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DAEMONES

Daemones Static Mars Lander Mission

L'SPACE Mission Concept Academy

Team 38 - Summer 2020

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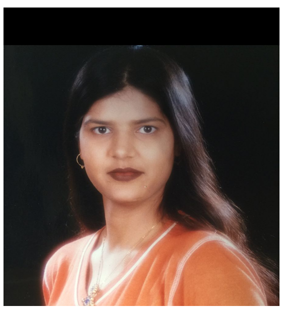
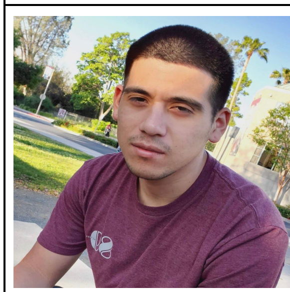
General Nomenclature

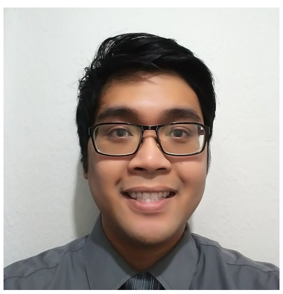
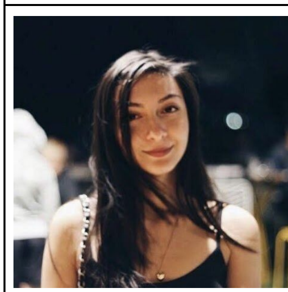
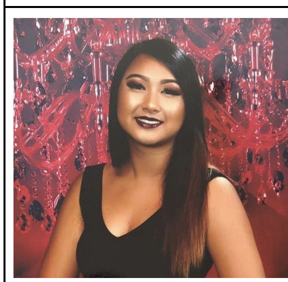
ADEPT	Adaptable Deployable Entry and Placement Technology
CheMin	Chemistry and Mineralogy Spectrometer
COMM	Communication
DAEMONES	Derived Analysis Establishing Mars' Objective of Necessary Ecological Science
DAN	Dynamic Albedo of Neutrons
EDH	Energy-Dispersive Histogram
EDL	Entry, Descent, and Landing
ERE	Employee Related Expenses
F&A	Facilities and Administrative Costs
FMEA	Failure Mode and Effects Analysis
HIAD	Hypersonic Inflatable Aerodynamic Decelerators
IHF	Interaction Heating Facility
IMU	Inertial Measurement Unit
ISIL	In-Situ Instrument Laboratory
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
MDL	Minimum Detection Level
MER	Mars Exploration Rovers
MIL-SPEC	Military Standard
MPF	Mars Pathfinder
MSDS	Material Safety Data Sheets
MSE	Mean Squared Equation
MTDC	Modified Total Direct Costs
NASA	National Aeronautics and Space Administration
NAVCAM	Navigational Camera
NPR	NASA Procedural Requirements
PDR	Preliminary Design Review
PPE	Personal Protective Equipment
R&D	Research and Development
RAT	Rock Abrasion Tool
RHU	Radioisotope Heater Unit
SPF	Space Power Facility
TPS	Thermal Protection System
TRL	Technology Readiness Level
V&V	Validation & Verification

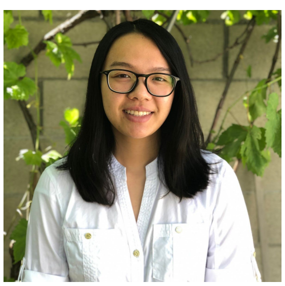
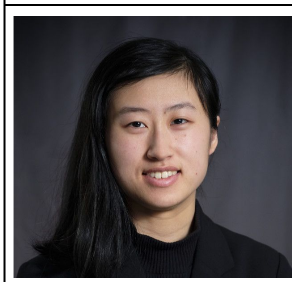
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

1. Introduction

1.1. Team Introduction

	**Isabel Anchondo** Isabel Anchondo is studying Aerospace Engineering at Arizona State University in Tempe, Arizona. Isabel has experience modeling and performing analysis using SolidWorks and is currently learning NX. She has experience in project management, prototyping, and proposal writing through the NASA Micro G Challenge that her club participates in every year.
	**Yogita Bali** Yogita Bali is currently pursuing Computer Science at Santa Monica College in Santa Monica, California, She has obtained a Law Degree from Lacc and a Bachelor's in Art's Education Major. She has experience with working as a project lead in IT. She became a Certified Agile Scrum Master, Agile Product Owner, and Salesforce Admin & Development. She worked and managed onsite and offshore teams for software project validations. Her strengths include managing teams, being organized, and punctuality. She is an out-of-the-box thinker, believes in solutions, can wear multiple hats, has good social skills, and treats others with respect.
	**Gerardo Baron Diaz** Gerardo Baron Diaz is currently studying Computer Science at Los Angeles Valley College in Los Angeles, California. He has experience with C/C++ and C# programming languages. He is excited to improve his communication skills, build strong team-working skills, and contribute his knowledge towards the project to the best of his capabilities.
	**Dana Chin** Dana Chin is studying Chemical Engineering with a focus in materials science at California State Polytechnic University in Pomona, California. She has experience working in collaborative teams and leading projects. Her strengths are planning, problem-solving, and organization.

	**Apoorva Gunti** Apoorva Gunti is currently studying Microbiology at Irvine Valley College in Irvine, California. She has experience with designing studies, doing research at her college and writing reports. She hopes to use this knowledge to help with the mission objective. Apoorva considers organization, flexibility, and resilience as her strengths.
	**Shayan Javid** Shayan Javid is currently pursuing Computer Science & Engineering at University of California, Los Angeles in Los Angeles, California. His areas of interest include data science, machine learning, and cybersecurity. He is most familiar with C/C++, Python, Prolog, circuit design, TensorFlow, and Scikit-learn. He is excited to contribute his problem solving skills and knowledge to the project.
	**Ronell Lim** Ronell Lim is studying Mechanical Engineering at California State Polytechnic University, Pomona, California. He has experience with Computer Aided Drawing (CAD) programs such as Solidworks and has worked in numerous school engineering projects. His strengths include making schedules, designs, and being organized.
	**Susana Salazar** Susana Salazar is currently pursuing Mechanical Engineering at California State University of Long Beach in Long Beach, California. As a researcher with a demonstrated history of working in the aviation and aerospace industry, her experience with CAD software, C/C++, Python, and lesson planning are some skills she brings to this project. She hopes to be proficient in NX, budgeting, and financial planning.
	**Jaira Shayne Farala** Jaira Shayne Farala is currently studying Physics at Oxnard College located in Oxnard, California. She has some experience with research and is skilled at writing reports. Organization, adaptability, and critical thinking are some of her strengths. Jaira believes that curiosity drives a good scientist.

	**Hannah Stickel** Hannah Stickel is a recent graduate with a Bachelors of Science in Aerospace Engineering, concentration in Astronautics, from Arizona State University in Tempe, Arizona. She has experience in hands-on prototyping, systems engineering, mission operations, and project management.
	**Erika Szaldobagyi** Erika Szaldobagyi is studying Materials Engineering at Moorpark College in Moorpark, California. She has experience using an X-Ray Diffraction machine for a personal research project at her college and hopes to use that knowledge to help the science and engineering teams on experiments and how to do them safely. Leadership, persistence, and organization are some of her strengths, which she is excited to bring to the table.
	**Bryant Ta** Bryant Ta is currently pursuing Computer Science at University of California, Los Angeles in Los Angeles, California. He currently works within the incident response field of cybersecurity and is most familiar with C/C++, C#, and Python programming languages. He is excited to contribute his IT knowledge, organizational skills, and creativity to the project.
	**Erika Trinh** Erika Trinh is currently pursuing Environmental Engineering at Pasadena City College in Pasadena, California. She has experience using SolidWorks and hopes to be fluent in NX at the conclusion of this project. Writing and organization are her strengths.
	**Maya Zeng** Maya Zeng is studying Computer Science at El Camino College in Torrance, California. She has experience with C++ and Java. Maya views resilience, resourcefulness, and adaptability as her greatest strengths.

1.2 Mission Overview

1.2.1. Mission Statement

The goal of this mission is to collect more information on Mars' past environment and use that analysis to determine the existence of past carbon-based life on Mars and project the habitability of the environment for humans in the near future. Studying the presence and characteristics of water and potential microbial activity on Columbia Hills can further the development of discovering possible habitable environments similar to that of Earth.

Some of the data gathered will include geological analysis for the presence of water and evidence of microbial activity in the past. More specifically, this mission is geared to help humans understand and find possibilities of life forms on Mars. Using the presence of water and sampling the geology for past microbial activity, scientists can be better informed of, not only potential beginnings of life on Mars, but also creating a model for how life on Earth could have emerged. The data collected from finding characteristics of water on Mars would provide as supplementary evidence for any data for findings of microbial activity.

1.2.2. Mission Requirements

The mission requirements are determined while considering the science mission objectives. The science drives the entire project decision making. Therefore, the Entry, Descent, and Lander (EDL) and Lander systems were designed to meet those science objectives. The size of the entire payload was determined to incorporate the Large Concept to accommodate the size of the science instrument required to complete the science mission objective. The mass constraints are 180 kg or less. The volume constraints are restricted to 24 inch by 28 inch by 38 inch (60.96 cm by 71.12 cm by 96.52 cm). This option has an extra mass allotment of 72 kg for the EDL. The provided transmission package is 0.075 kg with a required power of 5 watts. The budget allowed is $100 million or less. In addition, a separate COMM Package is dropped near the team's landing site, as stated by the L'Space mission concept, to be used as the communication between the team's system and the orbiter. The orbiter will then relay the communication back to Earth. These constraints were given by the L'Space mission concept and were considered throughout the decision making process.

To describe the team's mission requirements, flow charts are depicted in Figure 1.1 and 1.2, below, for the EDL and lander system respectively. The team first discussed the expected function and performance of the main system, in addition to the design requirements and constraints. Then, multiple subsystems were chosen to fulfill those requirements and enable the system to perform and function as required.

