - ☐ Lead Time: 9-15 months
    - ☐ The HRT440 is selected for its high data rate transmission capabilities essential for science data downlink. General Dynamics' experience in developing transmitters that can operate efficiently in the harsh space environment makes them the optimal choice for this subsystem.

- *Ultra-High Frequency Antenna*
    - ☐ Supplier: COTS (Commercial Off-The-Shelf)
    - ☐ Lead Time: 3-6 months
    - ☐ Given the availability of high-quality UHF antennas in the commercial market, selecting a COTS product ensures cost-effectiveness and reliability. A reputable supplier known for space-grade antennas will be chosen to ensure compatibility with mission requirements.

- *Sentinel M-Code GPS Receiver*
    - ☐ Supplier: General Dynamics Mission Systems
    - ☐ Lead Time: 12-18 months
    - ☐ The Sentinel M-Code GPS Receiver is critical for precise navigation and timing. General Dynamics offers advanced GPS receivers designed specifically for space applications, ensuring high performance and reliability. Their specialization in secure, resilient GPS technology justifies their selection.

- *X-Band Low-Gain Antenna*
    - ☐ Supplier: In-House / NASA
    - ☐ Lead Time: 6-12 months

- Considering the specific requirements and the capability of NASA to produce bespoke antennas, this component will be developed in-house. This decision allows for customization to meet unique mission requirements while adhering to NPD 1370.1, as there are no specific commercial entities that specialize in this component for the intended application.

- *X-Band High-Gain Antenna*
    - Supplier: Contractors
    - Lead Time: 18-24 months
    - For the high-gain antenna, a specialized contractor with expertise in high-gain antenna design for deep space missions will be selected. This component's critical nature for long-distance communication requires a supplier with a strong track record in delivering antennas that meet stringent space mission criteria.
    -
- *Low-power Solid-state Recorders*
    - Supplier: General Dynamics Mission Systems
    - Lead Time: 9-15 months
    - General Dynamics offers state-of-the-art solid-state recorders that are optimized for low power consumption and high reliability, crucial for long-duration space missions. Their specialization in space-grade data storage solutions makes them the preferred supplier for this subsystem.

- *Spaceborne X-Band Solid State Power Amplifier*
    - Supplier: General Dynamics Mission Systems
    - Lead Time: 9-15 months
    - The selection of General Dynamics for the solid-state power amplifier is due to their proven capabilities in providing high-performance amplifiers designed for space. Their amplifiers ensure efficient signal transmission which is vital for the mission's success.

2.1.3.5 CDH System Verification Plans

The development of a Command and Data Handling (CDH) system verification plan in a spacecraft project typically involves several crucial steps to ensure that the system functions reliably and meets all technical requirements. Here's a brief overview of a typical CDH System Verification Plan:

1. Requirement Verification

Objective: This step ensures that every specified requirement for the CDH system, whether functional, performance, or interfacing, is met. It is crucial for compliance with the mission's overall objectives and technical specifications.

Methods:

- Analysis involves theoretical evaluations and mathematical models to predict system behaviors under various scenarios.
- Inspection might include code reviews, hardware inspections, or manual checking of configuration parameters.
- Demonstration involves showing, in a controlled environment, that system features operate as intended.
- Testing encompasses running the system through scenarios that might occur during the mission to observe real-time performance and responses.

2. Functional Testing

Objective: This confirms that all CDH functions perform correctly and interact seamlessly to support spacecraft operations.

Methods:

- Simulation uses software to mimic the behavior of the spacecraft and its environment, enabling the validation of functions under simulated conditions.
- On-board Testing involves running tests directly on the spacecraft hardware, which is essential for verifying the actual responses of the CDH system.
- Hardware-in-the-Loop (HIL) testing integrates the CDH hardware with simulation software that replicates other spacecraft systems or environmental factors, providing a hybrid testing environment.

3. Interface Verification

Objective: Tests here ensure that the CDH system can communicate and operate effectively with other subsystems, such as power systems, thermal control systems, and payload operations.

Methods:

- Integration Testing checks the CDH interactions with other spacecraft subsystems to confirm that interfaces are correctly implemented and functional.
- Interface Simulation creates virtual models of other systems to test interface compatibility and performance without the need for physical subsystems.

4. Performance Verification

Objective: Ensures that the CDH system performs up to its design specifications under all expected operational environments.

Methods:

- Stress Testing involves pushing the system beyond normal operational limits to ensure it can handle unexpected or extreme conditions.
- Performance Benchmarking measures the system's performance parameters against predetermined standards or objectives.
- Environmental Testing simulates the physical conditions of space (like vacuum, thermal extremes, and radiation) to verify that the system will function as expected once deployed.

5. Redundancy and Fault Management Testing

Objective: Validates that the CDH system can continue to operate correctly in the event of component failures or other anomalies.

Methods:

- Fault Injection involves deliberately introducing faults to the system to ensure that it can handle errors and recover smoothly.
- Redundancy Switching tests the transition between primary and backup systems to ensure seamless operations during any failures.
- Recovery Procedures are verified to ensure that the system can recover to a normal operational state after handling a fault.

2.1.4 Thermal Control Subsystem Overview

The thermal management subsystem is composed of different components that all complement the rover for the mission. These will have the duty to keep all instruments, electronics and batteries functional for the best performance possible, by securing the integrity of the rover at all moments thanks to an automated system and cooling or heating systems to counterattack the change of temperature in this Martian environment.

A net thermal diagram was created to illustrate the thermal energy transfer that occurs in the rovers while having contact with Mars, space, and other sources of heat and radiation as the sun. To make this, five sources were identified to manage the thermal transfer within the rover:

1. Q radiation space
2. Q solar
3. Q radiation space & surface
4. Q conduction wheels & surface
5. Q radiation surface

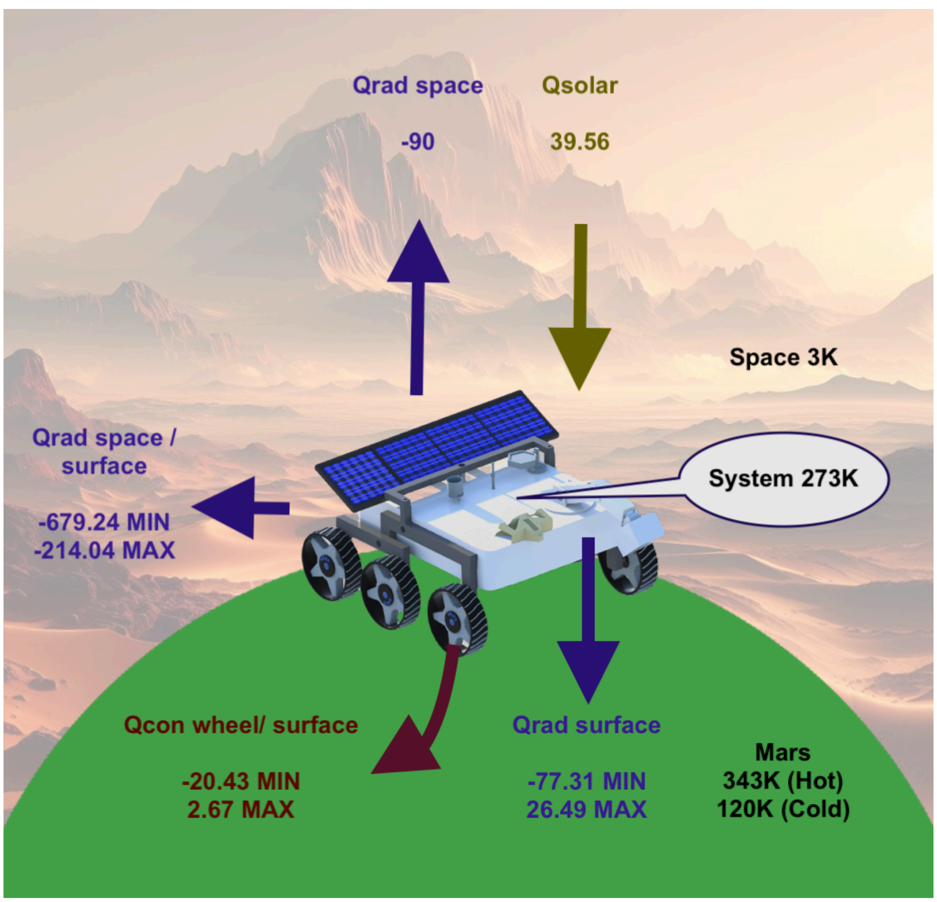


Figure 36

These were analyzed by keeping in mind the temperature of space (3 Kelvin), the Martian surface (120 Kelvin - 343 Kelvin) and the system's (273 Kelvin) average temperature where all components are able to work perfectly. Now, these were used to calculate the output and input powers of each source thanks to two formulas presented below:

Conduction formula:

$$Q = \frac{kA(T_1 - T_2)}{L}$$

Radiation formula:

$$Q = \varepsilon\sigma FA(T_1^4 - T_2^4)$$

In the end, the results obtained with the net temperature for the input and output temperature were calculated. In a cold environment, a Q in and out resulted in a loss of **772.43 Watts** and in the hot environment it gave a loss of **230.32 Watts**. Hence, these were based on the coldest and hottest possible circumstances to recognize a viable solution that would equal the net change in temperature to '0'. The results were that the rover would experience a loss of temperature in both cases, since the thermal energy would always be negative which means that the rover net temperature would always decrease in relation to its surroundings.

Solutions were created and the rover would in the end be integrated with several heaters that would stabilize its temperature by heating the components each time the rover would require functionality to fulfill the mission requirements. Not all heaters will be active at the same time, since power consumption needs to be optimal as the heaters are the components that use the most power among the thermal subsystems. Therefore, thermal switches will be implemented to activate and deactivate them whenever the automated system requires it. Additionally, more heaters will be added as backup for the critical components such as the battery and electronics.

2.1.4.1 Thermal Control Subsystem Requirements

Table 13: Thermal Requirements

WBS Level	Requirement ID	Requirement	Notes	Parent requirement	Verification Method

Level #	TCS-1	Will make use of passive insulation materials and paints.	These are useful to protect components and the spacecraft from solar radiation, conserve temperature flux and also components from temperature change.	MEC - 3.1	Analysis
Level #	TCS-2	Shall maintain a temperature to operate within the range of -75 °C and -20 °C	The components from the thermal subsystem shall operate within this range and regulate other devices from the rover.	SYS - 8.1	Testing
Level #	TCS-3	Rover shall keep manufacturing constraints from the mission objectives.	This includes costs, volume, masses, and others.	SYS-01 SYS-1.1 SYS-1.2	
Level #	TCS-1.1	Shall have an active or passive system surveilling the constant temperature from the spacecraft to have optimal performance.	Use systems such as passive insulation materials, heaters or cooler systems to control internal temperatures.	MEC - 3.2	Demonstration
Level #	TCS-3.1	Will keep the power usage under the dedicated power given to the subsystem	Adherence to the instructions given for the given power input for the thermal instruments which will come from solar energy	MEC - 3.3	Inspection

Level #	TCS-3.2	Will measure less than the dedicated volume for this subsystem	Given a volume constraint for the rover, the thermal subsystem will not exceed its part in the volume constraint	SYS - 2.1	Inspection
Level #	TCS-3.3	Will have a breakdown cost for each component	The tools are not able to succeed the budget set for the thermal subsystem	MEC - 3.1	Inspection

2.1.4.2 Thermal Control Sub-Assembly Overview

The overview of the thermal subsystem goes into what the overall spacecraft and rover will need to maintain a safe mission lifetime with its respective thermal applications. These include cooling for heated devices inside the rover, heating of the battery and other electronics that may decrease their efficiency under cold circumstances or even stop working, and finally keep the rover exempt from solar radiation and flux.

As key requirements and constraints for the components, these should keep working under an umbrella that involves a power of ~ 60 Watts (66.3% of the power given by solar panels) which would be used for the best performance at critical points, ~ 2.315 kg of the total 45kg of the rover, and a volume of ~15,496 mm^3.

Now, the instruments as subsystems chosen for the thermal control are the following:

- **Cry-cooler**: For cooling electronic devices that warm up and cause risks to the performance of the rover and the mission objective- no need of cooling during nighttime
- **Heaters**: Warm up battery and other electronic equipment that can be at risk due to the cold temperatures and could cause a decrease in its efficiency.
- **Solar panels**: Provide the basis of power to the system and thermal subsystem.
- **Black paint**: Absorb heat while playing a role as anti corrosive for the rover.
- **Thermal switch**: Wax paraffin contraction and expansion to stitch temperature flown.

Indeed, this comparative table illustrates the characteristics of each of the components and from a manufacturing source, which helps to find later on the Technology Readiness Level. Solar panel won't be included as it is part of the main assembly from which every subsystem will have a dedicated power.

Table 14: Thermal Assembly Components

Thermal subassembly components				
Component	**Cry-cooler**	**Heater**	**White Paint**	**Thermal switch**
Manufacturer/ Product	Ricor - K508N	HK5185R17.6L 12A - Minco Inc.	S13-GLO	MER Paraffin Heat Switch
Mass	0.475 kg	0.54Kg	0.5 Kg	0.8Kg
Operative temperature range	- 40 °C to 85 °C	- 200 °C to 200 °C	N/A	- 95 °C to 20 °C
Volume	115.5 x 8 x 58 mm	254 mm x 281 (15c.)	N/A	1mm x 170mm x 240m
Input Power MAX	5.5 W	50 W/in^2	N/A	1 W/K
Lifetime	15 years	N/ A	~ 2 - 3 years	20,000 cycles
Cost	Low cost	24,000 USD	602 USD	0.16M USD

➢ N/ A: Not applicable, the technology doesn't require it.

For this subsystem, solar panels will classify as heritage, as they are lead time schedule and cost effective, apart from the fact that the team will make use of them just as other rovers have done in Martian missions. Different from past documents, most of the components were changed based on the needs for the mission.

For instance, MLI (Multi Layer Insulation) sunshields were removed as they are not optimal for Martian missions, including rovers. These insulation materials that prevent the spacecraft from heating or cooling and trapping radiation have shown to not have an optimal effectiveness in atmospheric environments such as Mars, although they do work in space. This is the reason why it was removed, but it was replaced by white paint which also plays the role of reflecting heat and even radiation.

Therefore, the use of white paint was added as it reflects heat during day time and doesn't perform much work at night, thermal switches were introduced to make the thermal components work depending on the martian temperature and weather conditions, and finally the inclusion of a heater from a different manufacturer was included too.

Next, the components of the thermal subsystem will be further explained with the reasoning behind their selection and how they will affect the mission for further success.

Cryocooler:

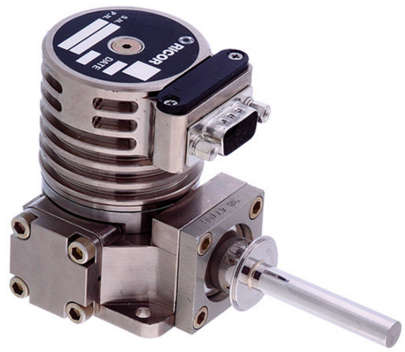


Figure 36 [28]

The cryocooler plays a vital role to maintain the operational role and temperature of the rover and sensitive electronic components just as science instruments like PIXL and RIMFAX. The wide temperature range of this apparatus between - 40°C and 85°C leads to the needed constraints of a Martian environment, where overheating can cause performance degradation, complete failure of electric circuits or even data corruption which would make the payload unmanageable. Its low power consumption of 5.5 Watts can effectively dissipate heat generated by these components which would at the end provide an optimal effectiveness for the work of the main instruments to ensure correct data collection related to subsurface water or energy sources for human life. Furthermore, this would be needed to fulfill Science objectives 1, 2 and 3.

Heater:

For this mission, the heater will effectively warm up critical subsystems such as batteries and electronics during freezing time in night times or winter seasons. Usually, when temperatures go below the operational temperature of many components, this heater that has a wide range of - 200°C and 200°C and a power output of 50 Watts will ensure that the thermal conditions prevent performance degradation for extreme cold conditions and also enable the continuous operations of the science instruments such as PIXL and RIMFAX for the three science objectives.

Figure 37 [29]

Now, the heater may require a high power input which would take about half of the total power created by the solar panels (renewable energy source) for all the components within the rover, but this one will just work in critical times when energy has been already stored inside batteries, and the main components are unable to work properly.

White Paint:

The efficacious albedo reflection of the white paint to dissipate heat from radiation sources such as the source helps mitigate the excessive heat absorption of the Rover during day-time by solar radiation by reflecting a significant portion of the energy. For example, in the NASA Thermal COntrol Engineering Handbook V4, the paint S-13 GLO, which will be used for this mission, has an absorbance of 0.2 - 0.5 and emittance of 0.88 for calculation purposes. Unfortunately, the paint tends to degrade over time because of the UV light exposure, which is why the mission needs to establish an expected life for the paint, which was set to be between 2 and 3 years before doing major calculations.

Consequently, this passive thermal control system reduces the thermal load for active cooling systems such as the cryocooler by optimizing power consumption and also increases the expected lifetime of the rover. This safeguards the performance and integrity of sensitive electronics by enabling accurate data collection for the three science objectives as well.

Thermal Switch:

Thermal switches history for Martian missions are exactly the technologies we need for our rover, as they were used for Mars Exploration Rovers (MER) to control battery temperature by changing a paraffin wax state from solid to liquid to actuate a mechanism by expansion or contraction and create or break the thermal contact.