EDL Mission Requirements

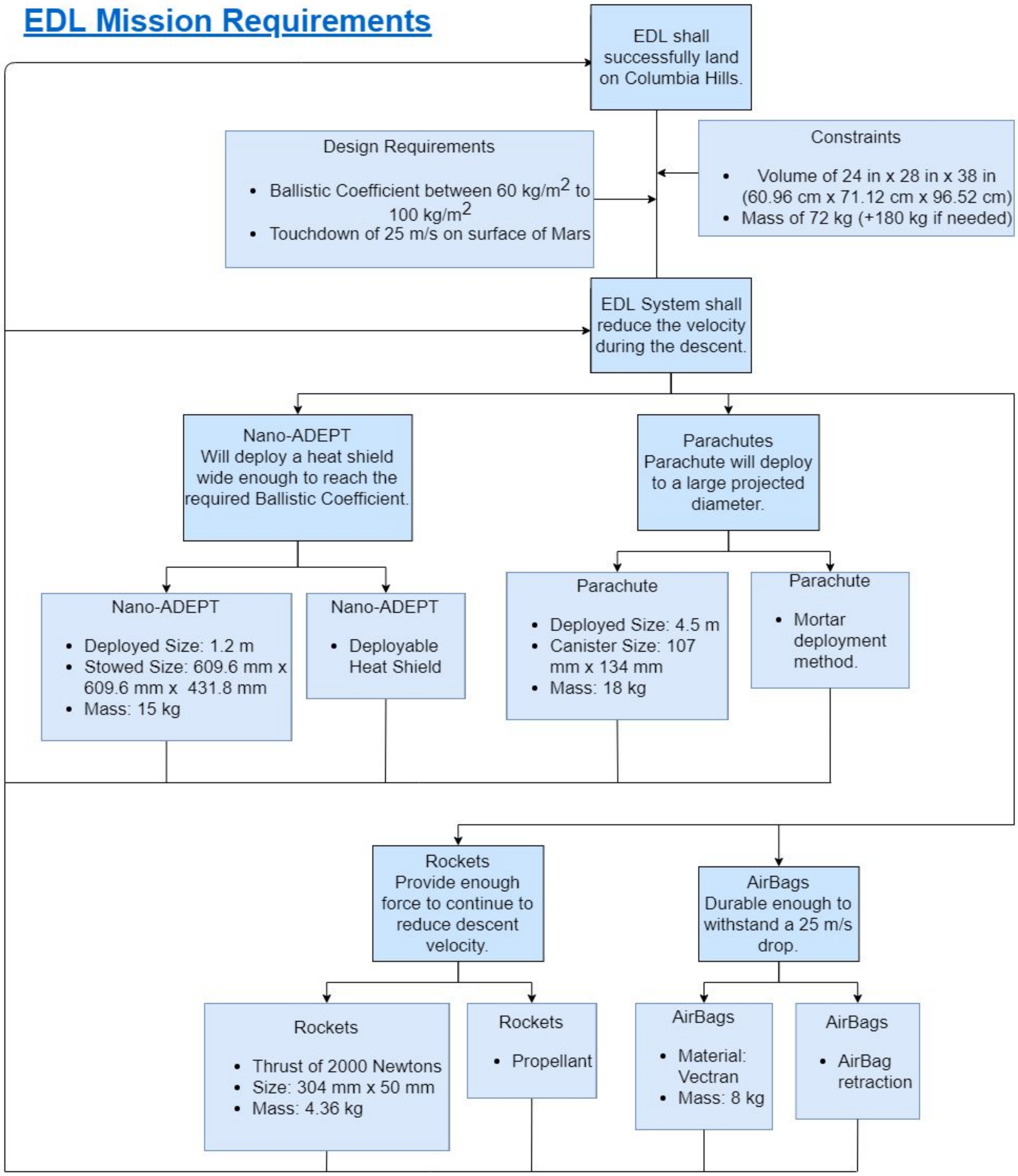


Figure 1.1: Flowchart of EDL Mission Requirements.

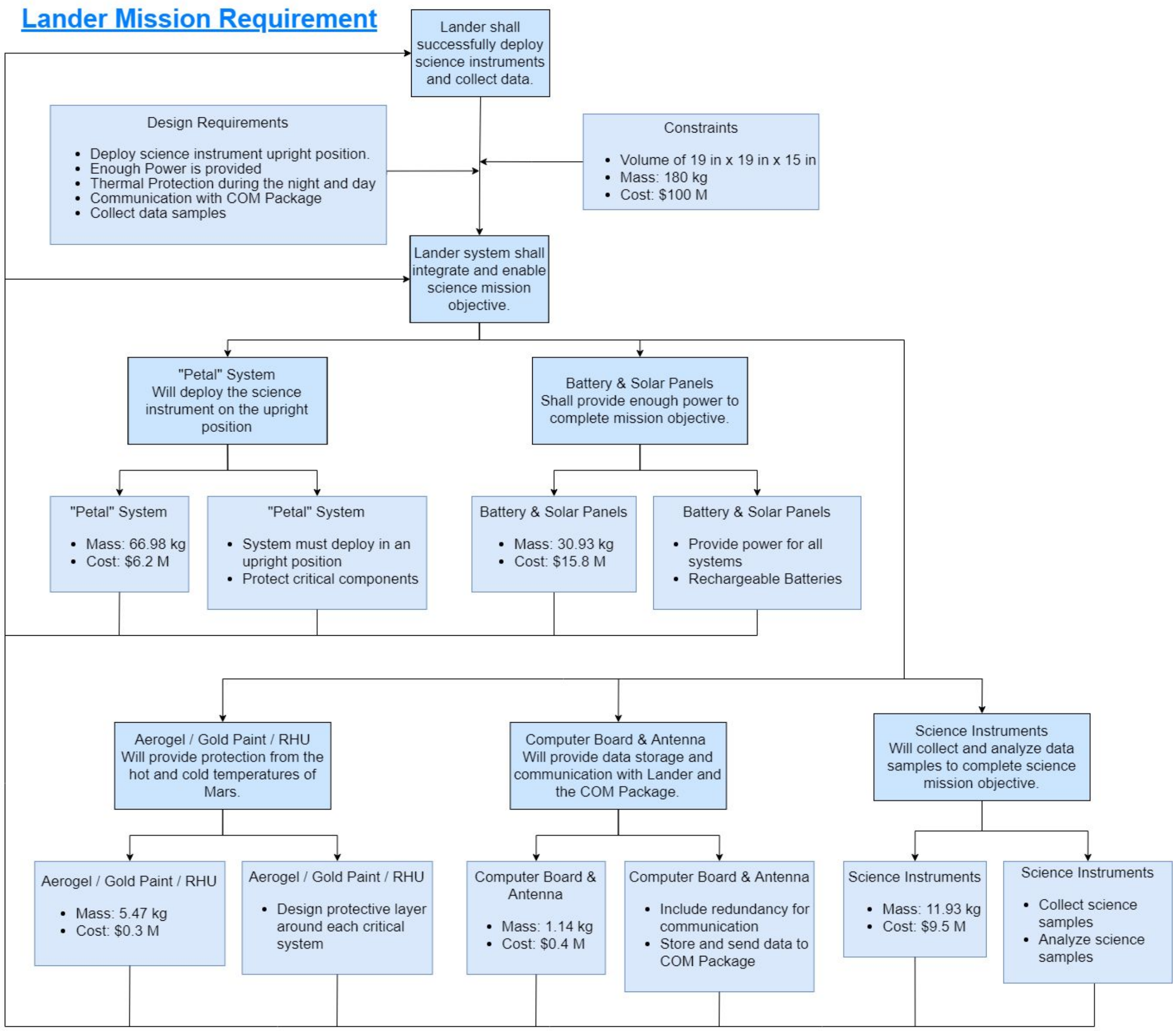


Figure 1.2: Flowchart of Lander Mission Requirements.

The EDL Mission Requirement is to successfully land on the target landing site, Columbia Hills. In order to land safely, the entire payload requires a ballistic coefficient range of 60 kg/m^2 to 100 kg/m^2 [1]. These are reference values from previous missions which can be used to determine a similar trajectory during the descent to Mars surface. A target touchdown of 25 m/s is required due to the potentially high durability of the deployed airbags used on previous missions [2]. The EDL team created their designs while working along the target reference values.

The Lander Mission Requirements are to deploy science instruments in the upright position, provide enough power, provide thermal protection during the night and day, provide communication using a transmitter package to the communications package (COMM Package), and collect data samples. These mission requirements were highly considered during the design process to successfully operate the science instruments to collect and analyze the surface of Mars.

1.2.3. Mission Success Criteria

The overall mission success criteria for the EDL and lander system is to safely land the science payload and enable the science mission objective on Columbia Hills. The amount of success of the mission is determined whether the system meets the levels of criteria. Shown in Table 1.1, the minimum EDL mission success criteria is to have a successful touchdown from cruise separation to the final drop. The mission success criteria for the lander is shown in Table 1.2. Reaching the top criteria means the mission was fully successful; the lander will successfully function. Once the EDL phase is complete, the lander will deploy the science payload in the upright position. A confirmation is required using the navigational camera (NAVCAM) by taking pictures of the landing site and sending to the COMM Package. In terms of the science mission success criteria shown in Table 1.3, success is determined by obtaining samples using the Rock Abrasion Tool (RAT) and characterizing the components using the Chemistry and Mineralogy Spectrometer (CheMin). The sample will then be used as a control for new samples gathered on Mars.

EDL Mission Success Criteria	
1	"Petal" System deploys the payload upright.
2	Air Bags survive the 25m/s drop.
3	Land a Splashdown of less than 25m/s
4	Parachute is deployed and not tangled at 0.746 Mach speed. Reduce decent velocity.
5	Nano-ADEPT withistands Mars' Atmospheric heat entry.
6	Nano-ADEPT is deployed before the cruise separation.

Table 1.1: EDL Mission Success Criteria.

Lander Mission Success Criteria	
1	Use NAVCAM to send pictures of confirmed Lander deployment.
2	Use an antenna to confirm communication is working.
3	After the Payload position is upright, the other sides will open.
4	The Computer Board commands the correct side to open and push the Payload in the correct upright position.
5	Accelerometer measures the pull of gravity to know which way is down.

Table 1.2: Lander Mission Success Criteria.

Science Mission Success Criteria	
1	CheMin detects composition in a known control sample
2	Before proceeding with testing on site, data from CheMin is compared to data collected before to make sure all components are detected properly
3	RAT collects samples from site by drilling rock samples
4	CheMin runs tests on samples collected by RAT
5	Data is compared to the control sample to determine if new, notable characteristics are detected from the sample

Table 1.3: Science Mission Success Criteria.

1.2.4. Concept of Operations (Graphic)

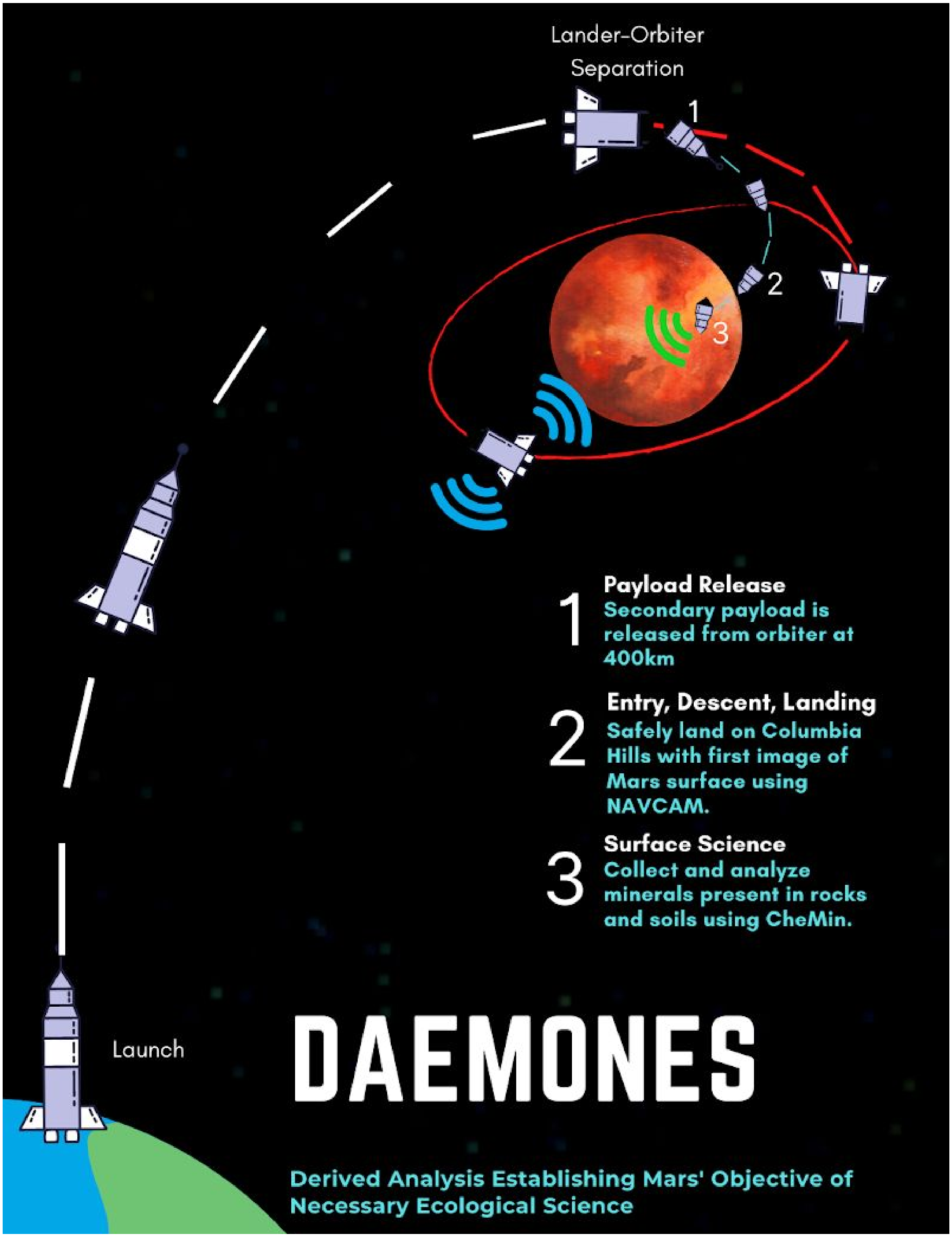
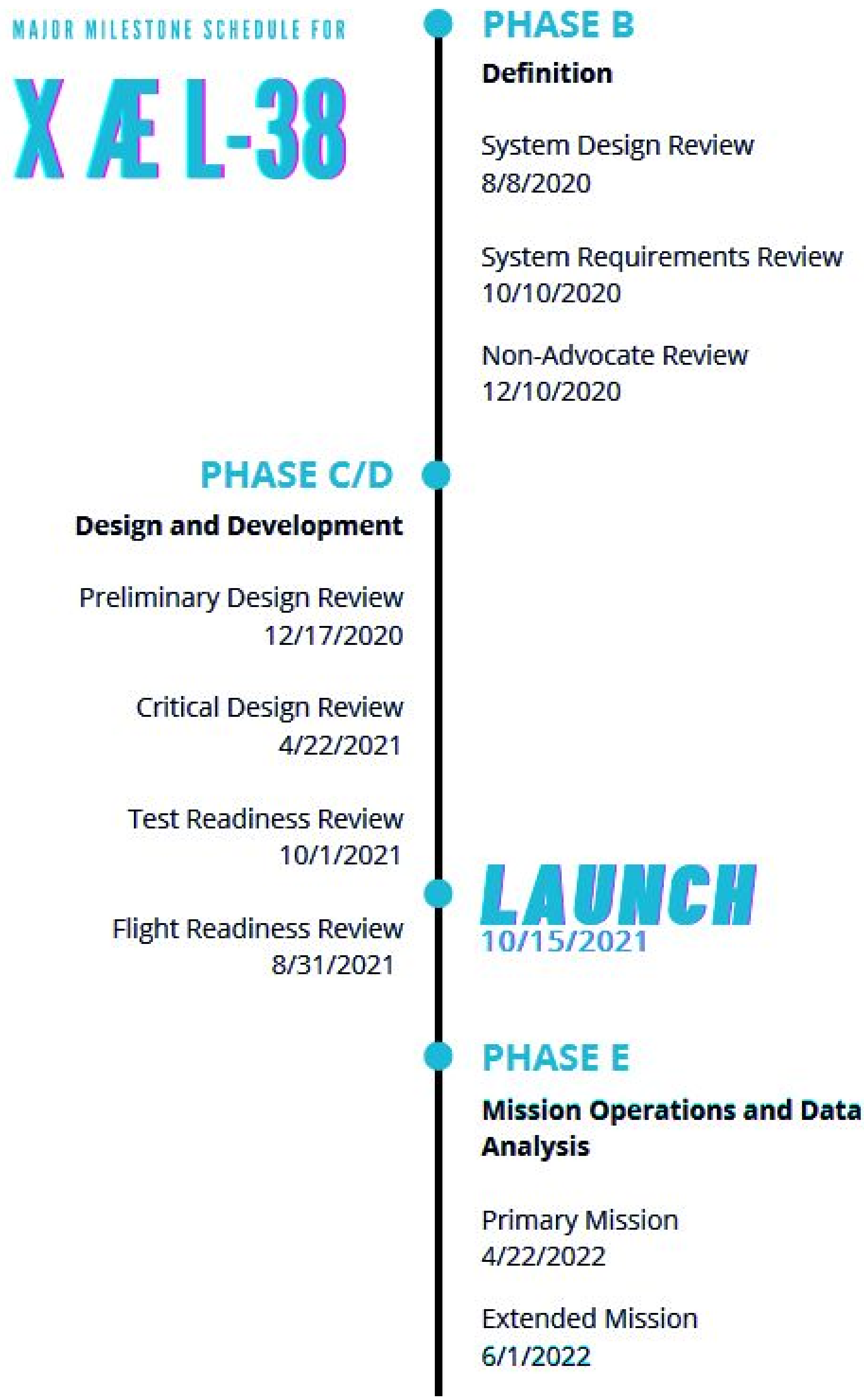


Figure 1.3: Concept of Operations.

The mission concept payload will hitch along a ride as a secondary payload on a spacecraft that will be in orbit around Mars The primary payload will not be determined by the team. They are set to launch from Earth on October 15, 2021 and the system will travel to Mars.

At Stage One of the Concept of Operations (COO), Figure 1.3, the payload will be released at a height of 400 km above Mars' surface. Immediately after, in Stage Two, the payload will go through an entry, descent, and landing phase through Mars' atmosphere. The EDL system will be deployed with respect to the descent velocity. At the end of Stage Two, the payload will land and take its first image of Mars surface using a NAVCAM. While Stage Two is occurring, the satellite travelling with the payload begins its orbit around Mars and will drop a COMM Package to be used as the payload's main communication relay. At Stage Three, the payload will spend a few months collecting surface science and sending the information to the satellite which will then transmit the information back to Earth. Once the surface science has been completed, the payload will continue to analyze the samples and take pictures around the landing site until the lander ceases to function.

1.2.5. Major Milestones Schedule



1.3. Descent and Lander Summary

The EDL will consist of a deployable heat shield, a parachute, rockets, and airbags. The size of the EDL meets the volume constraint of 60.96 cm by 71.12 cm by 96.52 cm with a dimension of 60.96 cm by 60.96 cm by 96.52 cm. The EDL design is 51.36 kg.

EDL System Mass		
System	Component	Mass (kg)
Backshell	Material: SLA 561V	10.00
Heatshield	Nano-Adept	15.00
Parachute	Disk-Gap Band	18.00
Rockets	Small-Sized Rockets (4)	4.36
AirBags	Material: Vectran	8
Total		55.36

Table 1.4: Total EDL Mass.

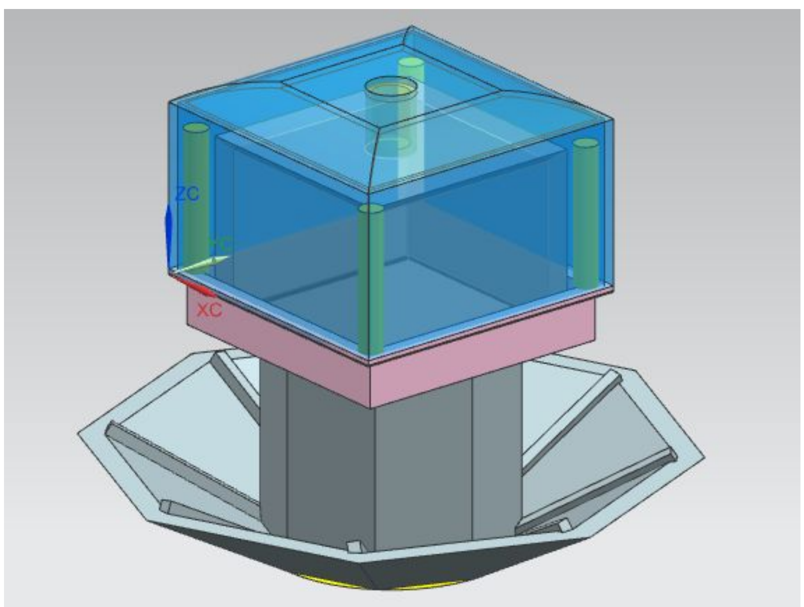


Figure 1.4: Diagram of Deployed EDL System.

To deploy the payload upon landing, the team has chosen to utilize a similar deployment system as the "petal" system used on the Mars Pathfinder (MPF) mission [2]. The lander vehicle will be performing an unguided, ballistic entry landing since the payload will only need to survey a general area, not a specific spot. The lander design is

117.03 kg, and has a volume of 48.26 cm by 48.26 cm by 38.1 cm. The lander encases the science instruments, batteries, thermal protection, and communication system.

Lander System Mass		
System	Component	Mass (kg)
"Petal"	Petal System/Material	66.98
Power	Medium-Powered Solar Panels (5)	30.00
Power	Battery (2)	0.93
Thermal Protection	Aerogel	5.31
Thermal Protection	RHU (4)	0.16
Thermal Protection	Electronic Thermometer/ Heating Cables	0.59
Thermal Protection	Gold Paint	Negligible
Communication	RAD750 3U (2)	1.10
Communication	GNSS Patch Antenna (2)	0.04
Communication	Transmission Package	0.08
Science Instrument	CheMin	7.00
Science Instrument	RAT	0.72
Robotic Arm	Material: Aluminum 7075	3.17
Robotic Arm/Petal	Motors (4)	0.82
Camera	NAVCAM	0.22
Total		117.11

Table 1.5: Lander Systems Mass.