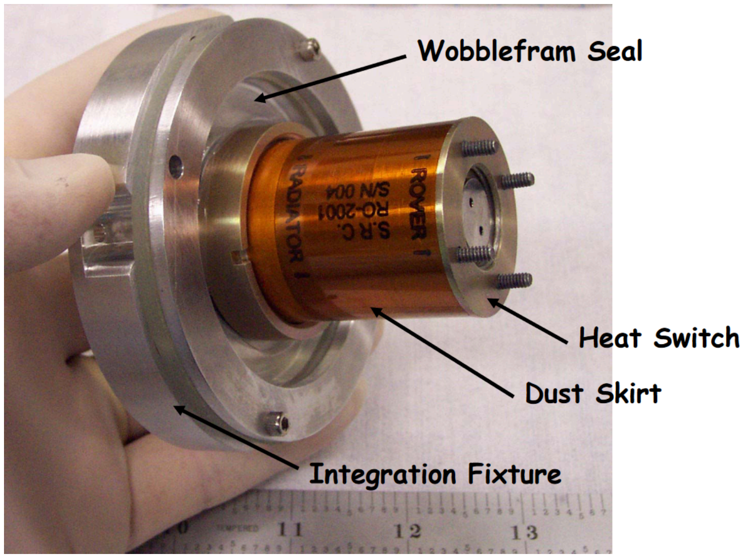


Figure 38 [30]

In this case, a paraffin heta witch was chosen due to its characteristics which were adequate for the mission constraints (mass, volume, costs, others). This one will optimize power usage by regulating the activation of heating or cooling mechanisms that are based on temperature fluctuations. Its range goes from - 95°C and 20°C with a heat transfer rate of 1 Watt per Kelvin which will lead to a controlled oriented Mars' dynamic environment. Also, it will extend the rover's operational lifetime which will increase the likelihood to achieve the three science objectives for human exploration.

Solar Panels:

These will be the primary source of energy for the rover, including the thermal subsystem and its respective components. Even Though they are an electrical engineering/ power main component, these need thermal management for a successful mission. So while not a direct thermal component is present here, these enable the efficient operation of active heating and cooling elements by giving the required electrical energy within the payload. This verifies the critical involvement and connection between the thermal and power subsystems to maintain the rover within the allowed temperature constraints.

2.1.4.3 Thermal Control Subsystem Recovery and Redundancy Plans

Redundancy plan and recovery for the thermal subsystem are crucial for successful completion of the system. These ensure a proper functionality of the rover and its components during its journey at Mars, and shall provide cooling just as heating systems to optimize its functionality in any environment and weather the river is found in. The following are the expected redundancy and recovery plans for it:

Redundancy:

- Cyocoolers will be implemented in two units, where one will become a backup of the other one in case one fails to cool the systems, which could risk the mission as the components would reach temperatures where their functionality will be decreased and even null.

- As shown in the table for the components that make up the thermal subsystem, several heaters will be placed inside the rover to heat all the artifacts that require thermal management during cold weather and extreme temperatures (batteries, electronics, others).

- Needed thermal switches will be integrated to activate and deactivate thermal components to guarantee a proper control of the rover.

- Thermal insulation redundancy will be established by white paint as a replacement for MLI (multilayer insulation) materials since they have a bad performance in atmospheres such as Mars.

Recovery (Contingency & Automatization):

- Plans such as thermal modeling with dust formation, power distribution, temperature fluctuations and other tests or analysis will be performed to adjust the components to provide the best performance for the rover's mission capabilities.

- Automated control systems will be implemented to detect anomalies, bad consumption of sources and others to protect the rover's critical components and assess recovery action in real time when needed.

2.1.4.4 Thermal Control Subsystem Manufacturing and Procurement Plans

Thermal subsystem will need the following manufacturing components to be able to provide the spacecraft and rover with the optimal features for a successful mission. These are all from private companies, but were selected upon the comparison that was made for each tool from their performance, schedule, costs, risks, and others. These were primarily suggested by NASA in a thermal control for SmallSats overview where they are also compared by their features. Next, bullet points will be used will be used to explain the procurement and manufacturing plans for each of the thermal components:

Crycooler:

➢ Product/ Manufacturer: K508N Ricor Model.
➢ Characteristics:
○ Acceptable mass, operating temperature range, volume, power input.
○ Exceptional: Lifetime.
➢ Rationale: High technology readiness level with necessary lead times for the rover assembly and integration.

Heater:

➢ Product/ Manufacturer: HK5185R17.6L12A - Minco Inc.
➢ Characteristics:
○ Acceptable mass, volume, power input, cost.
○ Exceptional: Temperature range, mission requirements.
➢ Rationale: Mission requirement with high temperature range necessary to heat critical components during extreme cold conditions in the Martian environment.

White paint:

➢ Product/ Manufacturer: S-13 GLO.
➢ Characteristics:
○ Exceptional: Albedo and emissivity, cost.
➢ Rationale: This component will cover the rover superficially and was chosen due to its high emissivity which prevents heat absorption, and reducing the heal load on the active loading systems.

Thermal switch:

➢ Product/ Manufacturer: MER Paraffin Heat Switch
➢ Characteristics:
○ Acceptable mass, volume, power input, cost.
○ Exceptional: Temperature range
○ Heritage: Used in Mars exploration rovers which proves its effectiveness.
➢ Rationale: Needed to optimize lifetime of the rover by regulating thermal components.

Manufacturing & Assembly:

All the components will be acquired from private contractors recommended by NASA in the thermal control engineering book and others, in addition to the heaters which were specifically chosen for this mission. Supplier selection at this moment is an estimate and is open to change based on the risk assessments and evaluating the proposals. They will all undergo testing and quality assurance before either integration into the rover, by evaluating their optimization and automation in space. Proper integration tests will be done after assembly and prior to launch with the necessary redundancy measures.

Procurement Plans:

Procurement for the rover and its assembly with the thermal system will be done according to programmatics to make sure there are no delays or cost overruns in the mission. In this way, the thermal subsystem will be equipped with the needed reliable components to have a successful mission and complete the three science objectives.

Even if the schedule for procurement is not settled yet, an estimate is based on the lead times for each component and are shown as a timeline (first to procure - last to procure):

1. <u>Crycooler (K508N Ricor):</u> 2 - 6 months.
2. <u>Heaters (HK5185R17.6L12A - Minco):</u> 2 - 4 months.
3. <u>White Paint (S-13 GLO):</u> 1 - 3 months.
4. <u>Thermal switch (Paraffin Heat Switch):</u> 3 - 6 months.
5. <u>Component Testing & Evaluation</u>: 2 - 6 months.
6. <u>Integration & Assembly</u>: 3 - 6 months.

2.4.1.5 Thermal Control Subsystem Verification Plans

Verification plans for the thermal subsystem are applied to make certain the requirements for the mission are met and that all components have the necessary characteristics to satisfy the rover's demands.

Crycooler:

- Verify the compatibility of the cryocooler and the rover's systems just as power interfaces.
- Performance test to ensure the specified characteristics such as temperature range, lifetime of a unit and cooling capacity are met.
- Vibration evaluation for launch and landing in Mars to simulate the mission from start to end.

Heater:

- Verify the compatibility of the heater and the rover's thermal system with activation controls.

- Performance test to ensure the specified characteristics such as power output, required temperature range and its ability to maintain temperature is working.
- Thermal cycling tests to analyze the effectiveness and operability of the component in extreme cold or hot environments.

White paint:
- Verify the thermal properties of the paint and its albedo/ emissivity properties.
- Performance test to ensure the paint can withstand Martian environment and how long its properties will last in this one.
- UV exposure testing for durability tests under Martian environment and how this paint degradates over time.

Thermal switch:
- Verify the ability of thermal switches to control components that regulate the temperatures in an automated system.
- Thermal cycling tests to analyze the compatibility of the switch with the rover's interfaces.

Now, apart from these testings that are specific for each of the components that compose the thermal subsystem, the following will be ones that involve the assembly testing:

Thermal interaction analysis:
- Perform thermal finite element analysis that evaluates the rover's integrity based on thermal effects and how each of the components interacts with each other.
- Include margin parameters to ensure that thermal deformation and stress levels are within the acceptable ranges,

Integrated rover testing:
- Test the overall rover capabilities, including the thermal system's one in this one.
- Verify the thermal subsystem does not negatively affect the structure of the rover and its performance for the mission requirements.
- Perform mission testing with scenarios similar to the Martian environment the payload will face on arrival to this planet, with its dedicated communications, power, and others.

2.1.5 GNC Subsystem Overview

The Guidance, Navigation and Control subsystem has an important role in the mission. It integrates various components and algorithms to enable precise control over the vehicle's movement, orientation, and velocity adjustments necessary for achieving mission objectives.

Guidance

Guidance plays a crucial role in the rover's mission, utilizing sensors to determine its location, direction, and trajectory necessary to achieve objectives. To ensure success, this component helps to predict the vehicle's future position, accounting for factors such as gravity, atmospheric conditions, and potential obstacles. Advanced algorithms are employed to detect and avoid obstacles in the rover's path, using sensors such as cameras.

Navigation

Navigation encompasses the determination of the vehicle's position, velocity, and attitude (orientation) relative to its surroundings. Its components include GPS and inertial measurement sensors. These sensors provide continuous updates on the vehicle's state vector, allowing the onboard navigation algorithms to track its position and velocity accurately. Navigation algorithms fuse data from multiple sensors to mitigate errors and uncertainties, providing estimates of the vehicle's current state throughout the mission.

Control

Control involves the execution of guidance commands to adjust the vehicle's velocity, rotation, and acceleration in response to navigation feedback. The control system utilizes actuators such as wheels and aerodynamic surfaces to apply the necessary steering controls. It aims to maintain stability, precision, and smooth travel along the desired trajectory while compensating for disturbances such as atmospheric winds or external forces. Control algorithms optimize the allocation of control inputs to minimize errors and deviations from the intended path, ensuring precise maneuvering towards the target.

GNC Components

Rocker-bogie wheels: Modeled after the Mars Science Laboratory, which boasts a total of six wheels made of aluminum, featuring cleats for traction and curved titanium springs for support. These wheels measure 20 mm in each and are equipped with their own motor. Both the front and rear wheels are outfitted with a steering motor, enabling the vehicle to execute full 360-degree turns, evade obstacles, and navigate tight curves. Notably, the rover's wheels demonstrate the remarkable capability to traverse obstacles equal to the size of one of its own wheels.

Magnetic Torque: Magnetic torquers are used to remove excess momentum from wheels; however, magnetic torques alone cannot provide three-axis stabilization. Their successful operation relies on a significant local external magnetic field, so it requires accurate investigation regarding their performance.

Sun sensors: The rover possesses 6 sun trackers deployed around the spacecraft, which are used to determine if there is sunlight and to estimate the direction of the sun. This information can be used for attitude estimation, but it requires at least one additional source to obtain a three-axis attitude. The sensors are typically only used during launch or in emergencies.

Inertial sensors: include gyroscopes and accelerometers that serve to gauge changes in velocity, respectively. These sensors are units integrating three orthogonal gyros alongside three orthogonal accelerometers (termed Inertial Measurement Units or IMUs). They play a pivotal role in maintaining the vehicle's state between updates from non-inertial sensors. For example, star trackers typically refresh attitude information at a low rate.

GPS Receivers: play a vital role in providing the rover with precise positioning information, enabling accurate navigation and localization. Additionally, these receivers compute the rover's velocity and time by processing signals received from multiple satellites.

Star trackers: The star tracker sensor is a vital component of a rover's guidance, navigation, and control (GNC) system, tasked with accurately determining the rover's orientation by observing the positions of stars in the sky.

Table 15

SUBASSEMBLY	MASS	VOLUME	MAX POWER	TRL
Rocker-bogie wheel	0.017	6.28mm3	1.047W	7-9

Magnetic torque	0.028	$1.037 \times 10^{-5} m^3$	0.42	7-9
Star Tracker	0.04	$1.6 \times 10^{-5} m^3$	0.6	7-9
Sun sensors	0.010	$4 \times 10^{-6} m^3$	0	7-9
Inertial sensors	≤0.025	$\leq 1 \times 10^{-5} m^3$	0.5	7-9
GPS receivers	0.4	$15 \times 10^{-5} m^3$	1.4	7-9

The data presented in the table above was sourced from the NASA Guidance, Navigation, and Control website and reflects measurements based on the overall size of the rover.

2.1.5.1 GNC Subsystem Requirements

WBS LEVEL	Reqt. ID	Reqt.	Parent Reqt.	Notes	Verification Method
GNC - 3	SYS – 8	Rocker- bogie Wheels	1	Shall allow the rover to go over obstacles. Each wheel has cleats, providing a better dislocation through soft sand	Demonstrative validation and testing
GNC - 3	SYS – 8	Magnetic Torquers	1.1	Shall remove excess of momentum from reaction wheels	Experimental testing
GNC - 3	SYS – 8	Star Trackers	2	Shall provide an accurate attitude by comparing a digital to an onboard star catalog	Analytical evaluation and testing
GNC - 3	SYS – 8	Sun Sensors	2.1	Shall locate the sunlight and use it to create power and shall also help the spacecraft to know where it's pointed.	Demonstrative validation and testing

GNC - 3	SYS – 8	Inertial Sensors	2.2	Shall provide 3-axis of information on its position making possible for the rover to make vertical, horizontal, and side-to-side movements	Experimental testing
GNC - 3	SYS - 8	GPS Receivers	3	Shall receive signals from satellites to determine the location, time and velocity	Experimental testing

Table 16: GNC Requirements

2.1.5.2 GNC Sub-Assembly Overview

The Rover Wheels

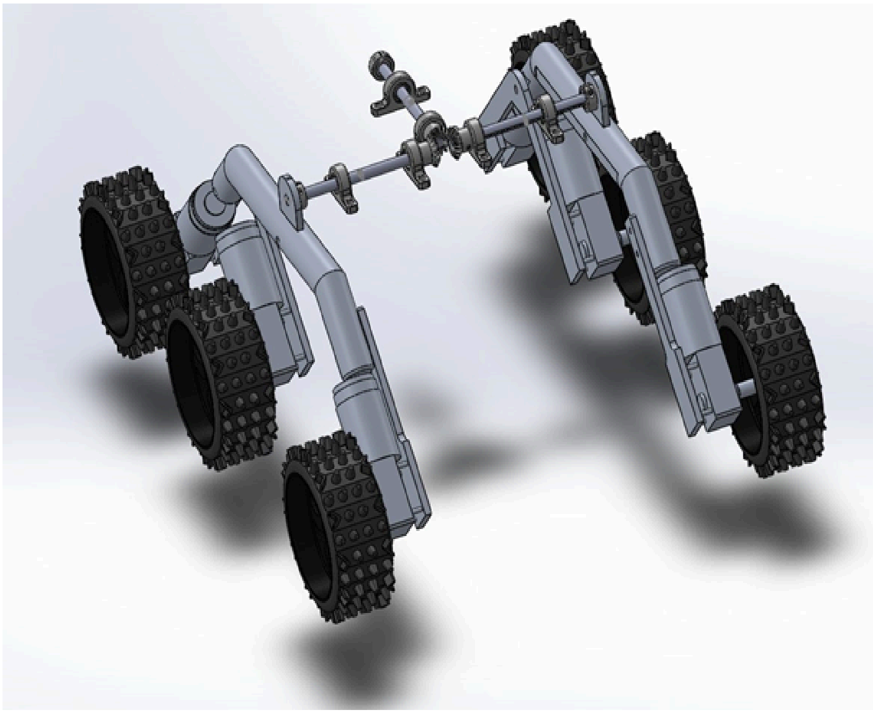

[31]

Figure 39

The Mars Exploration Rover features a six-wheel design with individual motorized wheels for independent movement, including front and rear pairs with steering motors for precise maneuverability, enabling 360-degree turns and curved motions. Inspired by the "rocker-bogie" concept from previous missions, this suspension system ensures stability and balance across rugged terrain by automatically adjusting when encountering obstacles to prevent tipping. Engineered to withstand tilts of up to 45 degrees, the rover's hazard avoidance software limits tilts to 30 degrees during traverses. With a maximum speed of 5 centimeters per second and hazard avoidance software prompting periodic pauses for terrain assessment, the rover maintains an average speed of 1 centimeter per second for safe progress.

Magnetic Torque


[16]

Figure 40

Magnetic torquers serve as pivotal components in spacecraft control systems, generating essential forces that facilitate orientation adjustments by acting perpendicular to the surrounding magnetic field. Their primary function often involves mitigating the build-up of excessive momentum in the wheels, ensuring spacecraft stability and maneuverability.

In the context of Mars exploration, the feasibility and efficacy of utilizing magnetic torquers warrant careful consideration due to the unique magnetic environment of the planet. Unlike Earth, Mars lacks a global magnetic field comparable in strength and stability. Instead, it possesses localized magnetic fields, primarily remnants of past magnetic activity.

When contemplating the deployment of magnetic torquers for spacecraft control on Mars, several factors come into play. Firstly, the strength and orientation of the local magnetic field at the mission site must be thoroughly assessed. While some regions may exhibit sufficient magnetic field strength for effective torquer operation, others may present challenges due to weaker or nonexistent fields.

Furthermore, the variability of Mars' magnetic environment poses challenges for sustained spacecraft control. As spacecraft traverse different regions of the planet, they may encounter fluctuations in magnetic field strength and orientation, necessitating adaptive control strategies.

In scenarios where the local magnetic field is insufficient for reliable torquer operation, alternative control methods become imperative. These may include the integration of additional propulsion systems, gyroscopic stabilization mechanisms, or advanced attitude control algorithms leveraging onboard sensors and actuators.

Ultimately, successful deployment of magnetic torquers on Mars hinges on a comprehensive understanding of the planet's magnetic environment and the development of adaptable control systems capable of navigating its complexities. Through planning and innovative engineering solutions, magnetic torquers could potentially play a valuable role in enhancing the maneuverability and stability of spacecraft during Martian exploration missions.

Inertial Sensors

In the operations of Mars rovers, inertial sensors are vital components within the guidance, navigation, and control (GNC) systems. They serve the crucial purpose of furnishing essential data concerning the rover's orientation, motion tracking, and localization, all without dependence on external references such as GPS.

These sensors encompass gyroscopes, accelerometers, and occasionally magnetometers. Gyroscopes, for instance, gauge angular velocity, enabling the rover to monitor its orientation and identify any shifts in its attitude while traversing the Martian landscape. This data is pivotal for maintaining stability, adjusting trajectory, and executing precise maneuvers, such as steering around obstacles.