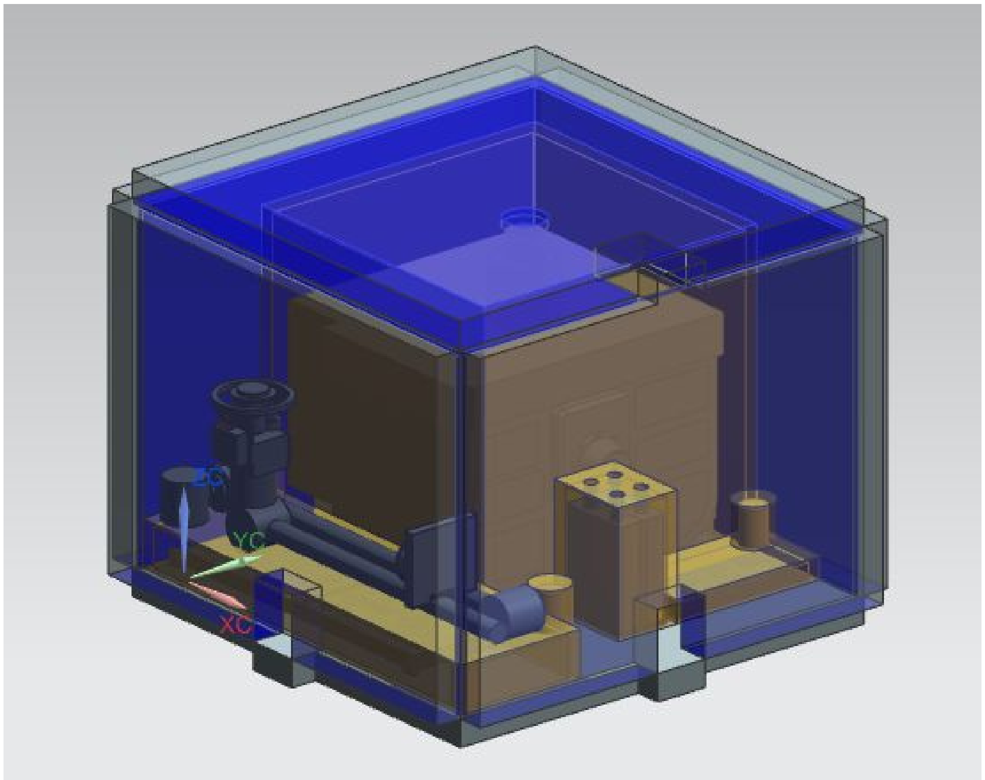


Figure 1.5: Diagram of Stowed Lander and Instruments.

The mission will begin 400km above Mars' surface with an initial velocity of 3362 m/s. An entry angle of zero is chosen to maximize the surface area for the ballistic coefficient during the descent. Currently, the ballistic coefficient is around 95 kg/m^2 which is similar to the ballistic coefficient of Mars Exploration Rovers (MER) [3]. Using MER as a reference, the EDL will follow a similar trajectory and entry profile. By calculating the terminal descent velocity for each phase of the EDL, the parachute will deploy at the terminal velocity of the heatshield at 275 m/s. The Nano-Adaptable Deployable Entry and Placement Technology (Nano-ADEPT) will separate at 70 m/s, the terminal velocity of the deployed parachute. The rockets and reduced weight from the separated heat shield will reduce the descent velocity to around 25 m/s, landing with an impact force that is absorbed by the airbags. The lander will deploy and enable the science mission stage. The process is summarized in Figure 1.6.

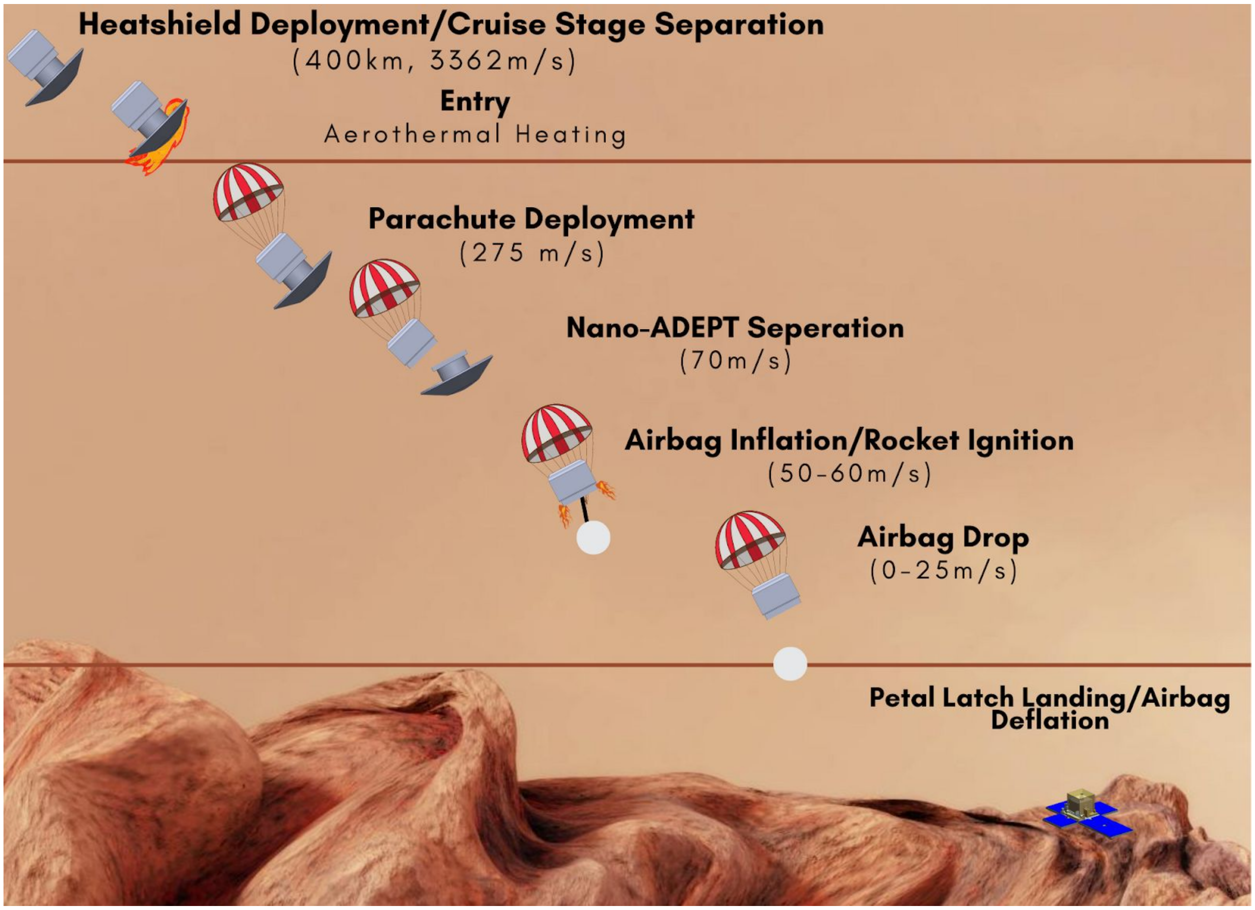


Figure 1.6: Entry, Descent, and Landing Process.

1.4. Payload and Science Summary

With heavy consideration and discussion, the team has concluded the scientific instruments to be included in the payload. The scientific instruments are the following: The Chemical and Mineralogy instrument (CheMin), the Rock Abrasion Tool (RAT), and the Mars Surveyor Robotic Arm. Considering the mission statement, the science team came to the conclusion that these are capable instruments that will reliably serve to complete and fulfill the mission. Each instrument is independent of one another but acts as a complete system to transport, collect, analyze, respectively. With the final decision of choosing a stationary lander, there is no need to consider a navigation system. However, a camera was still needed to select a desirable sample, collect the determined sample, and carefully transport the sample into the CheMin for analysis. For this, the team has chosen the NAVCAM. For reliable and consistent communication, the GNSS Patch Antenna was selected with its main purpose to transfer data to and from the COMMS Package deployed to the surface on Mars.

The CheMin will be able to determine the composites that make up the selected rock sample through a process called X-ray diffraction (XRD) and elemental composition through X-ray fluorescence (XRF). Ultimately, the CheMin will be able to detect past signs of water, an essential requirement for the building blocks for life. The CheMin will be mounted within the body of the stationary lander with its collecting tube exposed for collecting samples.

The RAT will be crucial for collecting data for analysis. It will be mounted on the end of the robotic arm for easy access to exposed rock. Once in contact with the desired rock sample, it will begin to “shave off” layers of rock and use its internal gears to grind its selected sample into rock powder. This rock powder will then be transported to be analyzed by CheMin via internal collecting tools within the RAT.

The robotic arm will be a crucial instrument as it will be supporting both the RAT and NAVCAM instruments. The NAVCAM will help scientists perform operations on the robotic arm by providing visual support. It will be mounted on the forearm of the robotic arm.

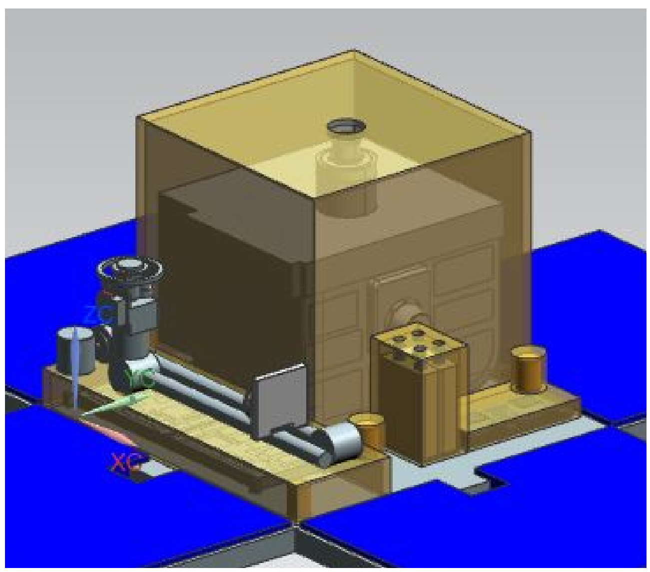


Figure 1.7: Instruments in Lander, Trimetric View.

Figure 1.7 depicts how the instruments would be placed on the base of the lander.

2. Evolution of Project

2.1. Evolution of Descent and Lander

Many designs were considered when conceptualizing the Descent and Lander system, with a handful of them being based on MPF and other MER. Changes were necessary in order to follow and accurately execute the mission objective, including the decision to land a stationary lander instead of the initially proposed rover. This required a change in design for the Descent and Lander system entirely.

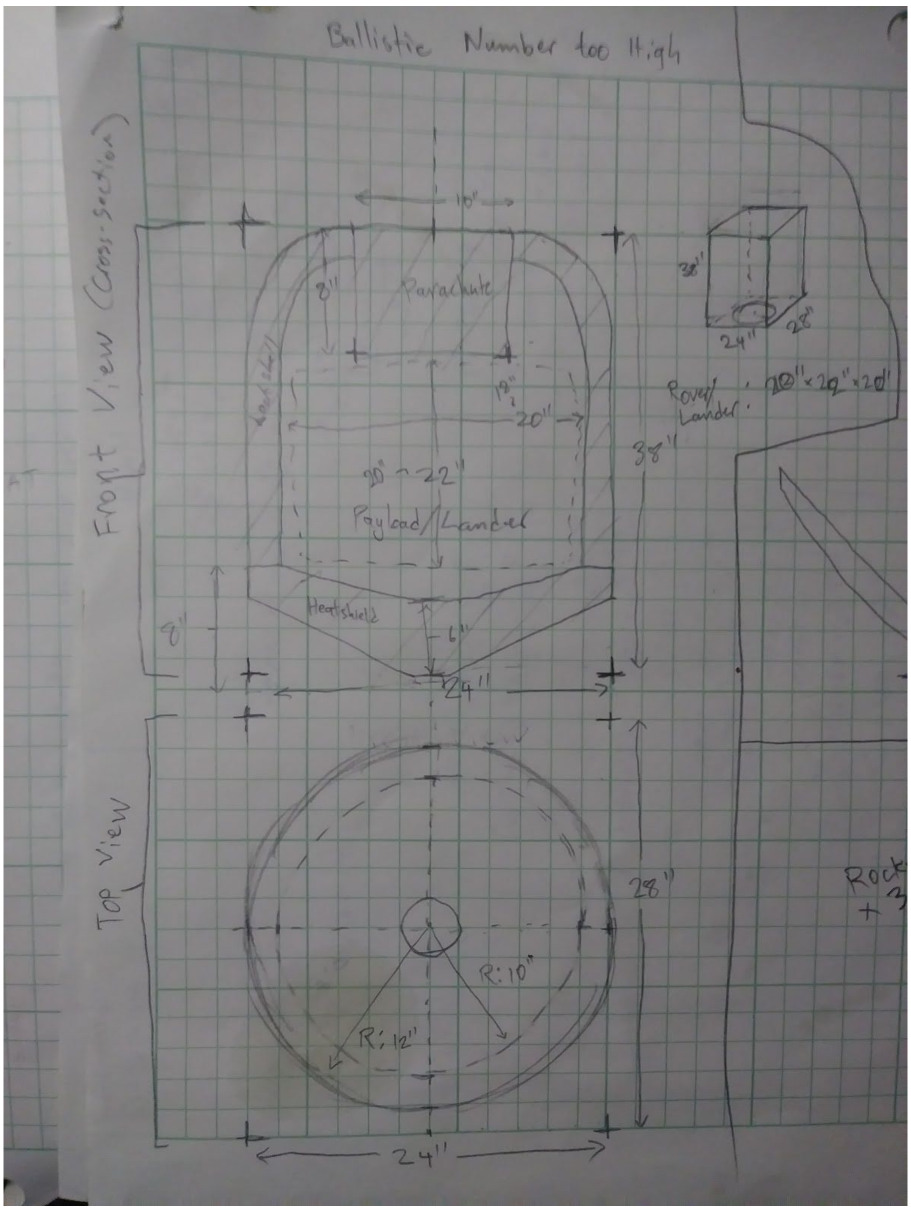


Figure 2.1: First EDL Design.

This draft of the heat shield featured a conic shape and rigid, 70-degree structure. Due to the ballistic number being too high, this design was scrapped.

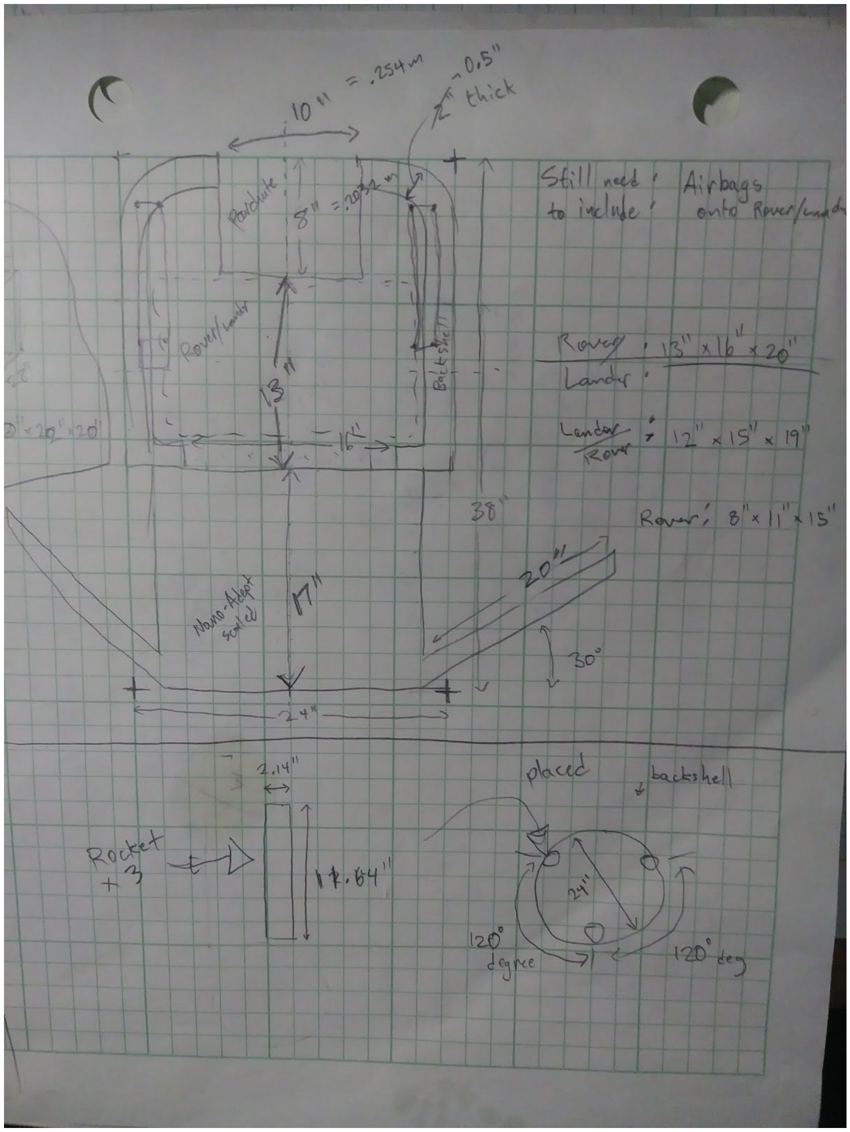


Figure 2.2: Second EDL Design.

This was the second EDL design, which became the final design to be used in the mission concept. The heat shield in this draft would be expandable in order to maximize surface area and decrease the ballistic number. Rockets were added to the design, along with airbags, to reduce the velocity of the lander upon entry.

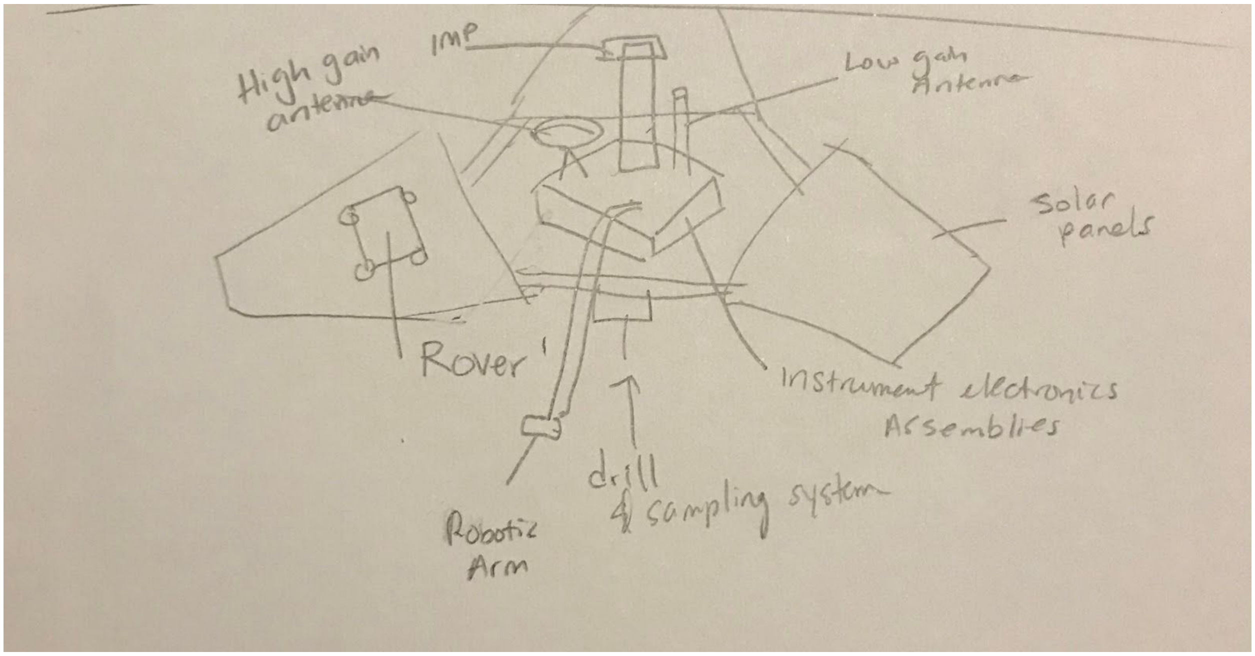


Figure 2.3: First Lander Design for the Rover.

In the early stages of developing an EDL design, the team had discussed using a rover. Referencing MPF, the rover would be encased in a lander with petals that would fold down and allow the rover to move off of the lander upon arrival [2]. Due to volume constraints with the amount of instruments on the payload, the rover design was scrapped.