Accelerometers, on the other hand, measure linear acceleration, thereby supplying information about the rover's velocity and alterations in speed along its path. By integrating these acceleration measurements over time, the rover can determine its position and velocity, facilitating navigation and path planning. Additionally, accelerometers aid in detecting terrain features and surface irregularities, essential for ensuring safe traversal over Martian terrain.

In certain scenarios, magnetometers may be incorporated into the sensor suite to gauge the strength and direction of the local magnetic field. While Mars lacks a global magnetic field akin to Earth's, it does exhibit localized magnetic anomalies. These anomalies can offer valuable navigational cues, particularly when combined with data from other sensors.

Collectively, these inertial sensors serve as the backbone of the GNC system, empowering the rover to autonomously navigate and explore the Martian surface with precision and reliability. By continuously monitoring its orientation, motion, and environment, the rover can adeptly respond to environmental challenges and carry out intricate scientific tasks, thereby enhancing our understanding of Mars and its potential for past or present habitability.

Sun Sensors

[16]

Figure 41

In the guidance, navigation, and control (GNC) systems of Mars rovers, sensors dedicated to detecting sunlight serve as indispensable tools for accurately measuring the spacecraft's alignment with respect to the Sun. These sensors play an important role in guaranteeing the rover's proper positioning and facilitating its movement across the Martian terrain.

Typically comprising arrays of photodiodes or phototransistors strategically mounted on the rover's exterior, these sensors are adept at capturing both the intensity and direction of sunlight. This data is then utilized for precise attitude control and navigation. By interpreting the information collected by these sensors, the rover's onboard computer can meticulously ascertain its orientation relative to the Sun.

Given the absence of dependable Earth-based landmarks for orientation on Mars, these sun sensors assume great importance. They empower the rover to uphold its desired alignment in relation to the Sun, thereby streamlining diverse operational tasks such as aligning solar panels, managing thermal conditions, and establishing communication with Earth.

Furthermore, sun sensors play a crucial role in mitigating the challenges posed by the Martian environment, including dust storms and fluctuations in solar radiation. By continuously monitoring the Sun's position, these sensors enable the rover to adapt its orientation, accordingly, thus ensuring optimal functionality and performance.

In essence, sun sensors stand as indispensable components within the GNC systems of Mars rovers, enriching their capacity to navigate and operate efficiently on the Martian surface by furnishing precise orientation data in relation to the Sun.

GPS Receivers

In the guidance, navigation, and control (GNC) systems of Mars rovers, GPS receivers are indispensable for pinpointing the rover's location and facilitating its movement across the Martian terrain. These receivers are essential for ensuring accurate positioning and effective route planning during rover missions.

Although similar to GPS systems used on Earth, those on Mars rovers operate differently due to the absence of a global network of GPS satellites orbiting Mars. Instead, Mars rovers rely on a combination of Mars orbiters and ground-based assets to receive navigation signals.

Mars orbiters equipped with GPS-like capabilities act as relay stations, transmitting signals to the rover's GPS receiver. These signals contain data about the orbiter's position and speed relative to Mars, allowing the rover to calculate its own location and velocity on the Martian surface.

In addition to orbiters, ground-based assets such as radio beacons or landmarks may also be employed to enhance the rover's navigation abilities. By measuring distances to these known points, the rover can refine its position estimates and improve navigation precision.

Although GPS receivers offer valuable localization data, they may face limitations in certain scenarios, such as when communication with orbiters is sporadic or when navigating in areas with obstructed views of the sky. In such cases, rover navigation systems must utilize alternative sensors and methods, such as inertial navigation.

Despite challenges posed by the Martian environment, GPS receivers remain crucial in the GNC systems of Mars rovers, providing vital location and velocity information for precise navigation and successful exploration of the Martian surface. Ongoing advancements in techniques and technologies continue to enhance the capabilities of these receivers, bolstering the effectiveness of Mars exploration missions.

Star Trackers

Star trackers serve as indispensable elements within the guidance, navigation, and control (GNC) systems of Mars rovers. Their primary function is to accurately ascertain the rover's orientation by observing the positions of stars in the sky.

Positioned either on the rover's body or mast, star trackers utilize advanced cameras and complex algorithms to detect and monitor the positions of known stars. By cross-referencing observed star patterns with an extensive catalog of celestial objects, these trackers can precisely determine the rover's orientation relative to the stars.

Star trackers offer numerous benefits for Mars rovers. Firstly, they establish a reference frame that is independent of the Martian surface, enabling accurate navigation even in regions with minimal visual landmarks or during adverse conditions such as dust storms. Moreover, these trackers empower the rover to autonomously ascertain its heading and orientation, minimizing the necessity for frequent communication with mission control on Earth.

However, star trackers may encounter challenges on Mars, including the presence of atmospheric dust that can obscure starlight and impact sensor performance. Nevertheless, ongoing advancements in sensor technology and image processing algorithms are continuously enhancing the reliability and precision of star tracking systems in Martian environments.

In essence, star trackers play an indispensable role in the GNC systems of Mars rovers, facilitating precise navigation and orientation determination crucial for the successful exploration of the Martian terrain.

2.1.5.3 GNC Subsystem Recovery and Redundancy Plans

Crucial components of the GNC subsystem, such as navigation sensors, control mechanisms, and communication systems, shall be duplicated to ensure redundancy. In case the primary system malfunctions, the backup system can seamlessly take over to ensure that essential mission requirements remain fulfilled.

Nevertheless, it's important to recognize that not every part of the GNC system will have a duplicate in place. Some components, such as antennas, may be identified as single point failures, indicating that their failure could potentially compromise the mission. These single point failures must be carefully documented and addressed through alternative measures, such as monitoring systems or contingency plans, to mitigate any adverse impact on the mission's success.

The rover's software continuously monitors various sensors and subsystems for any anomalies or errors. If a system error is detected, the software initiates a response to rectify the issue. The software executes predefined recovery actions based on the nature of the error encountered.

The GNC system collaborates closely with the software team to develop and implement comprehensive recovery plans for various scenarios. Recovery plans are integrated into the rover's software architecture and tested extensively in simulated environments to ensure effectiveness and reliability.

The rover's software autonomously evaluates the severity of system errors and prioritizes recovery actions based on predefined criteria. This autonomous decision-making capability allows the rover to respond promptly and effectively to unexpected events without requiring direct intervention from mission control.

After executing recovery actions, the software continues to monitor system status to ensure that the error has been resolved and that the rover has returned to a safe operating state. If necessary, the software may adapt recovery strategies in real-time based on evolving conditions or new information.

By integrating autonomous recovery capabilities into the GNC system and collaborating closely with the software team, the Mars rover can effectively address system errors and ensure mission success even in the absence of direct control from mission control.

2.1.5.4 GNC Subsystem Manufacturing and Procurement Plans

To the GNC (Guidance, Navigation, and Control) components of the rover, John Hopkins University has been selected as the contractor. With a great experience in spacecraft technology, covering a wide range, including rovers, the contractor is well-equipped with a diverse selection of materials essential for the GNC system, perfectly suiting the mission's needs. Moreover, the proven success in developing small spacecraft gives assurance in the capability to provide customized solutions for the small rover project.

Manufacturers:

- *Rocker Bogie Wheels*

Supplier: Blue Canyon Technologies

Lead time: 10 - 12 months.

Important to navigate during the mission, the wheels provided by this company ensures torques and momentum necessary for the spacecraft.

- *Star Trackers*

Supplier: Blue Canyon Technologies

Lead time: 6 - 9 months .

Blue Canyon Technologies has a reliable star tracker that can suit the most challenging missions.

- *Sun Sensors*

Supplier: CubeSpace Satellite Systems

Lead time: 6 - 9 months.

This manufacturer's sun sensor has great benefits for the mission, such as a wide field of view, low power consumption and high accuracy.

· *GPS Receivers*

Supplier: AAC Clyde Space

Lead time: 6 - 9 months.

This company provides low-cost equipment that provides an amplified hemispherical coverage.

· *Inertial Sensors*

Supplier: New Space Systems

Lead time: 6 - 9 months.

This company offers low-cost and low noise equipment. With a great performance bringing sensing and control across three axes of angular rate and linear acceleration.

The lead times for the GNC (Guidance, Navigation, and Control) components are derived from the manufacturer's specifications, sourced from CubeSpace Satellite Systems website, and also from past missions. These lead times have been tripled to allow ample room for any unforeseen challenges that may arise during the process, ensuring sufficient time for resolution of any issues. Therefore, the estimated time will probably be shorter.

2.1.5.5 GNC Subsystem Verification Plans

Rocker Bogie Wheels:

Verification Approach: Demonstrative Validation and Testing.

Verification Methods:

- The team shall execute practical tests to ensure the mobility and stability of the rocker bogie suspension system on simulated Martian terrain.
- The team shall conduct stress assessments to validate the endurance and weight-bearing capability of the wheels.
- The team shall analyze data from preliminary testing to confirm adherence to design specifications.
- Test Environment: Employ a testbed that replicates Martian surface conditions, encompassing various terrain features such as rocks, slopes, and soil compositions.

Star Trackers:

Verification Approach: Analytical Evaluation and Testing.

Verification Methods:

- The team shall utilize mathematical modeling and simulation to investigate the precision and accuracy of star tracking algorithms.
- The team shall perform controlled laboratory trials to validate the star tracking performance under conditions mimicking celestial navigation scenarios.
- The team shall evaluate the results of the star tracker assessments to ensure tracking precision and reliability.
- Test Environment: the team shall employ a controlled laboratory setting with a star field simulator to recreate celestial navigation environments.

Sun Sensors:

Verification Approach: Demonstrative Validation and Testing.

Verification Methods:

- The team shall execute calibration procedures to verify the precision of sun sensor measurements.

- The team shall conduct tests under varying illumination conditions to validate the responsiveness of sun sensors.
- The team shall analyze the outcomes of sun sensor evaluations to ensure alignment with anticipated results.
- Test Environment: the team shall utilize a solar simulator to replicate different solar angles and intensities.

Inertial Sensors (Including Gyroscopes and Accelerometers):

Verification Approach: Experimental Testing.

Verification Methods:

- The team shall perform calibration tests to confirm the accuracy and stability of inertial sensor readings.
- The team shall execute dynamic assessments to evaluate sensor response to rover motion and external influences.
- The team shall analyze the results of sensor evaluations to assess compliance with specified requirements. Test Environment: Utilize a motion simulation platform to expose the sensors to controlled movements and accelerations.

GPS Receivers:

Verification Approach: Experimental Testing.

Verification Methods:

- The team shall conduct tests to assess GPS receiver sensitivity and acquisition time for signal acquisition and tracking.
- The team shall perform assessments to evaluate the accuracy of GPS-derived rover positions.
- The team shall analyze data from GPS receiver tests to evaluate performance under diverse atmospheric and signal conditions.
- Test Environment: The team shall use a GPS signal simulator to generate controlled GPS signals in a laboratory setting.

Magnetic Torquers:

Verification Approach: Experimental Testing.

Verification Methods:

- The team shall conduct tests to measure the torque generated by the torquers under varying magnetic field strengths.
- The team shall perform attitude control assessments to evaluate the responsiveness and stability of the rover's attitude control system.
- The team shall analyze data from torque tests to confirm alignment with expected performance.
- Test Environment: The team shall utilize a magnetic field simulation chamber to replicate Martian magnetic field conditions.

2.1.6 Payload Subsystem Overview

The payload system consists of the instruments that would be applied to accomplish the science missions and science goals for this mission. The instruments that will be attached to the rover include the Planetary Instrument for X-ray Lithochemistry (PIXL) and the Radar Imager for Mars Subsurface Exploration.

The PIXL is an instrument that has been used on th perseverance rover and is a X-ray fluorescence instrument that maps the spectral compositon of an area of the sample under study using thousand of individual points within the maps. It works by using a X-ray laser beam to vaporize a small area of sample which is then analyzed and imaged with fluorescence based on the composition of the area.

The RIMFAX is an instrument that will map the texture and structure of the Mars surface within the region of interest as well as the stratas of subsurface underneath. It works by transmitting radio waves downwards and detect the radio waves deflected back by the layers. The time taken to be detected from transmission as well as the velocity will be used to determine the dielectric and physical properties of the sample.

The recovery and back up instrumental process is stated. The PIXL camera will be used to replace the RIMFAX instrument in case of complete failure but there is no direct replacement for the PIXL but the RIMFAX images can be use to indirectly determine the composition of th eregolith based of the texture and color form the high resolution images. The source of parts of the instruments have also been stated in the manufacturing and process plan.

2.1.6.1 Science Instrumentation Requirements

The requirements for the science instruments are as follows:

Planetary Instrument for X-ray Lithochemistry (PIXL)

1. The instrument shall collect and transmit absorbance spectra of a total sample area of 5 km^2.
2. The instrument will collect spectral readings for Calcium, Chlorine, Hydrogen and Oxyegn within the samples if present.
3. The instrument must be able to detect and record spectral wavelength readings between 130 and 900 nm.

Radar Imager for Mars Subsurface Exploration (RIMFAX)

1. The instrument will be able to map and analyze depths of no less than 30 feet.
2. The resolution of the MCC images must be greater than 5 inches thick.

2.1.6.2 Payload Subsystem Recovery and Redundancy Plans

Science Instrument 1 - PIXL (Planetary Instrument for X-ray Lithochemistry)

The Planetary Instrument for X-ray Lithochemistry is vital in determining the atomic or elemental identities and composition of samples obtained. This instrument will be geared towards obtaining spectral data on micro samples of regolith and rock samples within the Mars surface within possible landing and habitable zones that will be studied during this mission. The main elements of interest include Calcium, Oxygen, Chlorine, and Hydrogen which act as markers for the compounds Calcium Oxide, Calcium Perchlorate, and Water Ice. The instrument will record absorbance spectral data generated from the sample within a small sample within the region of interest by transmitting X-ray radiation to vaporize the samples from various unique areas within the chosen region of interest and analyze the X-ray fluorescence detected. Calcium is expected to produce bluish fluorescence. The expected data return is about 2 megabytes per day. The PIXL is also equipped with a nightlight as it requires pictures of the rock samples for autonomous positioning. The PIXL instrument is vital to the mission objectives. By determining the abundance of Calcium Oxide and Calcium Perchlorate, we can determine the approximate amount of energy that can be generated from reactions of Calcium and Carbon Dioxide. This energy will be geared towards warming liquids utilized during manned missions at nighttime because the temperature at night drops below the freezing point of vital liquids in the spacecraft. The abundance can determine how readily available these starting materials are and the sustainability of this chemical system.

The Mars ecosystem is known for its harsh weather conditions and cold temperatures. The rover will be designed with a heater to maintain an optimum temperature for the instruments and software. The software accompanying the PIXL will be configured with remote troubleshooting options to account for possible software and data storage glitches. The PIXL will also have a secondary data storage to minimize data loss There will be no direct replacement for the PIXL instrument due to mass constraints, but the RIMFAX can be utilized as an indirect complement or replacement during the periods of inactivity of the PIXL due to glitches or updates.

Science Instrument 2 - RIMFAX (Radar Imager for Mars' Subsurface Experiment)

The RIMFAX (Radar Imager for Mars' Subsurface Experiment works as a ground-penetrating radar instrument that is utilized to determine the subsurface structure of Mars. Different compositions of Mars's surface and subsurface from sand to regolith to ice to rocks reflect and scatter electromagnetic radiations differently. The RIMFAX uses a single antenna to transmit and receive electromagnetic waves over a frequency range of 150 to 1200 MHz into or from the subsurface layers in either active or passive modes. The transmitted waves are reflected and the received time for each reflected wave is recorded.

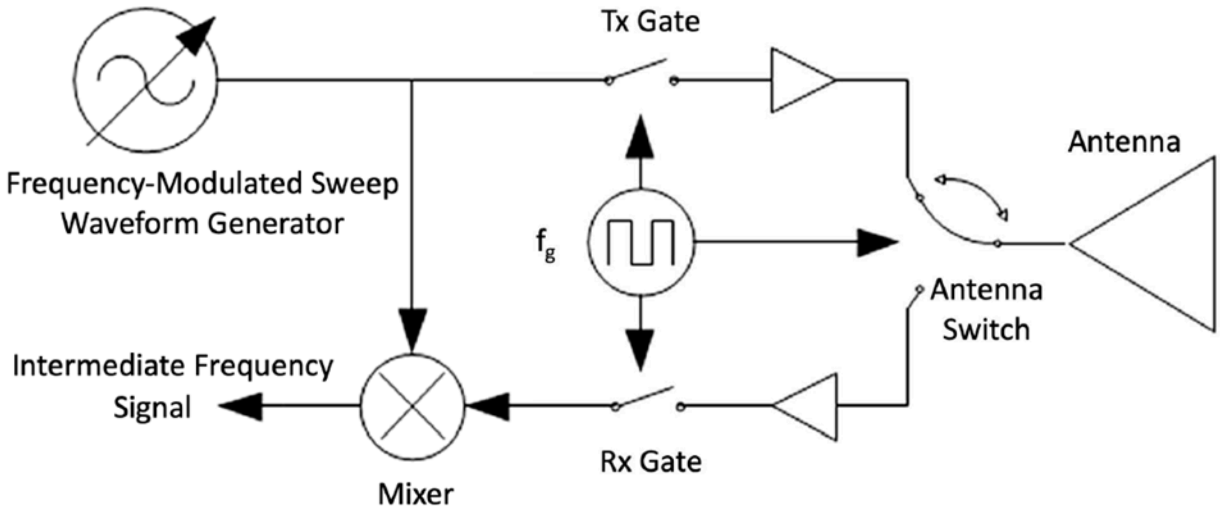


Figure 42

The radio wave signals, being electromagnetic waves, could be scattered by dust particles and high-speed winds disrupting the collection of data. The data shall also be stored on a secondary site in case of disruption of transmission until the transmission connection is fixed. This will be mitigated by the choice of landing site. In the case of irreparable damage to the RIMFAX, the PIXL instrument can be used to obtain spectral data to obtain the composition of regolith, rocks, and ice in that area. The camera and imager attached to the PIXL can also be used to complement or replace the RIMFAX. This camera can image regolith and rock to the size of a grain providing detailed information about the texture of the surface which can be used as a guide on possible erosion channels which can translate to early sites of flowing water.

2.1.6.3 Payload Subsystem Manufacturing and Procurement Plans

For the science instruments, the following components are needed to construct the required instruments to complete the mission’s science goals. Two instruments will be used: the PIXL and the RIMFAX, with some components manufactured and supplied from the same place. All components are manufactured in house at NASA facilities, as that provides the most compatible integration for the mission.

PIXL:

X-ray Tube

Supplier: NASA Goddard Space Flight Center - X-ray Astrophysics Laboratory

Lead Time: 9-12 months

The X-ray tube is a critical component of the PIXL, and as such, NASA's X-ray Astrophysics Laboratory at Goddard Space Flight Center would take charge of the development of the X-ray tube. The lead time accounts for the various testing and customizing the tube to meet the specifications of the mission.

Detector Assembly

Supplier: NASA Jet Propulsion Laboratory - Detector Development Group

Lead Time: 12-18 months

The Detector Development Group at NASA's Jet Propulsion Laboratory would create the detector assembly, which is essential for gathering and processing X-ray signals from Martian materials. In order to guarantee peak performance in the challenging Martian environment, extensive testing and calibration procedures are included in the lead time.

Sample Handling Mechanism

Supplier: NASA Ames Research Center - Intelligent Systems Division

Lead Time: 18-24 months

The Intelligent Systems Division of NASA's Ames Research Center would be in charge of creating and constructing the complex sample handling system needed for PIXL. The lead time takes into consideration the complex design and implementation of motion control systems specifically suited for the mission's science objectives.

Data Processing Unit

Supplier: NASA Goddard Space Flight Center - Instrument Electronics Development Branch

Lead Time: 12-18 months

NASA's Instrument Electronics Development Branch at Goddard Space Flight Center would create the data processing unit, which is crucial for deciphering X-ray signals and producing analytical conclusions. Design, testing, and integration of high-performance computer components fit for space missions are all included in the lead time.

Specialized Optics (Lenses and Mirrors)

Supplier: NASA Marshall Space Flight Center - Optics & Photonics Laboratory

Lead Time: 9-12 months

The Optics & Photonics Laboratory at NASA's Marshall Space Flight Center would be in charge of creating the unique mirrors and lenses needed to concentrate X-rays onto Martian samples and detectors. In order to satisfy the needs of space exploration, the lead time involves precision manufacturing and stringent quality testing procedures.

RIMFAX:

Radar Transmitter and Receiver

Supplier: NASA Jet Propulsion Laboratory - Radar Science & Engineering Group

Lead Time: 12-18 months

The Radar Science & Engineering Group at NASA's Jet Propulsion Laboratory would create the radar transmitter and receiver, which would be essential for transmitting and receiving radar signals to penetrate Martian subsurface layers. The lead time takes into consideration the planning, testing, and modification needed to satisfy the unique demands of the RIMFAX instrument.

Antenna Array

Supplier: NASA Glenn Research Center - Antenna & Optical Systems Branch

Lead Time: 18-24 months

The Antenna & Optical Systems Branch of NASA's Glenn Research Center would be in charge of creating and building the unique antenna array required for sending and receiving radar signals on Mars. The lead time covers the creation of unique antenna designs suited to the mission goals and the Martian environment.

Digital Signal Processor

Supplier: NASA Ames Research Center - Intelligent Systems Division

Lead Time: 12-18 months

The Intelligent Systems Division of NASA's Ames Research Center would create the digital signal processor that is necessary for processing radar data that is gathered by the RIMFAX sensor. Design, testing, and integration of high-performance computer components appropriate for space radar signal processing are all included in the lead time.

Power Amplifier

Supplier: NASA Goddard Space Flight Center - Microwave Instruments & Technology Branch

Lead Time: 9-12 months

The Microwave Instruments & Technology Branch of NASA's Goddard Space Flight Center would be in charge of developing the power amplifier needed to enhance radar signals sent by the RIMFAX instrument. To guarantee dependable operation in the Martian environment, extensive testing and optimization are part of the lead time.

Data Storage Unit

Supplier: NASA Johnson Space Center - Avionics & Software Systems Division

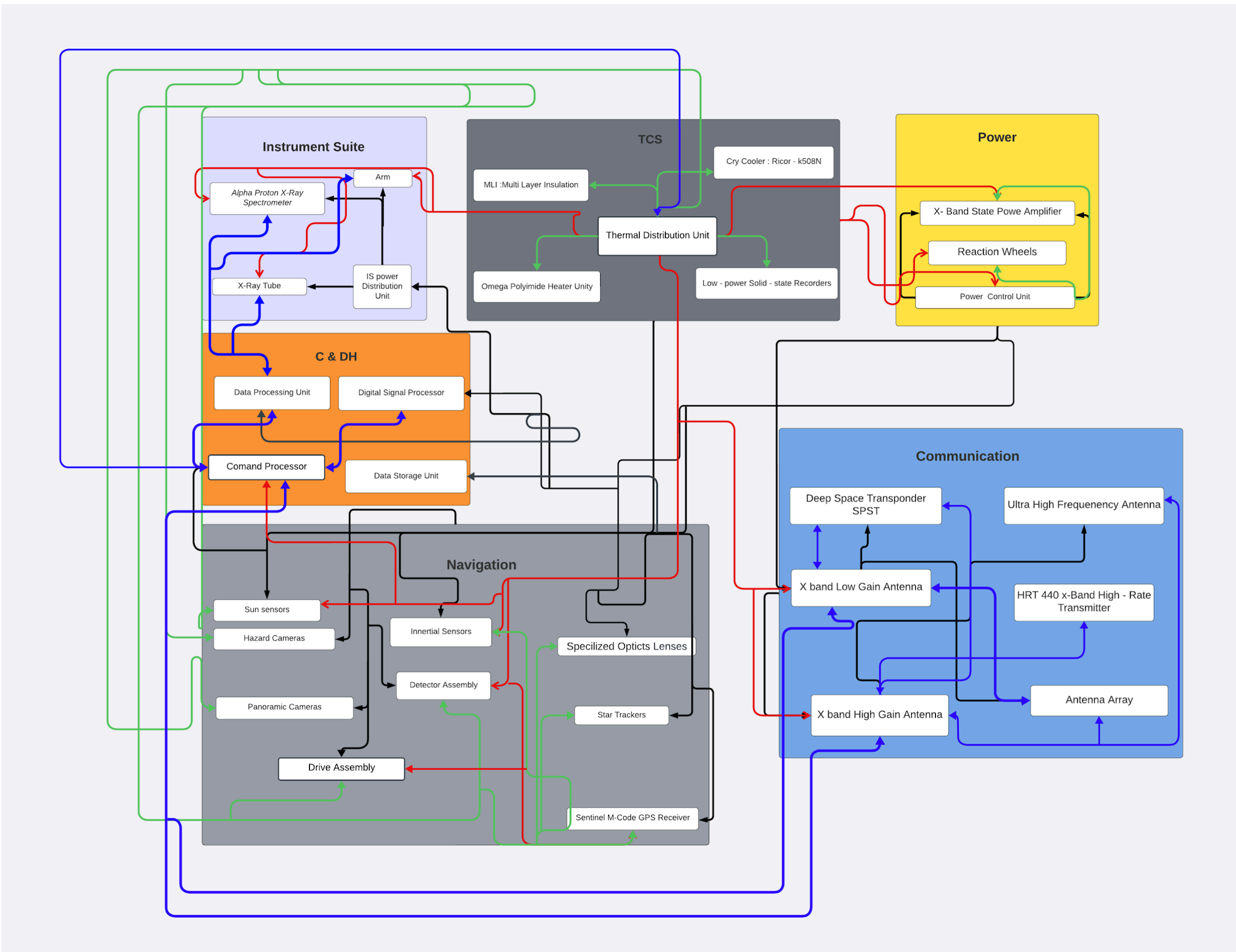
Lead Time: 12-18 months

The Avionics & Software Systems Division of NASA's Johnson Space Center would construct the data storage unit, which would be in charge of storing radar data gathered by RIMFAX before transmitting it to Earth. Design, testing, and integration of reliable data storage solutions fit for space missions are all included in the lead time.

2.1.6.4 Payload Subsystem Verification Plans

2.2 Interface Control

Functional Block Diagram



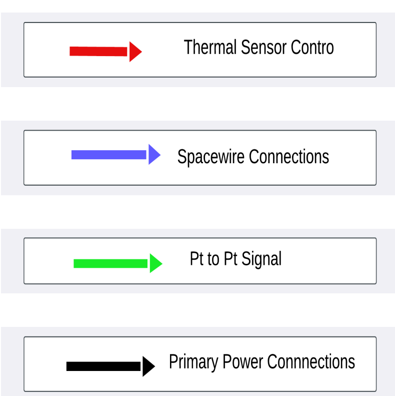


Figure 43: Block Diagram

N^2 Chart

Figure 44: N2 Chart

3. Science Mission Plan

3.1 Science Objectives

Science Objective 1: Determining possible sources of chemical energy on Mars. This objective involves the identification of possible sources of chemical energy on Mars, such as methane or hydrogen, which is crucial for both the sustenance of human exploration and the provision of resources for future missions. By comprehending the chemical energy distribution on Mars, the objective is to evaluate the practicality of using these resources to fuel different facets of human endeavors on the planet. This objective investigates potential energy sources that can sustain human exploration endeavors.

Science Objective 2: Determining the product of the decomposition of perchlorates on the Mars surface. Through the examination of the breakdown substances of perchlorates found on the surface of Mars, we will gain significant knowledge about the chemical makeup of the planet's soil. This data will not only provide information about possible dangers or difficulties for human investigation but will also reveal potential sources of chemical energy that may be utilized. In addition, comprehending the breakdown products adds to Science Goal 1 by offering crucial insights into chemical energy sources that might potentially support human exploration initiatives.

Science Objective 3: Determining locations of water sources in ice formations on Mars. The identification of water sources, especially inside ice formations on Mars, is essential for facilitating human exploration and ensuring the long-term survival of life on the planet. Water is an essential resource for a range of human activities, such as consumption, agriculture, and fuel generation. Identifying the precise locations of these water sources enables the setting of a foundation for developing the necessary infrastructure to efficiently collect and utilize water resources. This aim greatly contributes to Science Goal 1 by discovering prospective sources of water that might support human presence and exploration on Mars. Furthermore, it contributes to Science Goal 2 by supplying crucial data on available resources for upcoming missions.

3.2 Experimental Logic, Approach, and Method of Investigation

PURPOSE

The purpose of this experiment is to fulfill all the expected scientific objectives with the use of the PIXL (Planetary Instrument for X-ray Lithochemistry) and the RIMFAX (Radar Imager for Mars Subsurface Experiment). The experiment aims to determine the composition of the regolith and the abundance of Calcium Oxide and Calcium Perchlorate. This helps to determine prospective energy sources to sustain certain aspects of human exploration.

The main elements of interest include Calcium, Oxygen, Chlorine, and Hydrogen which act as markers for the compounds Calcium Oxide, Calcium Perchlorate, and Water Ice. The experiments will also aim to determine the products of the decomposition of Calcium Perchlorate thereby providing significant insight into the makeup of the surface of Mars and the history of Mars' surface. The RIMFAX Instrument will be used to determine the possible location of water sources in formations on Mars which can be used to support human explorations as water is a vital requirement in manned missions and life as humans.

INSTRUMENTATION

The experiment will be conducted autonomously when the rover has reached specific sites of interest within the habitable and exploration zone. The rover is equipped with two instruments: The Planetary Instrument for X-Ray Lithochemistry (PIXL) and the Radar Imager For Subsurface Exploration.

The RIMFAX (Radar Imager for Mars' Subsurface Experiment is a ground-penetrating radar instrument that is utilized to determine the sub-surface structure of Mars. Different compositions of Mars's surface and subsurface from sand to regolith to ice to rocks reflect and scatter electromagnetic radiations differently. The RIMFAX has an antenna to transmit and receive electromagnetic waves over a frequency range of 150 to 1200 MHz into or from the subsurface layers in either active or passive modes. The transmitted waves are reflected and the received time for each reflected wave is recorded. This instrument will be vital in finding possible locations of water ice within the exploration zone. This will aid in determining the nature of the material under the landing site and expected observation zones through the propagation of radar waves sensitive to certain properties of the materials that make up the strata.

The PIXL will be used to determine the the abundance of chemical compounds under study : Calcium Oxide and Calcium Perchlorate by determining the abundance of their elemental compositions using X-ray spectrometry and spectrophotometry. The absorbance of each element is unique and can be used to identiy the composition of the sample and hypothesize the compounds present within the regolith sample. For example, Calcium is expected to have a bluish fluorescence. The nightlight is a vital tool during the dark phases of the experiment and autonomous positioning for sample collection.

METHODOLOGY

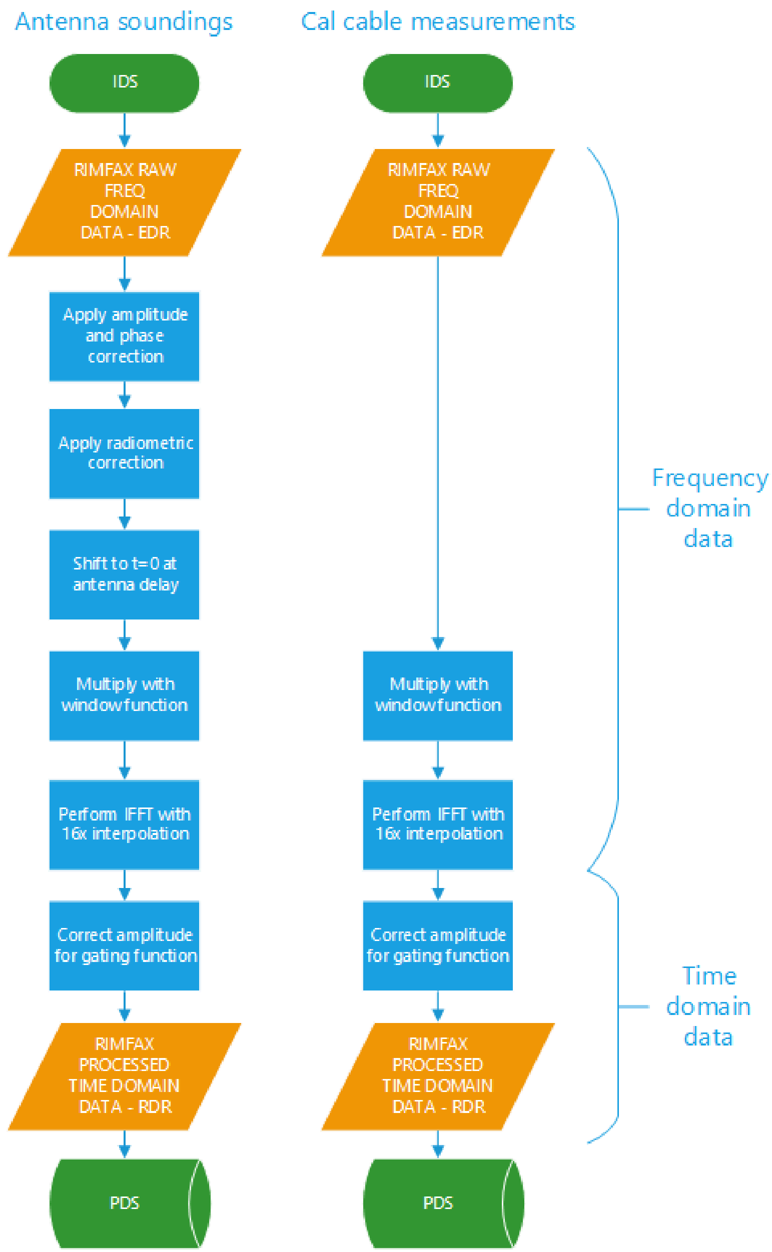
The PIXL produces high resolution images of samples of regolith using X-ray fluorescence. Over about 5 hours, the PIXL will autonomously scan regolith surface over a specific area of interest which is a possible calcium and water ice deposit site creating a spectral map containing thousands of individual points with the respective spectral and elemental compositions which will be overlaid on the map generated by th PIXL's micro-context camera and the RIMFAX camera. These combinations will produce information on the distribution and the abundance of the elements under study while also exposing more information on the physical texture and structure of the regolith up to a 10X magnification.

The light illuminator aims laser spots onto the target sample in a unique pattern while the MCC camera takes images of the surfaces with the laser patterns generated on the surface. The Instrument Flight Software uses the image to determine the distance from the target surface which can be used to analyse the surface. Data collection and observations will occur over a long duration and can also be done as an overnight operation as an experiment from Sol N to Sol N+1. The PIXL experiment begins by detecting a landmark of interest on Sol N collecting MCC images to serve as a reference image to test the PIXL uplink and select a target location. The PIXL collects MCC image on SOL N+1 then uses a feature tracking algorithm to determine the distance form the target location an adjust the hexapod so the sensor is align dwith the scan position. Additional MCC images are collected and Dwell spectra are also collected periodically to reveal presence of trace elements and elements of interest.

The RIMFAX sends transmitted waves downwards into the target sample until it is reflected back. The speed of the signal is affected by the material's dielectric and physical properties. While the rover moves horizontally, radar measurements are taken at fixed distance increments along the surface. The radar measurement is represented as an image called a radargram with respect to the traverse distance and time.

$$d = v * t$$

$$v = c / \mathrm{sqrt}(e).$$



3.3 Payload Success Criteria

The criteria for the success of the mission for the payload system is determined based on the efficiency of the instrument, its ability to carry out it's functions with little or no instrumental errors. This is expected for both instruments.

The RIMFAX is an instrument that works based on its ability to transmit radio waves to the target sample and detect the deflected waves from the target sample and this can be used to determine the iidentity and composition of the regolith sample based on the physical properties of the strata.

The success criteria for the RIMFAX instrument are as follows:

1. The RIMFAX Instrument must have a minimum depth penetration of 30 feets for all measurements taken to ensure a large amount of depth is read and studied to avoid any blind side.
2. Less than 5 % of data is lost during the remote transmission, storage of data and power outages.
3. The resolution of the MCC images must be greater than 5 inches thick.
4. The instrument produces readable data from which information can be inferred from.