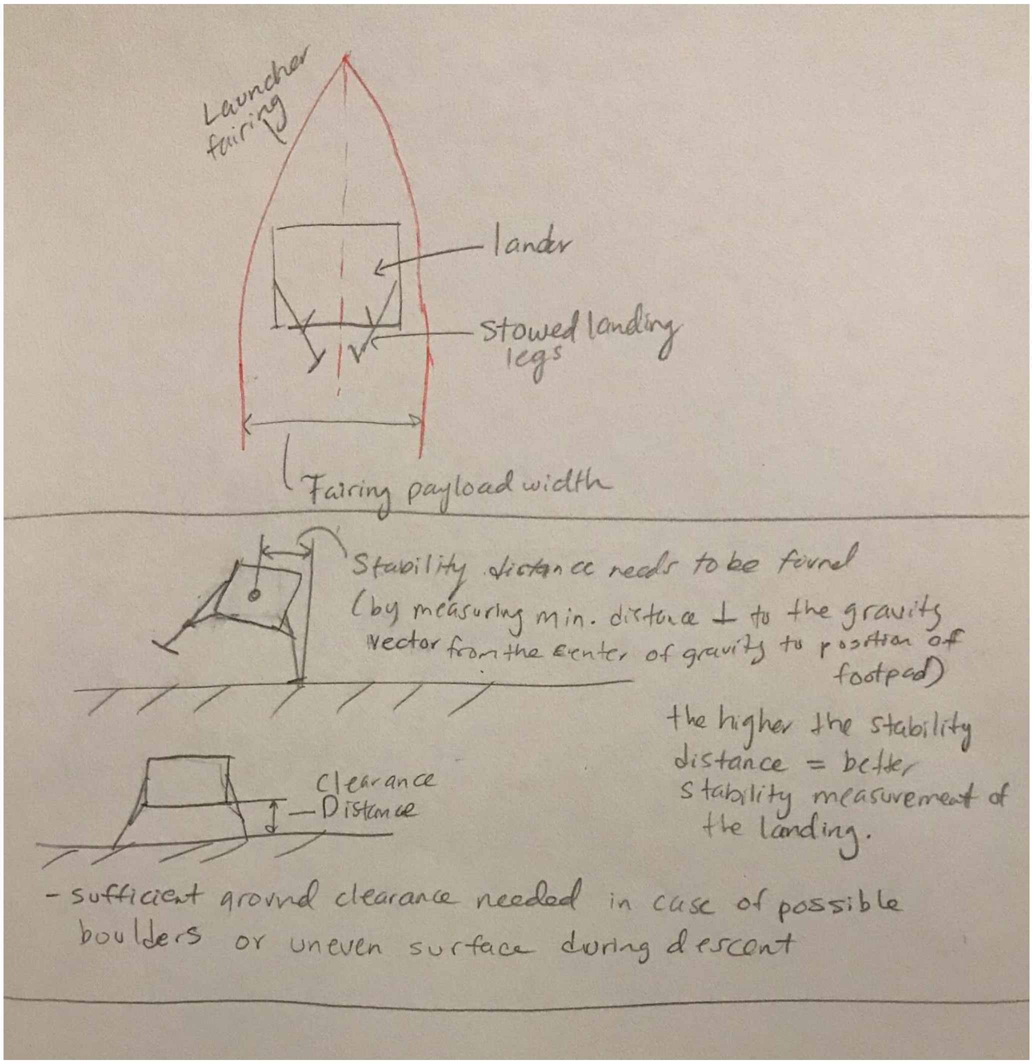


Figure 2.4: Second Lander Design.

After making the decision to use a stationary payload instead of a rover, changes were made for the lander design. This iteration of the lander design featured stowed legs to absorb impact upon landing, and uses a box-shaped design instead of a petal-shaped design. However, the stowed legs would need more height space to stow the legs which is not available due to the volume needed for the science instrument.

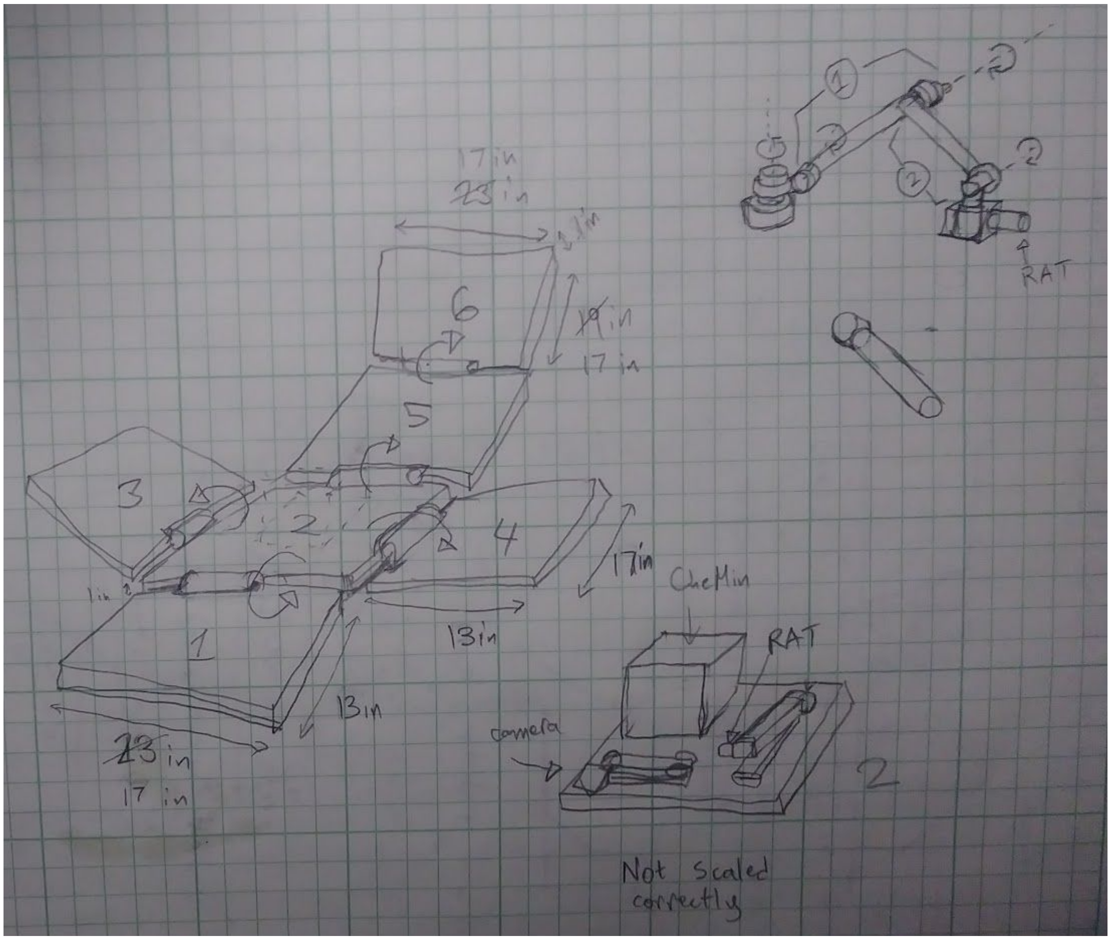


Figure 2.5: Third Lander Design, Featuring Deployment.

This is the final lander design, with more details on dimensions and the instruments being used. The box design maximizes the volume of the lander to integrate the critical science instrument, the CheMin. Similar to MPF, the lander would have each panel open in a sequence depending on the landing position [2].

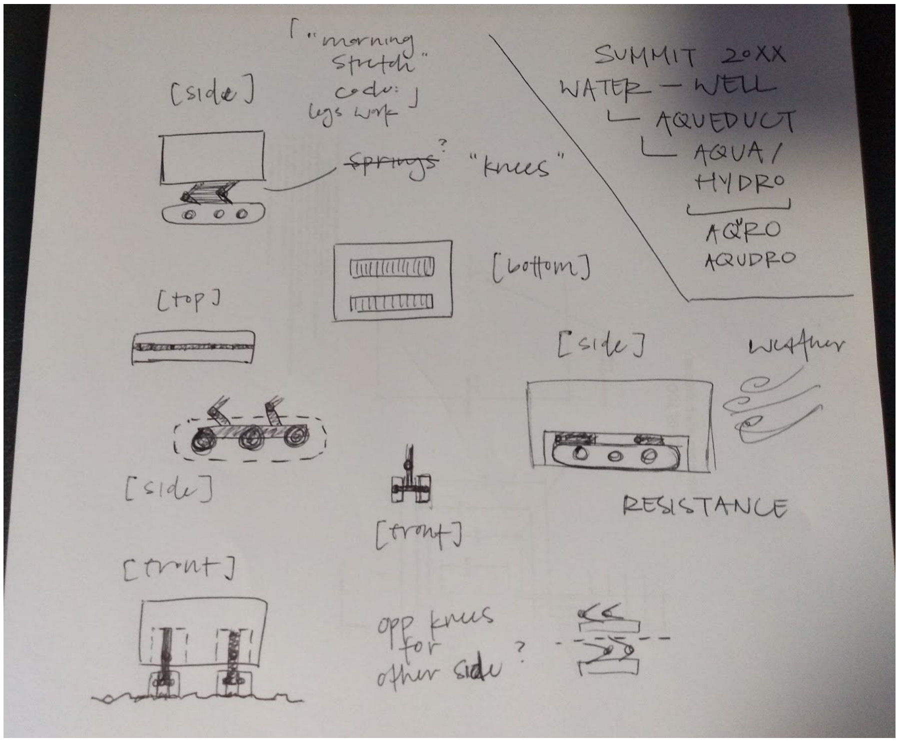


Figure 2.6: First Rover Concept Design.

This is the first rover design, featuring treads and "knees" that would be used to help the rover survive during extreme weather conditions like windstorms. The "knees" concept is similar to the stowed legs designed in the above lander sketch.

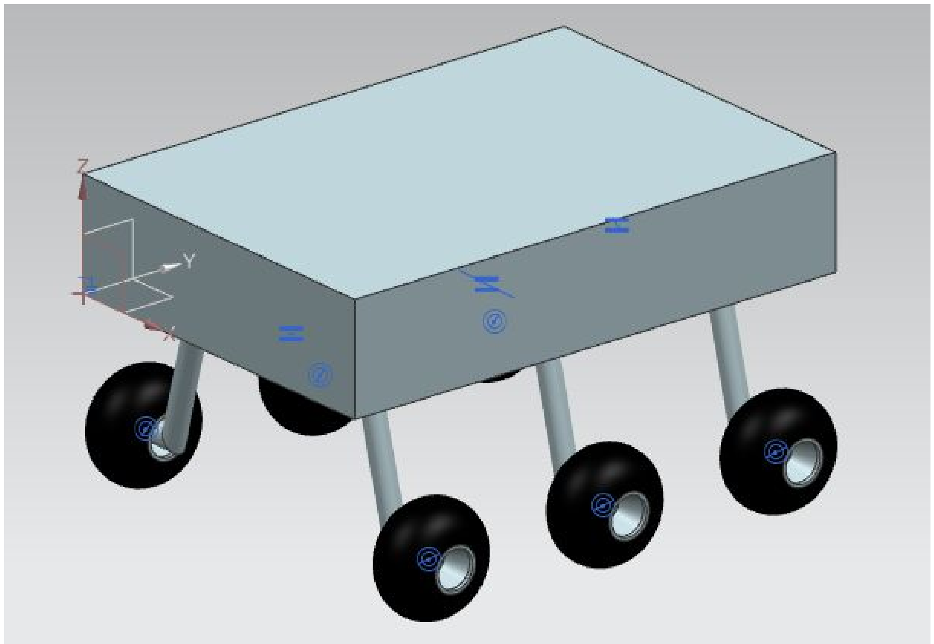


Figure 2.7: First Rover CAD Model.