The PIXL is a spectrophotometric instrument with a sensor and camera attached that works using the process of X-ray fluorescence. The PIXL is expected to produce high resolution images of various points across the area of the sample and determine the spectral and chemical composition of the sample. This data can be used to infer the type of compounds that make up the regolith sample.

The success criteria for the PIXL instrument are as follows:

1. The minimum spatial resolution of all images generated must be 0.12 mm. Lower resolutions will affect the ability to read data obtained and make accurate inferences.
2. The variable step size of images generated must be no greater than 0.1 mm
3. The PIXL must be able to detect elements at trace levels and concentrations of minimum of 10 ppm.
4. No more than 5% of experimental data can be lost during remote transmission and storge including power shortages and system updates.

3.4 Testing and Calibration Measurements

Testing and calibration of scientific instruments is the first and most vital step in instrumentations for experiments as it determines the precision and accuracy of data gatheredas well as the efficiency and success of the mission. This will aslo be vital to determine errors within the experiment and instruments as well as the source of the errors which can be fixed by updates or removal of error filled updates.

RIMFAX: Radar Imager for Mars' subsurface Experiment Calibration:

Upon reaching Mars, RIMFAX will conduct preliminary testing and calibration of readings by transmitting and receiving radar signals to confirm the transmission strength and sensitivity of the reception device multiple times to determine the precision and accuracy of readings over the same area and depth and within a fixed increment of time The site for calibration will be an already determined geographical are or geological formations on Mars, such as flat basaltic plains whose composition has been well recorded for comparison to the intensity and clarity of the returned signals taken before the launch.

The RIMFAX instrument will be calibrated on mars befor any major experimental readings are taken by comparing its measurements with the recorded physical characteristics at specific known regions determined by other instruments or earlier missions (such as MRO or Mars Insight) such as density and composition, The calibration process will mostly include adjusting the instrument's penetration depth and resolution parameters to align with the expected accurate readings.

The control variables for RIMFAX testing will include the radar frequency, power output, and integration time as well as the area and position of the samples . Modifications in these factorswill disrupt readings leading to very imprecise recorded data due to too many variations. The success of the project will depend on obtaining a correlation between the established characteristics of the calibration sites and the data outputs from RIMFAX, taking into account the Martian environmental parameters such as temperature and moisture content below the surface.

PIXL: Planetary Instrument for X-ray Lithochemistry

Initial testing:

The functioning of PIXL will be assessed by the performance of X-ray fluorescence (XRF) investigations on typical geological samples transported from Earth. These specimens, possessing established elemental compositions, will be utilized to verify the instrument's capacity to accurately detect and measure chemical elements. The testing will involve directing the XRF beam at the standard samples and then comparing the obtained findings with the anticipated elemental signatures.

On site calibration of PIXL will involve using Martian soil and rock samples from areas with previously characterized mineralogies by orbiters or by other rover instruments. This calibration process will aid in fine-tuning the PIXL data to account for the specific environmental conditions on Mars, such as the presence of dust or the amounts of ambient radiation. PIXL will employ onboard calibration targets of known compositions as a reference to optimize its sensitivity and accuracy.

Control Variables and Data Accuracy: For PIXL, control variables include the beam current, voltage, and the duration of exposure for each measurement. The instrument's accuracy will be assessed by comparing the XRF measurements obtained from Martian samples with the known values of the calibration targets and onboard standards, taking into account different environmental factors such as temperature and dust interference.

3.5 Precision and Accuracy of Instrumentation

Precise and accurate data are vital to every scientific experiment even those taken in space. In an unmanned mission, human errors are greatly diminished leaving only instrumental errors which can be tested using calibrations methods and fixed remotely via repair packages and updates. The precision of each instrument impacts the level of efficiency and credibility that may be placed in the interpretations and conclusions derived from the data. In cases where particular metrics are not provided, assumptions will be made as a grade for the precision and accuracy of the instruments.

RIMFAX: Radar Imager for Mars' subsurface Experiment

Accuracy and precision:

RIMFAX is a ground penetrating radar instrument that captures high resolution images of the the geographical and geological structure and substructure of the regions of interest on Mars. The accuracy of RIMFAX instruemnt is inked with its capacity to distinguish various strata or characteristics underneath the surface of Mars using high resolution images. RIMFAX is expected to have a vertical resolution accuracy of around 15 centimeters in the top meters of the subsurface. However, this accuracy decreases as the depth increases owing to the weakening of radar waves due to ebng absorbed over multiple layers of solid. The horizontal resolution, which is crucial for differentiating closely spaced subsurface structures, is roughly estimated to be 50 cm at shallow depths.

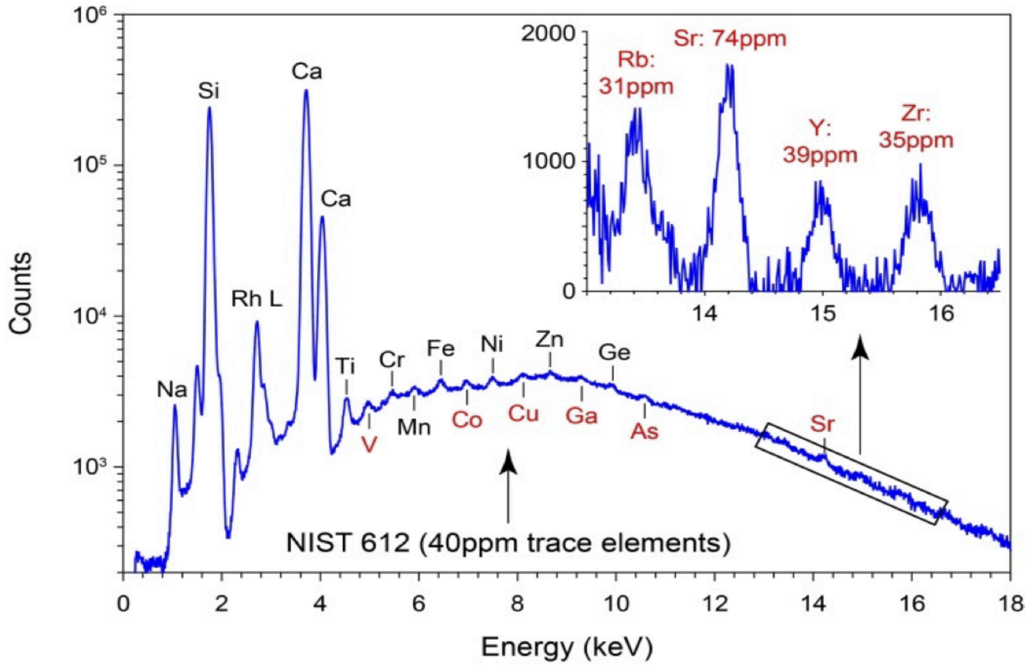
The amount of resolution has an impact on the ability to identify and characterize subsurface structures with a high level of detail. For instance, minute characteristics such as narrow sedimentary strata or slight discrepancies in soil composition may not be discernible if they fall below the resolution threshold. Hence, although RIMFAX offers significant data for comprehending extensive geological formations, it is essential to acknowledge its constraints when analyzing more intricate subsurface particulars.

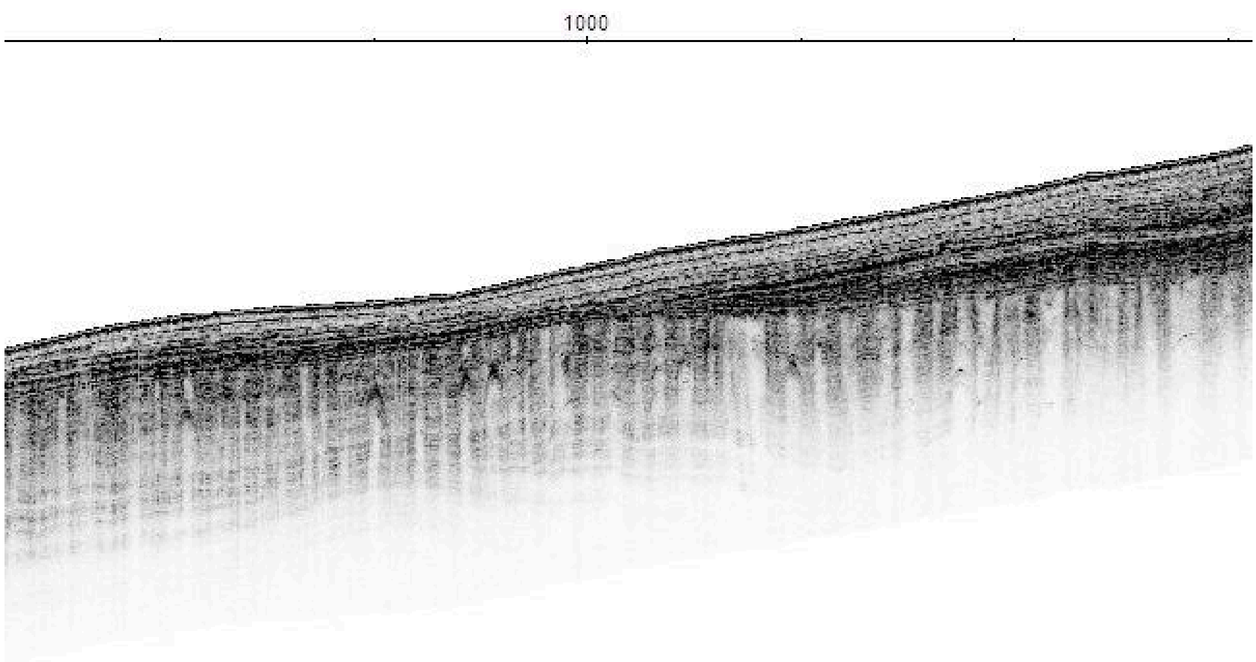
PIXL: Planetary Instrument for X-ray Lithochemistry
Accuracy and Precision:

PIXL provides high resolution data by studying th chemical make up of the martian surface minerals using X-ray fluorescence. In perfect conditions, the precision is around + or - 5% fro main elements and + or - 10% for trace elements. The degree of accuracy is sufficient tp differentiate between the types and compositions of the regolith of Mars using compositional analysis.

Effect on Data Collection: The precision of PIXL affects the capability to accurately detect the chemical composition of Martian materials. Inaccuracies in measurement may result in erroneous conclusions regarding mineralogy and, consequently, the environmental circumstances responsible for the formation of these substances. For instance, if there are small errors in the measurements of sulfur or chlorine, it might lead to incorrect conclusions about the historical levels of water activity. Moreover, PIXL's capacity to identify and examine minute features (measuring 100 micrometers) enables a very accurate depiction of the arrangement of components in rock textures. However, the accuracy of the instrument's focusing capabilities imposes some limitations on this capability.

3.6 Expected Data & Analysis





The supplied photos exemplify the type of data that may be collected by the RIMFAX and PIXL equipment during a trip to explore Mars.

RIMFAX is an experiment that uses radar to image the subsurface of Mars. The data collected by RIMFAX has certain characteristics.

The second image displays a radargram, which visually depicts the reflections of subsurface radar. The stratified patterns observed in the photograph suggest the presence of layers under the surface, which can offer insights into various geological formations and possible variations in composition.

Data Analysis: The interpretation of a radargram like this entails analyzing the reflectivity of radar waves to infer the geological strata underneath the surface. By analyzing the reflected signals, valuable information on the subsurface composition, including the existence of ice, water, or intricate sedimentary formations, may be obtained.

Implications for Martian Exploration: If RIMFAX were to generate a radargram resembling this one on Mars, it may reveal substantial findings on the planet's geological past, including indications of previous glacial or fluvial events. Furthermore, it would improve comprehension of the potential resources that exist below the surface.

Calibration and Error Analysis: The RIMFAX instrument is specifically developed to accurately determine features with a vertical precision of around 15 cm. To accurately understand this data, it is necessary to carefully calibrate it, considering the varied rates at which radar waves travel through different materials underneath the surface. When evaluating the accuracy of subsurface models, it is important to take into account any inaccuracies caused by signal attenuation or dispersion.

PIXL is an acronym for Planetary Instrument for X-ray Lithochemistry. Sample Data Data Attributes:

The initial picture displays the X-ray fluorescence spectrum, which exhibits clear peaks that correspond to the components identified in the studied sample. The position and strength of each peak on the spectrum are distinctive to certain elements, such as Si and Ca, while the region underneath each peak signifies the concentration of the element.

Data Analysis: The process of evaluating this data entails measuring the energies and intensities of the peaks in order to ascertain the elemental makeup. By calibrating against established standards, it becomes possible to make precise evaluations of the elemental concentrations. The mineralogical composition and geological processes responsible for the development of Martian soils and rocks may be deduced from this knowledge.

The implications for Martian exploration are significant. If PIXL were to achieve a similar spectrum on the Martian surface, it would yield a comprehensive chemical profile. This profile would enable the identification of different rock types and the determination of the environmental circumstances that contributed to their production. Deviation from anticipated elements concentrations may suggest previous occurrences of water activity or volcanic eruptions.

Calibration and Error Analysis: The anticipated accuracy range of PIXL for element detection is within ±5-10%. In order to maintain the accuracy and reliability of the data, it is imperative to conduct meticulous calibration using well-established references. Additionally, continuous error analysis is crucial to account for any potential effects from the Martian environment or equipment sensitivity.

RIMFAX and PIXL play a crucial role in creating a detailed representation of Mars' geological history and current state. The presented sample data showcases the extensive and meticulous research that can be conducted with these equipment, emphasizing their significance in the pursuit of comprehending Martian geology and evaluating the planet's potential for supporting life.

4. Mission Risk Management

4.1 Safety and Hazard Overview

In the course of the mission, diverse risks will emerge in all subsystems; affecting the mission performance or even worse, its cancellation. In order to reduce this, risks should be identified and traced constantly throughout the whole project while the subject matter experts find a way to reduce them ideally to a likelihood of 1 out of 5. However risks are not easily identified, for this reason, the team has been using a three-part process with the intention of identifying risks:

At the moment something new has been created by members of the team, they will make an analysis of possible risks that this could bring to the mission. In order to clarify, it will explain the process of how the solar panels of the rover were processed. In this case, after some trade studies and deciding what type of solar planes will be used in the rover, the mechanical engineer will make an analysis of the possible risks this new mechanism could bring (dust problems, energy problems, malfunctioning, etc).

After this has been done, the engineer will send out the information to the whole engineering team, so that there can be different interdisciplinary perspectives and easily identify possible problems. After some peer reviews and research about past projects, the information will be sent to the whole team, to have a final check. Following the solar panels example, in this phase, the programmatic team could determine that the price of them is too high, and could affect the mission budget. Therefore having all team's perspectives would be valuable for identifying risks.

In the case a risk emerges a two-phase process will be made; initially, the risk will be added to the risk identification table found from table 17 to 23 and will be given an unique ID (ex: MECH-1, THERM-3, GNC-9). There, it can evaluate the risk based on the likelihood and consequences on a scale of 1-5. In that way, the risk could be either low, medium, or high criticality for the mission. Additionally, it will determine its approach.

The second phase will consist of trying to reduce the risk as much as possible using Risk-Informed Decision Making (RIDM). In the first part, the team will identify alternatives based on the context of the objective [32]. The second part is the risk analysis of alternatives, in which the performance of each alternative is measured and quantified [32], and finally, it is going to select an alternative based on the performance, this will be done by the whole team with a votation, and in case of a draw, the PM will make the decision maker. This will be done with the help of the subject matter experts, which will allow the analysis of different alternatives.

Additionally, to avoid anchoring, sunk cost, confirmation bias, framing, or overconfidence, trade studies of each possibility will be made, and each alternative will be considered carefully. In this manner, the team will avoid choosing something that won't be the best thing for the mission.

After making the decision with the new alternative, the risk will still be monitored. In the case there are no alternatives, the team will look to reduce the likelihood of the risk until it is accepted.

The process mentioned is used for the development of the spacecraft design. However, this won't consider all the risks, due to the fact, that there are certain risks, such as budget cuts, that don't emerge in the development process. In order to identify different risks such as programmatics, the same process will be used, with the difference that different tools will be used. Such as: Gantt Chart, for monitoring mission schedile, MCCET, for calculating operational costs, and FMEA with the objective ot monitoring risks that are considered high criticality and likelihood.

At the time of manufacturing the rover, the programmatic team will have a huge role, since there are certain standards that need to be done in the production. Such as disinfecting the rover (to avoid sending life accidentally to another planet), or avoiding any data filtration that could delay the launch date.

To manage risks for the Command, Data Handling (CDH) system in space missions, a rigorous process is employed. It begins with identifying risks through detailed analyses of CDH components, software, interfaces, and environmental exposures. Each risk is assessed for impact and likelihood, prioritizing them accordingly. Mitigation strategies include designing redundancy, conducting thorough software testing, implementing protective measures against environmental hazards like radiation, and reinforcing cybersecurity. Continuous monitoring of the CDH system allows for real-time issue identification and resolution, with regular software updates to address new vulnerabilities. This comprehensive approach ensures the CDH system's reliability and functionality, crucial for mission success.

The following section depict the current risk matrix of the mission of different subsystems.