This rover design would have been used if there was no conflict with the volume constraints, and falls in line with the original mission objective of collecting samples from different areas surrounding the landing site.

2.2. Evolution of Payload

Phase 1 of payload design was centered around the initial plan of a mobile rover to set out and collect various rock samples around the immediate environment and analyze the Martian atmosphere. This payload design phase consisted of including the Dynamic Albedo of Neutrons instrument (DAN), as it served in meeting a crucial criteria of the mission statement by detecting past signs of water. DAN is able to detect velocity changes of neutrons leaving the martian surface when they are slowed down by the collision of hydrogen atoms in H– and OH– bearing materials in surface layers about 1 meter below the surface with its pulsing 14 MeV neutron source. It accomplishes this by tracking the abundance of minerals containing water molecules in crystal structures.

To compliment DAN, the Rover Environmental Monitoring Station (REMS), was to be included in the payload. Its purpose was to analyze the Martian atmosphere for potential human habitats by analyzing atmospheric pressure, temperature, humidity, winds, and ultraviolet radiation levels. It consists of two small sensors known as Booms. Boom 1 was equipped with infrared sensors that measure the intensity of infrared radiation that was emitting from the ground and would additionally analyze ground

temperature. Boom 2 was equipped with sensors that would track atmospheric humidity. Both booms carried sensors that analyzed air temperature.
For navigation around the Martian terrain, the NAVCAM was to be included during this design phase. It serves in providing a view of the rover's surroundings and to plan the route that the rover is to pursue and to avoid potential driving hazards.

Phase 2 involved some significant science instrument changes. Upon agreement with the science and instrumentation team, it had been concluded that the DAN would be replaced by the CheMin. Reasoning for this design change included the fact that CheMin would be able to accomplish multiple mission statements. For example, CheMin is able to study the mineralogy and chemical composition of rocks and soil. By analyzing the data collected from the samples, it will be able to detect potential bio-signatures, energy sources for life, and/or indicators of past habitable environments. Additionally, it would be able to analyze the compositions that make up the rock material and analyze if water has once been present in the environment. However, the CheMin relies on other instruments to gather rock samples. For this, the RAT has been selected to create and gather rock powder for CheMin to analyze. The RAT will be mounted onto the robotic arm for transportation to and from the Martian surface and the CheMin.

Phase 3 of science payload design consisted of heavy discussion of major design changes of the overall system. It came to the attention of the team that volume constraint will greatly hinder the progression of the rover design. Ultimately, the payload design had exceeded volume expectations. Through heavy consideration and discussion, the science and engineering team came up with two solutions to resolve this issue.

Phase 4 involved discussion of implementing the first solution to resolve size constraint issues. This solution was to completely redesign the science instrumentation payload in favor of smaller instruments that would fit under volume constraints. The solution consisted of implementing a different type of spectrometer, the Alpha Particle X-Ray Spectrometer (APXS), which would be able to use different kinds of radiation to measure the different types of chemical elements that are present in a selected sample. This was selected because of its smaller size dimensions and contribution to the mission statement. Furthermore, re-introduction of the DAN was favorable as it would be able to detect past signs of water and would fit under the size constraints. Therefore, it was agreed upon that the RAT would no longer be necessary, but the NAVCAM will still be included during this re-design phase. However, following this route of payload redesign involved changing the mission statement as the search for past microbial life would no longer be possible.

Phase 5 was the last and final phase of payload redesign and it was decided that the second solution would be implemented. Meeting the initial mission statement became top priority when discussing the solution to resolve the volume constraint issue.

With the mindset of “science drives the design,” the science and engineering team came to the conclusion that previous science instrument equipment would be kept as they were best suited to complete the mission. This included the CheMin, the RAT, the Robotic Arm, and the NAVCAM. To resolve the size constraint issue, the team agreed upon replacing a mobile rover with a stationary lander. Removing the wheels needed for a mobile rover freed up valuable volume space allowing the selected instruments to fit within the volume constraints.

2.3. Evolution of Mission Experiment Implementation Plan

Initially, the team wanted to create a rover that was mobile in order to explore the area around Columbia Hills. The mobile rover was intended to analyze the environment on Mars and more specifically analyze the rocks and soil surrounding the landing site. The data obtained from the Mars environment would determine if there was existence of life in the past and can also determine whether or not Mars would be habitable in the future.

The first instrument change that the team had decided on was to replace the DAN, which was the team’s initial instrument choice to detect past signs of water, with CheMin. This decision allowed the team to meet more of the mission statements with CheMin than with DAN alone. The CheMin can detect potential bio-signatures and indicate evidence of past habitable environments from analyzing the rock and soil samples. In addition to the CheMin, the RAT and a Robotic Arm were added.

Due to size constraints, the team decided to change the design to use smaller instruments and DAN was reintroduced into the design to replace the CheMin. This change focused the attention to detecting signs of water rather than detecting bio-signatures and past habitable environments with the CheMin. This changed the mission statement because it would be impossible to search for past microbial life without the use of CheMin.

The final design was aimed at meeting the mission statements that the team initially agreed upon. It was concluded that the design would utilize the CheMin, RAT, and the Robotic Arm. However, the mobility of the rover will be lost in order to stay within the volume requirement.

3. Descent and Lander Design

3.1. Selection, Design, and Verification

3.1.1. System Overview

The subsystems of the EDL include a Nano-ADEPT, parachutes, rockets, and airbags. These subsystems were chosen to achieve the EDL mission requirement of reducing the descent velocity to successfully land in Columbia Hills. Shown in the EDL graphic below, Figure 3.1, is the step by step process of the descent utilizing the subsystems to reduce the velocity.

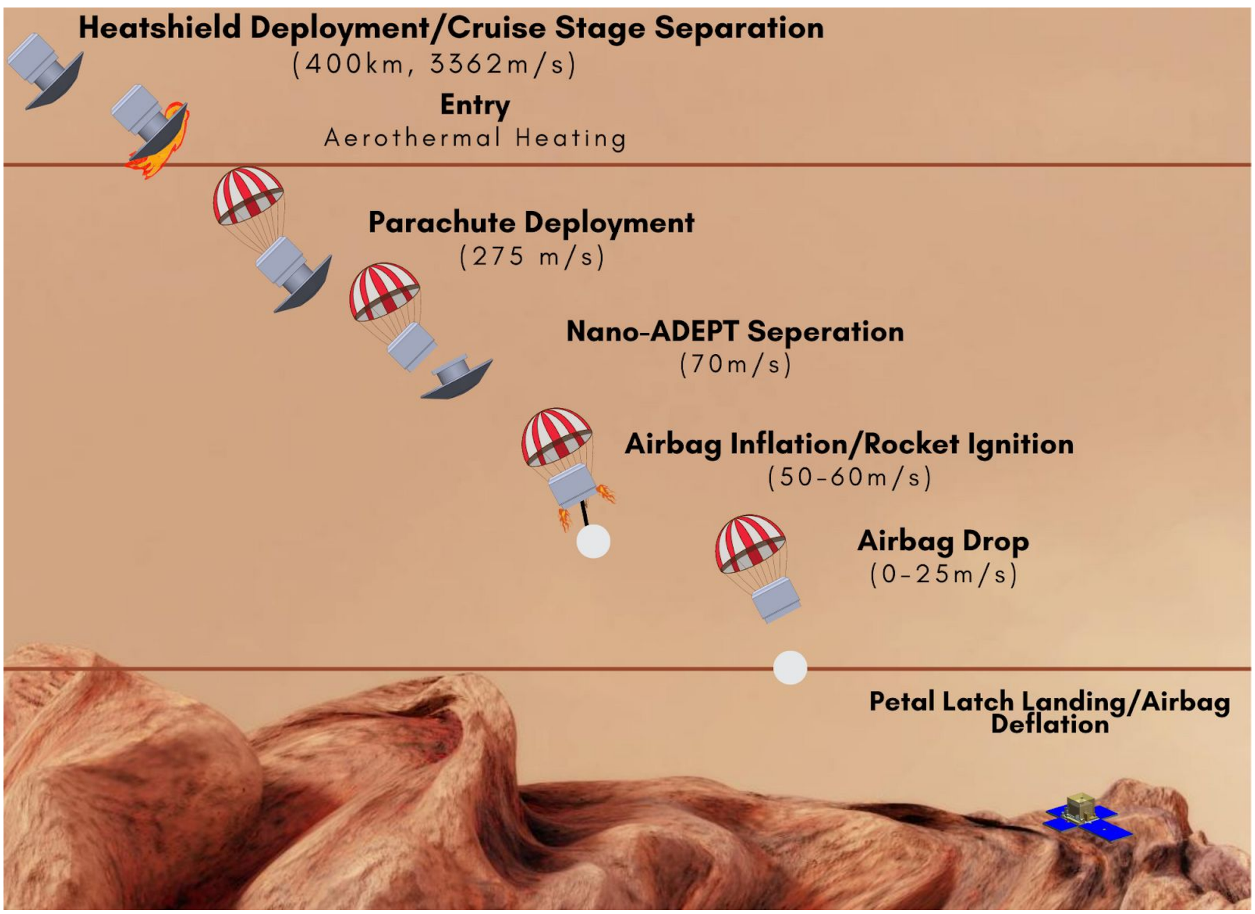


Figure 3.1: EDL Graphic.

During the hypersonic entry, an expandable heat shield called Nano-ADEPT was chosen to protect the payload from the heat produced by friction as it enters Mars' atmosphere. This innovative expandable technology will have an expandable diameter of 1.2 meters and a stowed diameter of 0.6 meters [4]. The Nano-ADEPT will have a mass of about 15 kg [5].

For the parachute, a single disk-gap-band parachute was chosen. The parachute will be released upon entry into Mars' atmosphere to assist with landing and has been proven successful on the Viking Lander mission [1]. To fit within the mission concept size, the parachute will have to be scaled down by about 72% so that the deployed parachute would still have a deployable nominal diameter of 4.5 meters. The rationale for proposing a 4.5 meters parachute is discussed later with Figure 3.11. Originally, the diameter of the deployed parachute was 16 m with a canister size of 0.38 m in diameter and 0.475 m in length weighing at 50 kg [1]. Thus, when scaled 72%, the canister for the parachute will be 0.107 m in diameter and 0.134 m in length with a mass of 14 kg. This will result in a parachute with a deployable diameter of 4.5 meters.

After the parachute has reached the terminal velocity of 70 m/s, the Nano-ADEPT will separate from the EDL and the rockets will be activated at 50-60 m/s to further reduce the velocity to 25 m/s. Four small sized rockets will be ignited to reduce the descent velocity, before the airbags are deployed. These rockets will be 0.3048 m long and 0.0508 meters wide [6]. The total mass for the rockets is about 4.36 kg [6]. Overall, the total mass of the descent system is about 51.36 kg. The airbags will protect the payload as it lands. Airbags have been proven to work on the MPF to safely land the payload [2].