4.1.1 Risk Analysis

In this section, the risk identification tables will be presented from each subsystem. Each table will contain the following information:

1. ID: A unique identification number assigned to each risk
2. Summary: A brief text explaining the text
3. Likelihood and Consequence: Based on a scale 1-5
4. Trend: Determines if risk is increasing, decreasing, remains the same, or is new
5. Approach: It can be categorized as accept (A), mitigate (M), watch (W), or research (R)
6. Risk Statment: Explains shortly the risk and the possible effects on the subsystem and mission.
7. Status: Indicated whether the risk is active or inactive

Table 17: CDH Risks

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
CDH - 1	Component failure	1	5	↓	A	Critical components might fail, leading to mission failure or significant data loss, needeing a robust mitigation strategy	Active
CDH - 2	Supply Chain Delay's	2	3	↓	W	Supply chain delays could cause project delays and cost overruns, warranting close monitoring and proactive engagement with suppliers	Active
CDH - 3	Incompatibility between components	2	4	→	W	Component incompatibility could lead to integration problems causing problems between different subsystems	Active
CDH - 4	Cybersecurity Threats	1	5	↓	A	Cybersecurity threats could compromise mission integrity for this reason the rover should secure communication protocols and ongoing vulnerability assessments	Active

Table 18: GNC Risks

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
GNC - 1	Rover unable to be autonomous	2	3	→	M	Due to Mars's soil, and dust storms there exists the possibility of them getting into the cameras or sensors, which will affect the GNC system and affect the autonomous driving of the rover	Active
GNC - 2	Rover unable to be autonomous	1	4	↓	M	Since the area to analyze is covered with dark sand and there is uneven terrain there is a probability of the rover not detecting certain things due to the lack of visibility, affecting the GNC Subsystem and therefore autonomous driving	Active
GNC - 3	Radiation Exposure	2	4	↓	W	Over the mission time, the radiation exposure can degrade electronic components and sensors. Impacting the accuracy and reliability of the rover subsystems, including the GNC to navigate.	Active
GNC - 4	Communication Interrupts	1	5	↓	A	The communication between Mars and Earth can face delays that may affect the GNC subsystem, making it hard for the rover to navigate.	Active
GNC - 5	Software or Firmware Issues	1	5	↓	A	The GNC subsystem may face software bugs or firmware issues that can affect its functionality or performance	Active

Table 19: Instruments Risks

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
INST - 1	Wrong Calibration	1	4	→	R	The PIXL needs a really precise calibration, and any minimum change in the way it measures data would ruin completely all the information obtained, for this reason, would affect the whole mission objectives and requirements	Active
INST - 2	Instrument	1	3	↓	M	Since the RIMFAX is located on the lower rear of the rover, there exists the risk of it getting damaged due to the rocky surface, causing it to malfunction. If this happens the primary requirement of the mission will be affected	Active

Table 20: Mechanical Risks

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
MECH - 1	Wheels getting damaged	1	5	↓	A	Since the exploration area is covered in sharp rocks, there is a chance of the wheels getting damaged, affecting the movement of the rover and creating a huge impact on the mission	Active

MECH - 2	Dust clogging Mechanisms	2	4	→	R	Given that Arcadia Planitia is dense with dust, there exists the possibility of the dust clogging the mechanisms, which will affect the mechanical parts, and therefore losing a key subsystem of the rover	Active

Table 21: Programatics Risks

ID	**Summary**	**L**	**C**	**Trend**	**Approach**	**Risk Statement**	**Status**
PRG - 1	Team going over budget	1	5	→	A	The mission cost is more than $200M, creating a possibility of exceeding the $300M cost cap, which can result in a cancelation of the mission	Active

Table 22: Power Risks

ID	**Summary**	**L**	**C**	**Trend**	**Approach**	**Risk Statement**	**Status**
PWR - 1	Solar panels stop working	1	5	→	A	Given that Arcadia Planitia is dense with dust, there exists the possibility of the dust covering the solar panels, which will affect the solar panels, and therefore create problems	Active

						with the power.	
PWR - 2	Thermal and power system failing	1	4	↓	W	Mars's temperature can be as high as 20° Celcius or as low as -153°, for this reason, there is a chance that the whole rover gets affected because of the thermal subsystem failing. Creating different problems with the rover's functionality	Active
PWR - 3	Extreme Temperature Variation	1	4	↓	W	Survival Temperature (-140 to 110°C) may cause solar cell degradation or damage, leading to a reduction in power output or array failure.	Active
PWR - 4	Cell Damage During Launch or Deployment	3	4	→	R	Mechanical stress during launch or deployment may cause damage to solar cells, decreasing efficiency or resulting in cell failure.	Active
PWR - 5	Overcharging or Overheating of Lithium-ion Batteries	3	4	→	R	Failure in the battery management system or extreme conditions may lead to overcharging or overheating of batteries, reducing battery life and posing safety hazards.	Active
PWR - 6	Voltage Fluctuations Beyond Operating Range	1	3	↓	W	PM system malfunction or extreme conditions may cause voltage fluctuations beyond the operating range, potentially damaging batteries or connected systems.	Active
PWR - 7	Battery Cycle Life Exceeding Estimates	2	4	↓	R	Unforeseen conditions may result in battery cycle life exceeding estimates, posing a risk of potential power supply loss during the mission.	Active
PWR - 8	Malfunction in Power Switches or Converters	3	4	→	R	Electrical or design failures in the P31U PMD system may cause malfunctions in power switches or converters, resulting in loss of power distribution capability.	Active
PWR - 9	Inadequate	1	3	↓	A	Lack of thorough testing simulating launch and space	Active

	Environmental Testing					conditions may lead to insufficient environmental testing, risking potential system failure due to unanticipated stress.	
PWR - 10	Incorrect Voltage Output from Converters	1	4	↓	A	Calibration or design errors in the PMD system may cause incorrect voltage output from converters, potentially damaging connected systems or devices.	Active

Table 23: Thermal Risks

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
THM - 1	Rover stop working due to thermal failing	1	5	→	A	Due to low temperatures, there is a possibility that if the battery heaters don't work, the battery won't be able to turn and work properly. Which will cause the rover to stop working for the rest of the mission affecting the battery efficiency.	Active

Table 24: Risks Summaries 1

CDH Risks	GNC Risks	Instruments Risks	Mechanical Risks

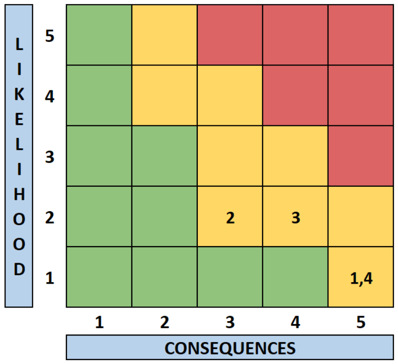
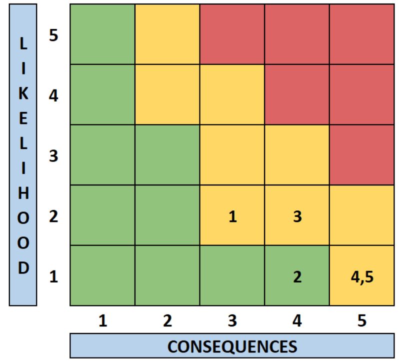
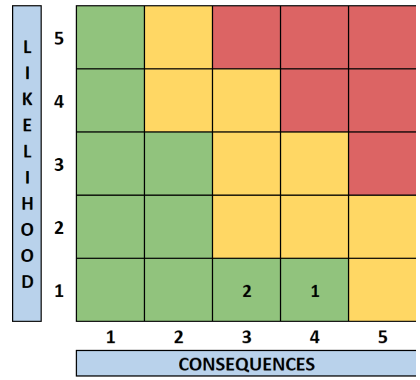
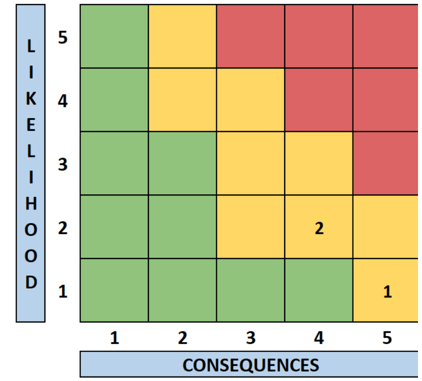
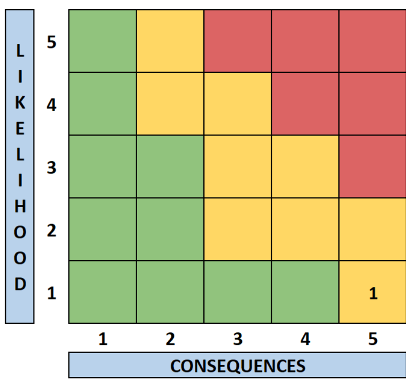
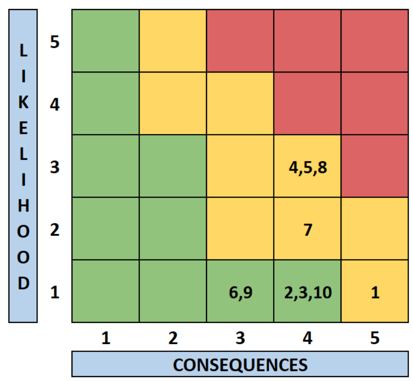
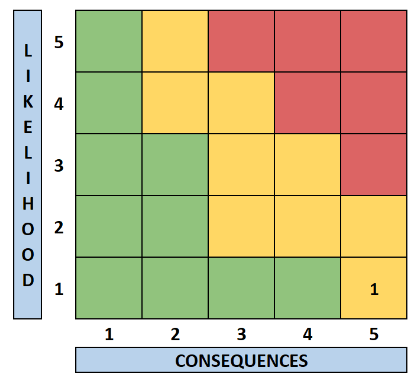
			

Table 25: Risks Summaries 2

Programmatics	Power Risks	Thermal Risks
		

4.1.2 Failure Mode and Effect Analysis (FMEA)

The following table will illustrate the FMEA of the mission, illustrate the major risks of the mission, and a deep analysis of each one. It illustrated the function that is being at risk, with the causes and consequences it has on the rover. Additionally, the severity (sev), occurrence (Occ), and detection (det) are shown on a scale of 1-10. Besides that, each risk has a Risk Priority Number (RPN) which will allow the team to know what risks to prioritize when trying to reduce them.
Overall it can be seen that one of the major risks during the mission is the presence of Dust that could affect the mechanical, electrical, power, and GNC subsystems. Therefore they are the ones with lower RPN since they also have a big severity on the mission. Furthermore, the presence of high and low extreme temperatures also causes a huge risk to the mission, since it can cause permanent damage to some important subsystems, such as mechanical and electrical.

Table 26: FMEA

Systems Failure Mode and Effect Analysis									
Function	**Failure Mode**	**Effects**	**Sev**	**Cause**	**Occ**	**Prevention**	**Det**	**RPN**	**Actions**
Communication and Data Handling SubSystem	Antenna Deployment Failure	Inability to communicate with ground stations	9	Mechanical failure or software error	2	Rigorous testing, redundant systems	2	36	Activate redundant antenna, assess and repair if possible
	Transmitter Failure	Loss of data transmission capability	8	Electrical failure or overheating	3	Use of high-reliability components, thermal management	3	72	Switch to backup transmitter, modify mission data priorities
	Power supply Failure to	Total loss of communication capabilities	10	Power system malfunction, unexpected power	2	Redundant power supplies, power management	2	40	Switch to backup power supplies, prioritize power allocation to ensure communication system

	Communication Equipment			drain		protocols			remains operational
	Overheating of Communication Components	Temporary or permanent damage to communication hardware, leading to reduced functionality or failure	7	Inadequate thermal management, unexpected operation beyond designed limits	3	Effective thermal design, monitoring component temperatures, operational limits	2	42	Reduce operational load, initiate passive or active cooling measures, switch to backup components if necessary
Power SubSystem	Dust covering solar panels	Reduction in power generation and absorption	6	Arcadia's terrain is very dusty and any storm could cause the panels to get covered	5	Regular cleaning of solar panels, and having the solar panels tilted	3	90	Having a mechanism which would allow clean up the dust
	Malfunction in power switches or converts	Loss of power distribution capability creates the possibility of an electrical failure	5	Electrical or design failure, causing cables to interact and causing power failure	2	Regular testing and maintenance of power switches and converts	2	20	Implement redundancy in power switches and converters to mitigate the risk of loss of power distribution capability.
	Overcharging or overheating of lithium-ion batteries	Reduction in battery life, safety hazards, causing the rover to stop working before	7	Extreme conditions in temperature or solar panels	2	Implement thermal monitoring and protection systems	4	56	Implement an automatic shutdown mechanism on overheating to mitigate safety hazards.

		expected							
Thermal Subsystem	Failure of the cooling component for electronic devices	Stoppage or improper functioning of all electronic components	4	Failure of the cooling component due to dust or power	3	Regular maintenance and cleaning of cooling components; redundancy in cooling systems	5	60	Implement backup cooling systems; ensure robust dust protection for the component.
	Thermal subsystem failure due to extreme temperatures	Various problems with rover functionality due to extreme temperature swings or failure of radiators	9	Extreme temperatures on Mars	4	Design robust thermal insulation and regulation systems	2	72	Implement redundant thermal regulation systems; enhance insulation to mitigate the effects of extreme temperatures on the rover's functionality.
Science Instruments	Precise calibration failure in PIXL	Loss of accurate data, affecting mission objectives and requirements	8	Minimum change in measurement ruining data, bad calibration	3	calibration checks and maintenance Regular	2	48	Implement redundant calibration systems; rigorous data validation to mitigate the risk of inaccurate data due to calibration failure.
	Damage to RIMFAX due to rocky surface	Malfunction of RIMFAX, affecting primary mission requirement and not allowing the team to get essencial data	8	Risk of damage due to rocky surface and sharp corners	3	Enhanced protection measures for RIMFAX; robust design	3	72	Implement backup RIMFAX units; consider relocating to a safer location to mitigate the risk of damage due to the rocky surface.
Mechanical	Wheels	Affects the	8	Exploration area	2	Implement robust	3	48	Regular inspections; carry spare

Subsystem	getting damaged due to sharp rocks	movement of the rover, significant impact on the mission, not allow the rover to move around thearea		covered in sharp rocks that could damage the wheels		wheel designs; incorporate protective measures			wheels for replacement
	Mechanisms clogging due to dense dust in Arcadia Planitia	Affects mechanical parts, leads to loss of subsystem and does not let the rover to certain actions	8	Arcadia Planitia is dense with dust and sand storms	4	Implement dust-resistant designs; regular cleaning and maintenance	2	64	Design redundancy; conduct periodic maintenance and checks
Guidance, Navigation and control	Soil and dust entering cameras or sensors	Impaired GNC system, affecting autonomous driving of the rover	8	Mars's soil and dust storms are constant in Arcadia Planitia	3	Implement protective measures for cameras and sensors	3	72	Regular cleaning and maintenance of cameras and sensors to prevent soil and dust buildup.
	Lack of visibility due to dark sand and uneven terrain	Inaccurate detection, affecting GNC subsystem and autonomous driving of the rover	6	Dark sand and uneven terrain affecting cameras and sensors	4	Improve sensor technology; implement terrain mapping algorithms	3	72	Implement advanced obstacle detection and avoidance strategies to compensate for lack of visibility in dark sand and uneven terrain.

4.1.3 Personnel Hazards and Mitigations

Machinery operation Hazards

Hazards associated with the operation's machinery and equipment such as an angle grinder, welding machine, circular saws, and nail guns. would have to be a primary risk in the integration process. For example, there might be potential injuries related to the operation of machinery and equipment. Team members may suffer from cuts and scrapes if they come into contact with sharp edges, blades, or moving machinery parts. Improper lifting techniques or repetitive motions while operating machinery may lead to strains in muscles and joints.

Solutions: Provide the necessary training concerning machine operations for all team members. Place protective guards and emergency restriction mechanisms on the machines. Make sure all members follow the operating procedures closely. Have supervisors at all times to avoid mistakes. Use autonomous machines when possible.

Electrical Hazards

Risks associated with electrical elements should also be a common concern in the manufacturing processes. Electric shocks risk during equipment testing could appear due to faulty wiring or malfunctioning electrical components. It is possible that an Insulation on a conductor inside a testing device can become damaged or wear out over time. If workers touch the exposed conductor during testing, they may experience an electric shock.

Solutions: First of all, provide enough insulated tools. All team members should be expected to possess the proper experience in electrical safety procedures. Regular inspections must be performed to maintain the electrical systems. Additionally, they should wear insulated gloves when operating electrical devices.

3) Fire Hazards

There might be potential fires during electronic devices or machinery testing. Longevity or high electrical currents can cause components to overheat, leading to fire risk if not adequately monitored. Another risk during testing processes involving gas-operated equipment may lead to leaks. If the leaked gas comes into contact with an ignition source, it can likely result in a fire. It is also important to say that testing equipment near combustible materials, such as paper, cardboard, or flammable liquids, poses a fire risk.

Solutions: Ensure that all flammable materials are stored in secure areas and that there are enough extinguishers and evacuation plans. Additionally, at the moment of testing thermal and electrical equipment, workers should be aware of the high possibility of a fire.

4) Radiation Exposure

Exposure to radiation during testing phases is a risk with less likelihood however, the team should pay careful attention to the dangers that it can pose. For example, workers involved in the testing of devices that emit radiation, such as microwave transmitters or industrial irradiators, may be exposed to radiation.

Solutions: Thus, restricting access to radiation areas and using shielding would be possible solutions. It also provides personnel with radiation monitoring devices and enforces strict protocols for handling radioactive materials. Also when near radioactive things like the PIXL, radiation suits should be worn.

5) Noise Exposure

Prolonged exposure to high noise levels during testing. Technicians conducting group testing of aircraft engines may be exposed to intense noise levels for extended periods, potentially leading to hearing damage if proper hearing protection is not worn. It should also be said that workers involved in testing turbines, generators, or other machinery in power plants may face prolonged exposure to high noise levels.

Solutions: Supply hearing protection equipment. Implement noise control measures where feasible. Rotate team members to minimize exposure. Make experiments on sound-proof rooms

6) Ergonomic Hazards

Musculoskeletal issues due to poor ergonomics during manufacturing.
An example would be a lack of training on proper ergonomic practices, leading to employees unknowingly engaging in activities that contribute to the strains on muscles and joints.

Solutions: Design ergonomic workstations, provide adjustable furniture and tools and conduct route ergonomic assessments and training. Use a machine when heavy parts should be moved.
7) Chemical Exposure

Exposure to dangerous chemicals during manufacturing and testing phases. For example, handling acids during the manufacturing process poses risks of burns or skin corrosion.

Inhalation of toxic gasses emitted during testing is also a high risk as it can cause respiratory distress or long-term health effects.

Solution: Ensure adequate use of personal protective equipment. Enforce strict adherence to chemical handling protocols. Conduct regular training sessions on chemical safety. Have a supervisor at all times to avoid any mistakes

5. Activity Plan

5.1 Project Management Approach

To accomplish the mission, the total personnel needed was estimated to be fifty. This number was approximated by considering the initial team of fifteen and proportioned accordingly. For example, the initial team featured four scientists, which was scaled onto a team of fifty to count ten scientists, which states the maximum number of people employable for the role. The same procedure was applied to every role except for the project management category, which was kept at a constant of four people. In addition to the roles featured by the initial team of fifteen, the roles of technicians and administration were added. Remembering that these roles feature fluctuations during the whole mission due to their relevance in the mission phase is essential. Table 19 shows how many people were needed for each role during each phase and their estimated stipends.

The mission is divided into subsystems, each with a team lead, usually an expert from the selected discipline, who holds responsibilities and accountability over the entirety of the subteam. Each subsystem team lead responds to the project manager, who oversees the entirety of the mission. The main subsystems are managers, engineers, scientists, technicians, and administration personnel. The science team presents a different sub-subsystem, one for each instrument. The engineering subsystems are also divided into different sub-subsystems: thermal, GNC, computer hardware, and electrical.

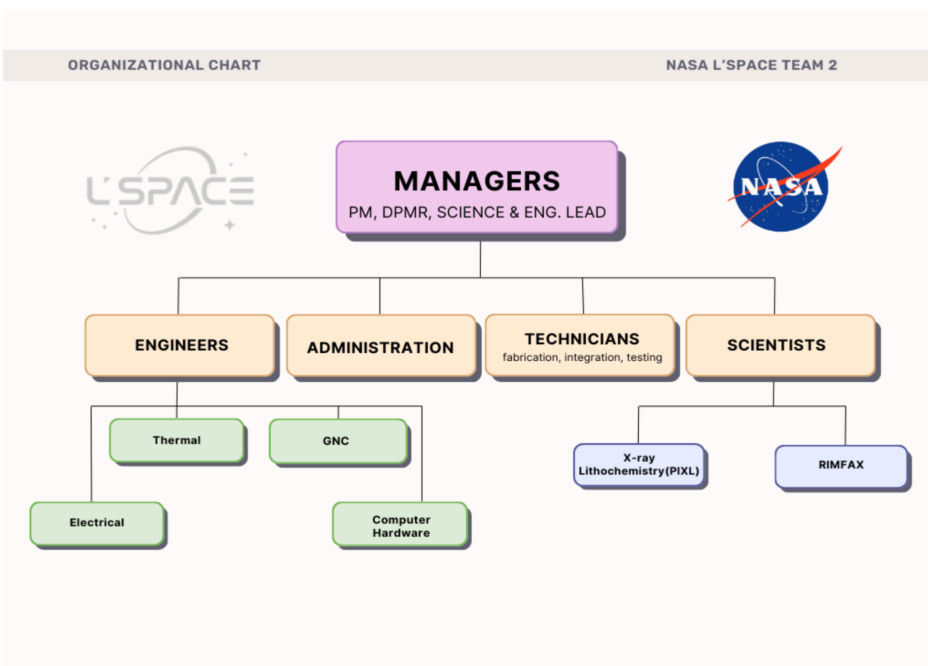


Figure 45: Organizational Chart

5.2 Mission Schedule

5.2.1 Schedule Assumptions

5.2.2 Mission Schedule

5.3 Budget

Table 27: Total Budget

NASA L'SPACE Mission Concept Academy Budget - *Team 2*							
Mission Phase	Phase C	Phase D	Phase D	Phase D-E	Phase E	Phase E	Phase F
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**
PERSONNEL							
Science Personnel	$400,000	$400,000	$400,000	$ 800,000	$800,000	$800,000	$ 400,000
Engineering Personnel	$1,600,000	$1,600,000	$1,600,000	$ 1,600,000	$400,000	$400,000	$ 400,000
Technicians	$540,000	$540,000	$540,000	$ 540,000	$120,000	$120,000	$ -
Administration Personnel	$240,000	$120,000	$120,000	$ 180,000	$180,000	$180,000	$ 300,000
Project Management	$480,000	$480,000	$480,000	$ 480,000	$480,000	$480,000	$ 480,000
Total Salaries	$ 3,260,000	$ 3,140,000	$ 3,140,000	$ 3,600,000	$ 1,980,000	$ 1,980,000	$ 1,580,000
Total ERE	$ 909,866	$ 876,374	$ 876,374	$ 1,004,760	$ 552,618	$ 552,618	$ 440,978
TOTAL PERSONNEL	$ 4,169,866	$ 4,016,374	$ 4,016,374	$ 4,604,760	$ 2,532,618	$ 2,532,618	**$ 21,872,610**
TRAVEL							
Total Flights Cost	$108,361.67	$108,361.67	$108,361.67	$ 7,930	$108,361.67	$108,361.67	$108,361.67
Total Hotel Cost				$ 13,500			
Total Transportation Cost				$ 900			
Total Per Diem Cost	$212,145.83	$212,145.83	$212,145.83	$ 1,125	$212,145.83	$212,145.83	$212,145.83
Total Travel Costs	$ 320,508	$ 328,841	$ 337,174	$ 25,284	$ 353,840	$ 362,173	$ 362,173
TOT with 30% margin							**$ 2,985,705**
OUTREACH							
Total Outreach Materials							**$ 870,000**
Travel							**$ 200,000**
Social Media Campaign							**$ 540,000**
Total Outreach Venue Costs							**$ 300,000**
Total Outreach Costs (with margin & inf)							**$ 2,270,000**
DIRECT COSTS							
Mechanical Subsystem							**$ 14,400,000**
Power Subsystem							**$ 14,400,000**
Thermal Control Subsystem							**$ 12,500,000**
Comms & Data Handling Subsystem							**$ 17,000,000**
Guidance, Nav, & Control Subsystem							**$ 29,000,000**
Science Instrumentation							**$ 27,497,588**
Total Spacecraft Direct Costs							**$ 114,797,588**
FINAL COST CALCULATIONS							
Total F&A							**$ 11,479,759**
Total Projected Cost							**$ 153,405,662**
Total Cost Margin							**$ 61,362,265**
Total Project Cost							**$ 214,767,927**

5.3.1 Budget Assumptions

Budget assumptions are vital in determining a project's financial plans and projections. This section outlines the prime assumptions the team has considered key to ensuring a successful project. The main schedule, closely connected to the budget, was shaped by dividing the project by its key dates (launch, arrival on Mars, etc.) through fiscal years. The budget was also divided as such, as seen in Table 17 (which also presents about 30% margins). The budget for this mission was calculated using U.S. dollars as the main currency. It was taken into an assumption that the global economy will maintain its predicted course over the years and U.S. dollars will remain stable. Most direct costs were estimated using the Mission Concept Estimate Tool (MCCET) to produce reasonable estimates when cost research was impossible. This tool provides equations to estimate expenses for mass, power, and design life, as well as manufacturing and testing facilities costs, divided into phases (C is 57% of the total cost, and phase D is 39% of the total cost). Finally, a budget cut of 50 million dollars was applied, lowering the total budget from 300 million to 250 million dollars.

5.3.2 Personnel Budget

Personnel is one of the mission areas for which an estimate could be produced from the earlier deliverables, and it has been modified and improved gradually since then. As mentioned in the schedule and budget sections, the budget was shaped by NASA's fiscal years (September to October). As seen in Table 19 Phase C, final design and fabrication, goes from October 2026 until March 2027 and includes five members from the science team, twenty from engineering, nine technicians, four administration, and four managers for a total of 3,260,000 dollars. Phase D, system assembly, integration, test, and launch, goes from April 2027 until December 2028, spanning over two fiscal years and features, on average, five from the science team, 20 from engineering, nine technicians, four from administration, and four managers. Phase E, operations and sustainment, starts right after launch in January 2029 and ends in September 2031; it spans over two fiscal years and a half and features a team of 10 scientists, five engineers, two technicians, three administrators, and four managers. Phase F, the closeout, lasts from October 2031 to March 2032 and features five scientists, five engineers, five administrators, and four managers for a total of 1,580,000 dollars. The total over seven fiscal years is 18,680,000 dollars, which doesn't account for ERE, employee-related expenses, also known as fringe benefits.

Table 28

Fiscal Year	Total # of Personnel
1	42
2	40
3	40
4	46
5	24
6	24
7	21

	Final Design & Fabrication		System Assembly, Integration, and Test, Launch					Operations & Sustainement					Close Out	
	October 2026 - March 2027		*April - September 2028*		*October 2027 - September 2028*		*October - December 2028*	*December 2028 - September 2029*	*October 2029 - September 2030*		*October 2030 - September 2031*		*October 2031 - March 2032*	
	Phase C		**Phase D**		**Phase D**		**Phase D**	**Phase E**	**Phase E**		**Phase E**		**Phase F**	
	FY 1		FY 2		FY 3		FY 4		FY 5		FY 6		FY 7	
People on Team	# of people /team	Total Cost Stipends	# of people /team	Total Cost Stipends	# of people /team	Total Cost Stipends	# of people /team	Total Cost Stipends	# of people /team	Total Cost Stipends	# of people /team	Total Cost Stipends	# of people /team	Total Cost Stipends
Science Personnel:	5	$400,000	5.00	$400,000	5.00	$400,000	10	$800,000	10	$800,000	10	$800,000	5	$400,000
Engineering Personnel:	20	$1,600,000	20.00	$1,600,000	20.00	$1,600,000	20	$1,600,000	5	$400,000	5	$400,000	5	$400,000
Technicians:	9	$540,000	9.00	$540,000	9.00	$540,000	9	$540,000	2	$120,000	2	$120,000	2	$0
Administration Personnel:	4	$240,000	2.00	$120,000	2.00	$120,000	3	$180,000	3	$180,000	3	$180,000	5	$300,000
Management Personnel:	4	$480,000	4.00	$480,000	4.00	$480,000	4	$480,000	4	$480,000	4	$480,000	4	$480,000
Total /FY		$3,260,000.00		$3,140,000.00		$3,140,000.00		$3,600,000.00		$1,980,000.00		$1,980,000.00		$1,580,000.00
TOTAL														**$18,680,000**

Table 29

- **Scientists** for the design of your experiment and analysis of data - $80,000 salary/year
- **Engineers** for designing, building, and testing your mission concept and for mission operations - $80,000 salary/year
- **Technicians** for assisting engineers and scientists with manufacturing, assembly, and testing of instruments and systems of the mission concept - $60,000 salary/year
- **Administration** for tracking schedule and mission costs - $60,000 salary/year
- **Managers** for organizing mission personnel, budgets, and schedules - $120,000 salary/year

Figure 46: Personnel salaries yearly costs (NASA L'SPACE, Mission Task, Page 7) [1]

5.3.3 Travel Budget

Budgeting for travel expenses holds a pivotal role in the success of a mission. This section presents a detailed overview of how the travel budget was developed, structured, and allocated to ensure the efficient utilization of financial resources while fulfilling the objectives and requirements of the mission. For the required travel for the launch, the following measures were taken: to calculate the average flight prices, the US was divided into three main regions (Eastern, Central, and Western), and the main five airports of each zone were chosen (Table 21). The most expensive fares of the flights to Orlando International Airport (MCO) were researched for each airport. Also taken into consideration were costs for accommodation, approximately 180 dollars per night [6] (for a total of five nights), other needed transportation (like a taxi from the airport to KSC) for 60 dollars a person, and per diem cost for each member of the team evaluated to be around 75 dollars per day from the Meals & Incidentals (M&IE) rates and breakdown on the U.S. General Services Administration website [4]. However, other travel expenses were estimated for the duration of phases C to F, like trips to centers, facilities, KDPs (one to three days), and SRBs (one week). They were estimated by taking a proportion of the values calculated for the launch trip and spread throughout all the phases with the help of Figure #, for which the total budget estimated for travel was $3,000,000. Finally, the total estimated cost for travel expenses was $2,985,705, including 30% margin and inflation.

Table 30: Budget Table “Travel” portion

TRAVEL							
Total Flights Cost	$108,361.67	$108,361.67	$108,361.67	$ 7,930	$108,361.67	$108,361.67	$108,361.67
Total Hotel Cost				$ 13,500			
Total Transportation Cost				$ 900			
Total Per Diem Cost	$212,145.83	$212,145.83	$212,145.83	$ 1,125	$212,145.83	$212,145.83	$212,145.83
Total Travel Costs	$ 320,508	$ 328,841	$ 337,174	$ 25,284	$ 353,840	$ 362,173	$ 362,173
TOT with 30% margin							**$ 2,985,705**

Table 31: Average Flight Costs [5]

EASTERN US FLIGHTS TO MCO	Highest Prices
ATL	$ 650.00
JFK	$ 700.00
CLT	$ 680.00
EWR	$ 600.00
PHL	$ 620.00
CENTRAL US FLIGHTS TO MCO	
ORD	$ 600.00
DFW	$ 600.00
DEN	$ 700.00
IAH	$ 580.00
MSP	$ 600.00
WESTERN US FLIGHTS TO MCO	
LAX	$ 680.00
SFO	$ 800.00
SEA	$ 750.00
LAS	$ 700.00
PHX	$ 700.00
	$ 7,930.00

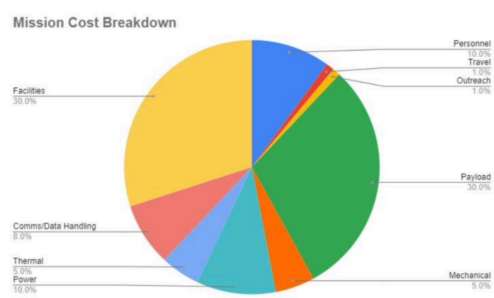


Figure 47: Mission Cost Breakdown (NASA L’SPACE, Project Management Module, Slide 38) [3]

5.3.4 Outreach Budget

The Mars rover mission's outreach budget has been carefully planned to support extensive participation and instructional programs regarding the mission's goals and achievements. A portion of the financial resources, $540,000.00 [7], is allocated to a comprehensive social media campaign on sites such as Instagram and TikTok, with the goal of captivating users with eye-catching material and providing real-time updates on the rover's whereabouts. Meanwhile, a sum of $200,000.00 has been set aside to pay for experts' and representatives' travel costs when they give talks and presentations, guaranteeing face-to-face engagement with a range of audiences and communities. This component of the outreach plan increases outreach efforts by going beyond digital platforms to include offline interactions, such pop-up exhibits with a rover theme in major cities like Los Angeles, New York City, Houston, Chicago, and Washington, D.C.

Partnerships with prestigious organizations such as the Smithsonian National Air and Space Museum and the American Museum of Natural History expand the mission's reach and generate interest in Mars exploration and rover technology across the country. In order to guarantee that a diverse range of people have access to information about the Mars rover mission, partnerships with educational organizations and projects, such as Girls Who Code and the National Society of Black Engineers, also provide $1,098,000.00 for contests, instructional activities, and staff stipends. In addition, $432,000.00 has been set aside for talks, webinars, and related costs in order to give thorough explanations of the mission's goals and possible findings. The $2,270,000.00 outreach budget seeks to inform and excite people of all backgrounds about the wonders of space flight and Mars exploration through these cooperative projects.

Table 32: Budget Table "Outreach" portion

OUTREACH			
Total Outreach Materials		$	870,000
Travel		$	200,000
Social Media Campaign		$	540,000
Total Outreach Venue Costs		$	300,000
Total Outreach Costs (with margin & inf)		$	2,270,000

Table 33: Outreach Campaign Budget

OUTREACH				
Social Media Campaign		Price /month	Total Years	Total Cost
	Instagram	$1,500.00	2.5	$45,000.00
	TikTok	$2,500.00	2.5	$75,000.00
	Staff/Stipends	$14,000.00	2.5	$420,000.00
			Total:	$540,000.00
Travel			Total:	$200,000.00
Competitions/Educational Programs				
	Staff	$21,000.00	1.5	$378,000.00
	Venues	$30,000.00	1.5	$540,000.00
	Materials	$10,000.00	1.5	$180,000.00
			Total:	$1,098,000.00
Lectures/Webinars				
	Staff	$21,000.00	1	$252,000.00
	Venues	$10,000.00	1	$120,000.00
	Other	$5,000.00	1	$60,000.00
			Total:	$432,000.00
			TOTAL:	**$2,270,000.00**

5.3.5 Direct Costs

Thermal subsystems had the following direct costs derived from the product's cost directly from the manufacturer. These don't include the personal budget nor delivery at the moment, and they are a complete estimate, bearing in mind the amount of volume needed for each material.

- Heater: HK5185R17.6L12A Minco Inc.
  - *Costs*: about 24.000 USD per heater, including possible shipping and taxes but not manufacturing.
- Cry-cooler: Ricor - K508N
  - *Costs*: Low cost - It doesn't exceed 1,500,000 USD, but it can't be determined until the manufacturer makes the order. Two or more cryocoolers will be used.
- White Paint: S-13 GLO
  - *Costs*: 602 USD a gallon, which would round up to about 40,000 USD for the mission with shipping and taxes.
- Thermal switch: MER Paraffin Heat Switch
  - *Costs*: 0.16 M USD per heat switch; overall cost approximate to 1,5 M USD.

Manufacturers were selected by recommendation of the thermal engineering NASA book, which provides a list of possible private contractors that have previously worked in missions. Some of the chosen ones were Ricor, Minco Inc., and Mars Exploration Rover components.

In addition, the research was aided by comparison with past missions. The NASA Sojourner mission cost about 25 million dollars. However, it featured a rover of much smaller dimensions and bigger teams [2].

The science instruments have the following costs derived from identifying the instrument types and using the MCCET:

- RIMFAX:
  - Final manufacturing cost per unit (manufacturing + wraps):**$11,600,000.00**
  - Final testing facility cost per unit:**$3,500,000.00**
- PIXL:
  - Final manufacturing cost per unit (manufacturing + wraps): **$23,700,000.00**
  - Final testing facility cost per unit:**$7,100,000.00**

These costs have been estimated using a parametric cost estimating tool, the MCCET. The two instruments in this mission are both in situ instruments; however, the PIXL is an arm-mounted instrument, and the RIMFAX is a body-mounted instrument, so the calculation differed for each instrument. When calculating for both instruments, an overestimate was added to both instruments' weight and power to provide flexibility in manufacturing time and cost, as these will differ with manufacturers. Also, the values provided are adjusted to inflation as of 2024

(166.8%). The testing costs include four tests: Thermal Vacuum (TVAC), Electromagnetic Interference (EMI), Vibration Testing (VIBE), and Ambient Testing.

The total cost estimate for the Mechanical subsystem was derived from the use of the MCCET tool, and it was estimated that the final manufacturing cost per unit, rounded up to the nearest 100K, was **11,100,000** dollars, while the test facility cost was **3,300,000** dollars.

The cost estimate for the GNC (Guidance, Navigation, and Control) subsystem was derived from an analysis of previous missions and calculations of mass and power requirements. It's important to note that this estimate is subject to change, as component prices may vary. Assessments were conducted to determine the mass and power consumption of each individual component within the subsystem. The price of each component was adjusted for inflation in 2024, and the MCCET tool was utilized to obtain the following information:

- Final manufacturing cost per unit (manufacturing + wraps): **$22,300,000.00**
- Final testing facility cost per unit: **$6,700,000.00**

The Power Subsystem was chosen for the Mars mission due to its vital role in providing the necessary electrical power for spacecraft operations and scientific instrument functionality. Precisely computed with the Mission Cost and Cost Estimating Tool (MCCET), the cost estimate took into consideration several variables, such as production and testing costs and inflation corrections. The **$14,400,000** USD estimated total direct cost accounts for labor, materials, and administrative costs while incorporating factors like the manufacturing of solar arrays, batteries, and PMAD system components. Furthermore, testing expenses that span a range of demanding tests such as Electromagnetic Interference (EMI) and Thermal Vacuum (TVAC) guarantee subsystem dependability in the Martian environment. The inflation adjustment, which is projected to be 166.8 percent in 2024, is essential due to maintaining the accuracy of the estimates, reflecting anticipated economic changes.

The precise cost of the CDH (Communication and Data Handling) subsystem—which is essential to the Mars mission—is $**17,026,000.00** USD. This estimate includes essential parts like the Sentinel M-Code GPS Receiver, Ultra-High Frequency Antenna, and HRT440 X-Band High-Rate Transmitter. The Spaceborne X-Band Solid State Power Amplifier, Low-power Solid-state Recorders, and X-Band Low-Gain and High-Gain Antennas are also featured. To guarantee precise resource allocation and budget planning, the expenses associated with the purchase, production, testing, and integration of each component are taken into account.

Table 34: Direct Costs

DIRECT COSTS		
Mechanical Subsystem		**$ 14,400,000**
Power Subsystem		**$ 14,400,000**
Thermal Control Subsystem		**$ 12,500,000**
Comms & Data Handling Subsystem		**$ 17,000,000**
Guidance, Nav, & Control Subsystem		**$ 29,000,000**
Science Instrumentation		**$ 27,497,588**
Total Spacecraft Direct Costs		**$ 114,797,588**

5.4 Scope Management

5.5 Outreach Summary

Specialists are designated to guarantee precise and engaging social media sharing information in the Mars rover mission strategy. Using eye-catching Instagram postings, this involves providing updates on the rover's features, goals, and progress on its Mars mission. Concurrently, brief videos showcasing the rover's capabilities and the difficulties it encounters on Mars will be produced for TikTok, leveraging popular forms to enhance visibility.

Largely populated areas like Los Angeles, New York City, Houston, Chicago, and Washington, D.C. will have rover-themed pop-up displays in an effort to expand the outreach beyond social media. The public, educators, and students will be able to completely immerse themselves into the excitement of space travel with interactive displays throughout these exhibits.

The outreach will also be expanded through collaborations with nearby science centers, museums, and libraries, such as the American Museum of Natural History in New York City, the California Science Center in Los Angeles, and the Smithsonian National Air and Space Museum in Washington, D.C. Working with these prestigious organizations guarantees broad exposure to a variety of audiences, encouraging interest in rover technology and Mars exploration across the country.

Organizing NASA representatives to visit schools, especially those that serve marginalized communities, will improve scientific and mission teaching regarding the rover. Diverse access to Mars rover mission education is ensured through partnerships with groups like Girls Who Code, National Society of Black Engineers (NSBE), Society of Hispanic Professional Engineers (SHPE), and Boys & Girls Clubs of America.

In order to encourage creativity and innovation in Mars exploration, educational competitions will be held to get students involved in creating simulations and rover experiments. As an example, consider suggesting studies to examine how soil composition varies in various Martian regions or creating simulations to set up the rover's autonomous navigation on the planet's surface.

In addition to public presentations on Mars exploration made possible by partnerships with astronomy clubs and universities, webinars and virtual lectures will be held to provide a deeper knowledge of the mission's objectives and possible discoveries. The purpose of the Mars rover is to excite and inform people from all walks of life about the glories of space travel through these cooperative endeavors.

6. Conclusion

In order to support future missions and human exploration, we have described a plan to explore Mars in this Preliminary Design Review (PDR). Our goal is to find and analyze viable energy sources and vital resources. The mission's main goals are to locate water sources inside Martian ice formations, determine chemical energy sources like hydrogen and methane, and investigate the breakdown of perchlorates. We want to obtain critical information for determining human mission zones and defining water supplies with cutting-edge science instruments such as the Planetary Instrument for X-ray Lithochemistry (PIXL) and the Radar Imager for Mars' Subsurface Experiment (RIMFAX).

The mission's success will have a big impact on how Mars is explored in the future and whether it is feasible for humans to live there. We can perform this research effectively because of our mission's compact, low-cost robotic reconnaissance technology and the strict mass, volume, and cost limits. We increase our chances of success by carefully choosing locations near the Arcadia Planitia, which shows indications of water ice at comparatively low altitudes.

The Critical Design Review (CDR), where we will polish and complete the design of our rover and payload systems, is one of our upcoming benchmarks. Updating and improving our payload verification plans will be our top priority in order to make sure that our instruments are thoroughly tested and calibrated to fulfill the requirements of the mission. We will also concentrate on improving our backup and recovery instrumental procedures in order to reduce the possibility of any malfunctions during the mission.

In order to ensure comprehensive testing and validation of our instruments, we would allocate more resources to improving our payload verification plans if we had more time. We would prioritize this component in light of the crucial role payload verification plays in the accomplishment of our goal.

In conclusion, our mission is a critical advancement toward comprehending Mars' potential for long-term human habitation and exploration. We seek to unravel the secrets of Mars and clear the path for upcoming missions by utilizing cutting-edge technologies and careful planning.

Bibliography

[1] NASA L'SPACE. "Mission Task - Spring 2024." Google Docs. Accessed April 6, 2024. https://docs.google.com/document/d/12384uZFpmnMvHBdXrT_rnh_07CpwS_LDcfaTFys3vJY/edit.

[2] "NASA Facts - Mars Pathfinder." NASA. Accessed March 22, 2024. https://mars.nasa.gov/internal_resources/815/

[3] "Nasa SPACE Program: NASA SPACE Program: United States." NASA L'SPACE Academy. Accessed April 6, 2024. https://www.lspace.asu.edu/.

[4] "FY 2023 per Diem Rates for Cape Canaveral, Florida." GSA. Accessed April 6, 2024. https://www.gsa.gov/travel/plan-book/per-diem-rates/per-diem-rates-results?action=perdiems_report&state=FL&fiscal_year=2023&zip=&city=Cape+Canaveral.

[5] Google Travel. Accessed April 6, 2024. https://www.google.com/travel/flights.

[6] Google Travel. Accessed April 6, 2024. https://rb.gy/gzd33l

[7] WebFX. "What's the Cost of Social Media Advertising?" Nutshell, April 2, 2024. https://www.nutshell.com/blog/cost-of-social-advertising#:~:text=Average%20social%20media%20 advertising%20 pricing,(paid%20to%20 ad%20networks).

[8] Gander, Fabian, "The Relationships of Team Role- and Character Strengths-Balance With Individual and Team-Level Satisfaction and Performance." University of Zurich, 2020, 13.

[9] "Aluminum 6061-T6; 6061-T651" Aerospace Specification Metals. Accessed April 5, 2024. https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6

[10] "State-of-the-Art of Small Spacecraft Technology" NASA. Accessed April 5, 2024. https://www.nasa.gov/smallsat-institute/sst-soa/structures-materials-and-mechanisms/

[11] "Aluminum 7075-T6; 7075-T651." Aerospace Specification Metals. Accessed April 5, 2024. https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma7075t6

[12] NASA. "Wheels and Legs: 2020 Perseverance." Accessed April 1, 2024. https://mars.nasa.gov/mars2020/spacecraft/rover/wheels/.

[13] "Premature Wear of the MSL Wheels." NASA, September 26, 2017. Accessed April 8, 2024. https://llis.nasa.gov/lesson/22401.

[14] "RE 30 Ø30 mm, Precious Metal Brushes, 15 Watt". MAXON. Accessed April 9, 2024. https://www.maxongroup.us/maxon/view/product/motor/dcmotor/re/re30/448595

[15] Jet Propulsion Laboratory. "Who we are." Accessed April 9, 2024. https://www.jpl.nasa.gov/who-we-are

[16] NASA. "Guidance, Navigation, and Control." Small Spacecraft Systems Virtual Institute. Accessed April 14th, 2024. Available at: https://www.nasa.gov/smallsat-institute/sst-soa/guidance-navigation-and-control/.

[17] Rover Wheels and Legs." NASA Mars Exploration Rover Mission. Accessed April 14, 2024. Available at: https://mars.nasa.gov/mer/mission/rover/wheels-and-legs/.

[18] "Magnetic Augmented Rotation System (MARS) - An Update." ResearchGate. Accessed April 14th, 2024. Available at: https://www.researchgate.net/publication/348975867_Magnetic_Augmented_Rotation_System_MARS-An_Update#:~:text=MARS%20is%20a%20device%20that%20realizes%20contactless,of%20this%20paper%20is%20to%20study%20the.

[19] NASA. "Spacecraft Guidance and Navigation." National Aeronautics and Space Administration Technical Report. Washington, D.C.: NASA, 1969. Accessed April 14th, 2024. Available at: https://ntrs.nasa.gov/api/citations/19690020961/downloads/19690020961.pdf.https://www.nasa.gov/smallsat-institute/sst-soa/guidance-navigation-and-control/

[20] "Guidance and Navigation - Sensors." NASA. Accessed April 14th, 2024. Available at: https://mars.nasa.gov/mro/mission/spacecraft/parts/gnc/sensors/#:~:text=The%20accelerometer%20measures%20acceleration%20(changes,each%20axis%20of%20the%20spacecraft.

[21] NASA. "The 2022 GNC Discipline Year in Review." Accessed April 14th, 2024. Available at: https://www.nasa.gov/centers-and-facilities/nesc/the-2022-gnc-discipline-year-in-review/.

[22] NASA. "Guidance, Navigation, and Control Sensors." NASA Mars Reconnaissance Orbiter Mission. Accessed April 14, 2024. Available at: https://mars.nasa.gov/mro/mission/spacecraft/parts/gnc/sensors/.

[23] Huang, Xin, Wei Xu, Xiang Luo, and Lei Wang. "Fault Detection and Isolation for Star Sensors Based on Robust HOSVD and Independent Component Analysis." Advances in

Astronomy 2018, Article ID 1493954 (2018). Accessed April 14th, 2024. Available at: https://www.hindawi.com/journals/aa/2018/1493954/.

[24]———. n.d. "RIMFAX (Radar Imager for Mars' Subsurface Exploration)." https://an.rsl.wustl.edu/help/Content/About%20the%20mission/M20/Instruments/M20%20RIMFAX.htm.

[25] Crombie, M. Katherine, Kyle Uckert, California Institute of Technology, Indigo Information Services, LLC, and Jet Propulsion Laboratory, California Institute of Technology. 2021. "Mars 2020 PIXL Archive User's Guide." https://pds-geosciences.wustl.edu/m2020/urn-nasa-pds-mars2020_pixl/document/pixl_user_guide.pdf.

[26] "Research Guides: Persistent Links for Library Resources: JSTOR." JSTOR - Persistent Links for Library Resources - Research Guides at University of Oregon Libraries. Accessed April 15, 2024. https://researchguides.uoregon.edu/c.php?g=677249&p=4775416.

[27] NASA Passive Thermal Control Engineering Guidebook. Accessed April 16, 2024. https://ntrs.nasa.gov/api/citations/20230013900/downloads/NASA Thermal Control Engineering Guidebook v4.pdf?attachment=true.

[28] "K508N." Ricor. Accessed April 15, 2024. https://ricor.com/products/k508n/.

[29]"Catalog." Minco, February 22, 2024. https://www.minco.com/catalog/?catalogpage=product&cid=3_1_2-polyimide-FEP-thermofoil-heaters&id=HK5185R17.6L12A.

[30] Paraffin actuated heat switch for Mars Surface Applications. Accessed April 16, 2024. https://pdfs.semanticscholar.org/c8a9/37244ad071b0c6e7275544e7c4689f65549a.pdf.

[31] Arxterra. "Rocker-Bogie Suspension System." Accessed April 4th, 2024. https://www.arxterra.com/rocker-bogie-suspension-system/.

[32] Dezfuli, Homayoon. *NASA Risk Management Handbook.* Washington, 2011. https://cutt.ly/HwMNPdNi.

[33] NASA. "Rover Brains." Mars Exploration Rover Mission. April 15th, 2024. https://mars.nasa.gov/mer/mission/rover/brains/.

[33] "EUCASS 2019-1016." Accessed April 15th, 2024. https://www.eucass.eu/doi/EUCASS2019-1016.pdf.

[34](General Dynamics Mission Systems. "HRT-440 X-band High Rate Transmitter." Accessed April 14th, 2024. Available at: https://gdmissionsystems.com/products/communications/spaceborne-communications/mission-data-links/hrt-440-x-band-high-rate-transmitter.)

[36]NASA. "Communications: UHF Antenna." Mars 2020. Accessed April 14th, 2024. Available at: https://mars.nasa.gov/mars2020/spacecraft/rover/communications/#UHF-Antenna.)[37]General Dynamics Mission Systems. "Sentinel M-Code GPS Receiver." Accessed April 14th, 2024. Available at: https://gdmissionsystems.com/products/communications/spaceborne-communications/spaceborne-gps-receivers/sentinel-m-code-gps-receiver.)

[38](General Dynamics Mission Systems. "X-Band Solid State Power Amplifier." Accessed April 14th, 2024. Available at: https://gdmissionsystems.com/products/communications/spaceborne-communications/mission-data-links/x-band-solid-state-power-amplifier.)

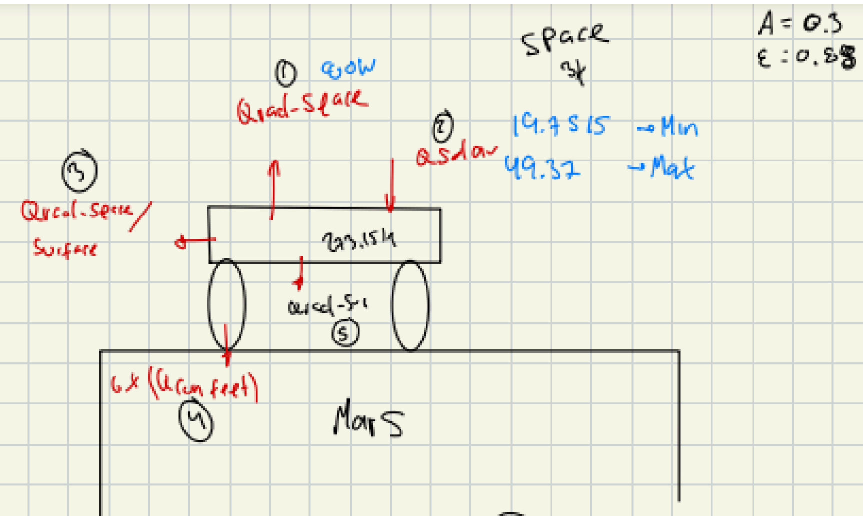
[39](NASA. "Fault Management Handbook." Accessed April 15th, 2024. Available at: https://www.nasa.gov.

[40](European Cooperation for Space Standardization. "Space Engineering: Software." ECSS-E-ST-40C, 2009. Available at: http://www.ecss.nl.)

[38](NASA. "Systems Engineering for Space Systems." Accessed April 15th, 2024. Available at: https://www.nasa.gov.

Appendix

[1] Thermal subsystem governing equations and calculation for the thermal sources within the chart.



① $Q = \varepsilon \sigma F_A (T_1^4 - T_2^4)$

$Q_1 = (0.85)(5.67 \cdot 10^{-8})(0.3)(273^4 - 3^4)$

$Q_1 = -80W$

② $q_{solar} = 329.1926147 \frac{W}{m^2}$

$Q_{solar} = 34.56W$

③ $4(60) + 4(77.31)$

$= -629.24 \rightarrow$ Min

$= -214.04 \rightarrow$ Max

④ $Q = \frac{kA(T_1 - T_2)}{L}$

$Q = \frac{(0.022)(0.607)(170-273)}{(0.1)}$

$Q = -20.43W \rightarrow$ Min

$2.674 \rightarrow$ Max

⑤ $Q = (0.05)(5.67 \cdot 10^{-8})(0.3)(273^4 - 170^4)$

$Q_{min} = -77.31 \rightarrow$ Min

$Q_{max} = +26.491025$

Cold

$\Sigma Q_{in} = 34.56$

$\Sigma Q_{out} = -806.56$

$Q = 772.42W$

Hot

$\Sigma Q_{in} = 67.72W$

$\Sigma Q_{out} = -294.04$

$Q = 230.32W$