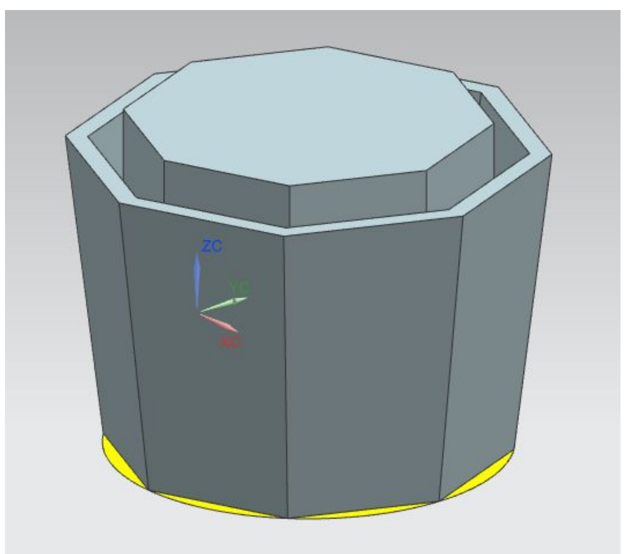


Figure 3.2: Heat Shield Stowed, Trimetric View.

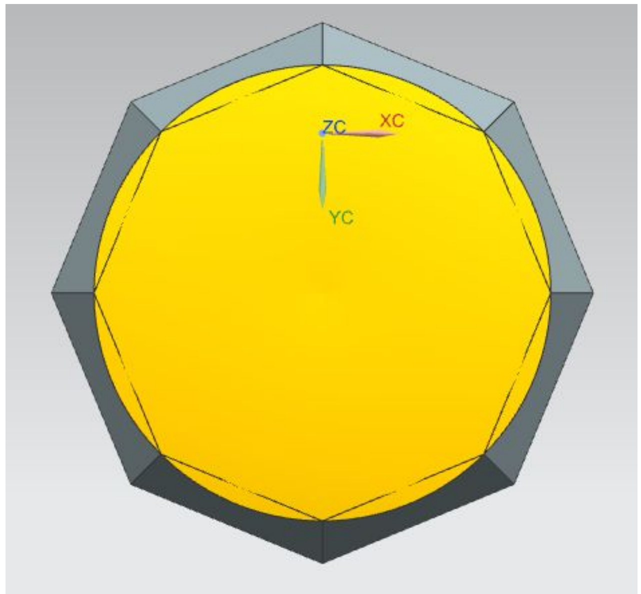


Figure 3.3: Heat Shield Stowed, Bottom View.

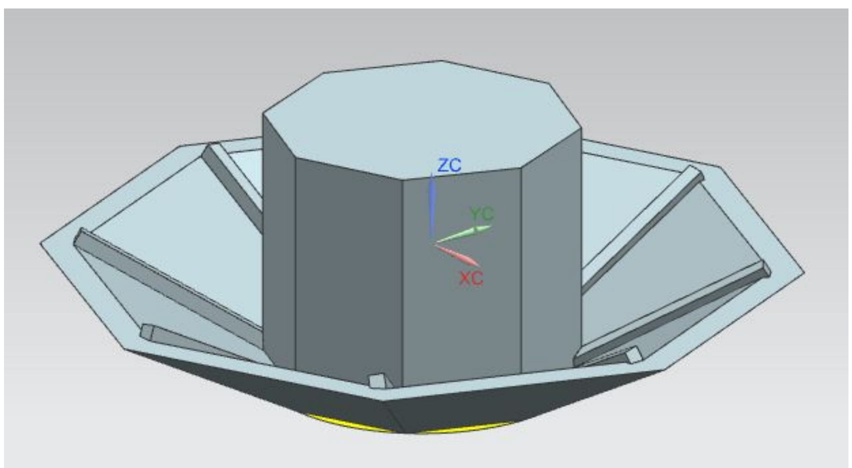


Figure 3.4: Heat Shield Deployed, Trimetric View.

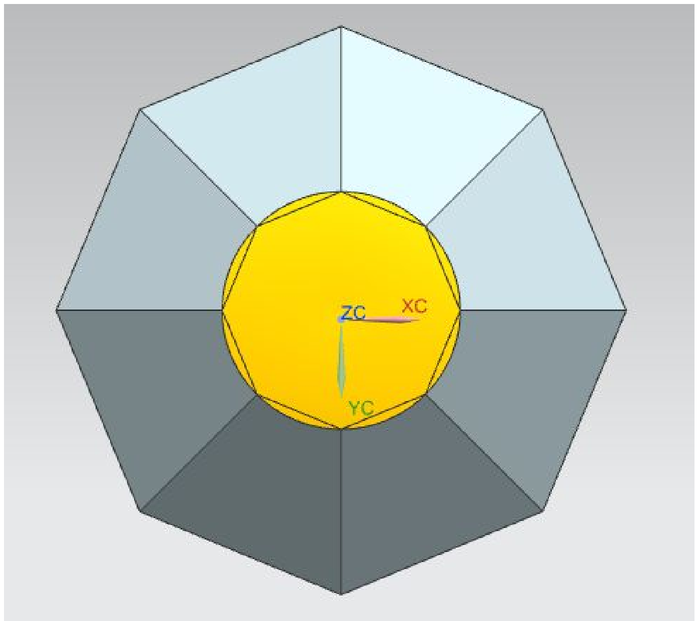


Figure 3.5: Heat Shield Deployed, Bottom View.

The yellow circular component is the nose cap of the Nano-ADEPT. The diameter of the stowed Nano-ADEPT is 0.602 meters and the diameter of the deployed Nano-ADEPT is 1.2154 meters. The heat shield drawings can be referenced in Section 3.1.3.

A significant change in dimensions of the heat shield can be seen in the stowed and deployed versions. A stowed heat shield has a Nano-ADEPT diameter of 0.602 meters and stays within the volume constraints. Whereas the deployed heat shield has a Nano-ADEPT diameter of 1.2154 meters, which allows for a more controlled descent. It is advantageous to utilize the retractability of the Nano-ADEPT to stay within the restricted volume and contribute to a safe landing.

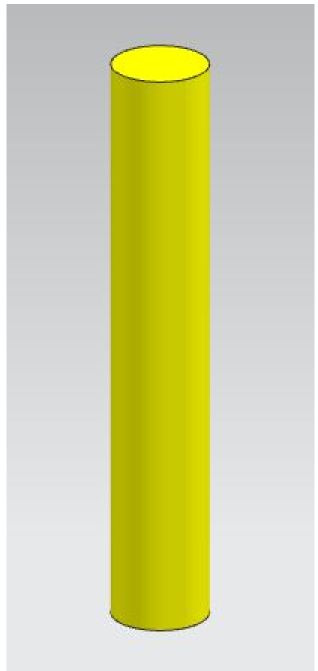


Figure 3.6: Rocket, Trimetric View.

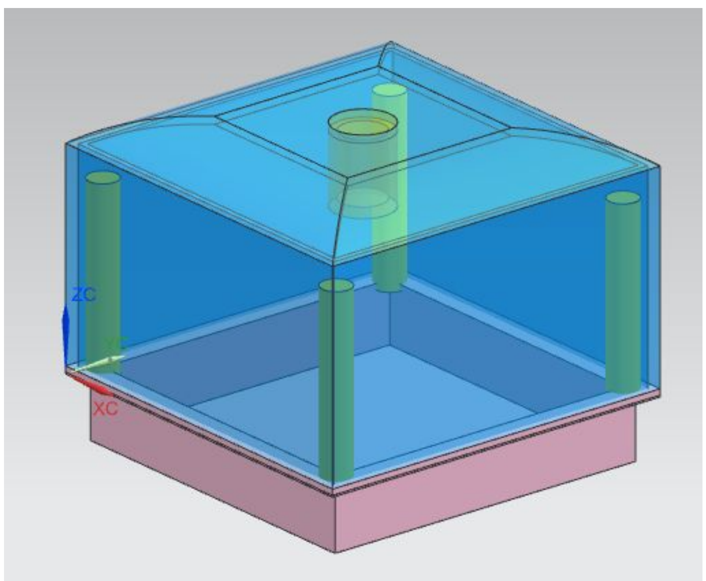


Figure 3.7: Backshell, Trimetric View.

The green cylindrical component in the middle connected to the backshell cover, in blue, is the parachute canister. Rockets are placed at the four corners of the backshell cover. The bottom piece is the payload hold shown in pink.

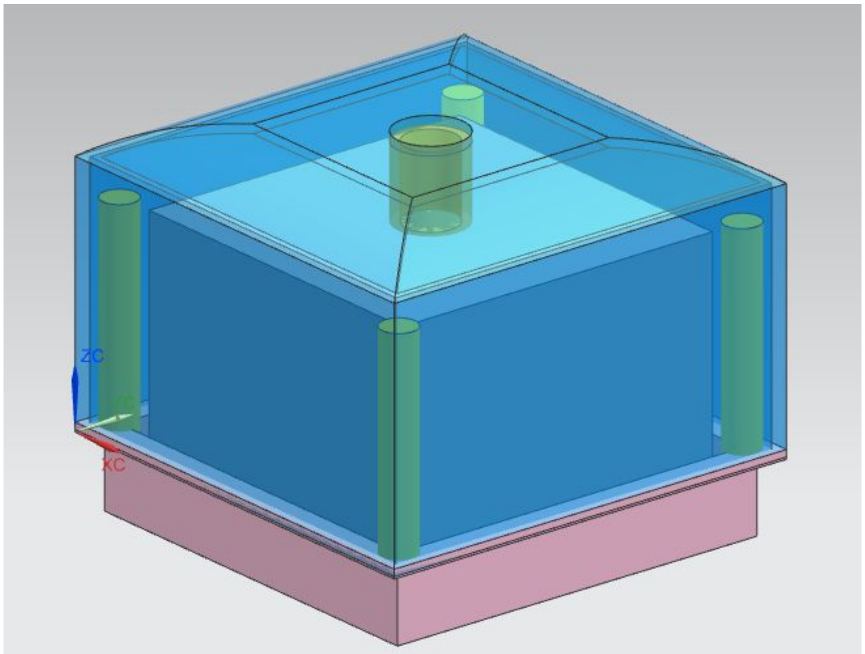


Figure 3.8: Backshell with Lander, Trimetric View.

Figure 3.8, above, illustrates how the lander will be situated in the backshell.

The main constraints considered when choosing the descent system were the size and mass. The team's volume constraint is 24 inch by 28 inch by 38 in (60.96 cm by 71.12 cm by 96.52 cm). The mass constraint is 180 kg with an additional 72 kg just for the EDL system. In addition, the Engineering team had to make sure the design would be large enough to reach a similar ballistic coefficient as previous Mars missions [3]. Obtaining a similar ballistic coefficient would help achieve a similar trajectory, thus increasing the probability of a safe landing.

The maximum mass of the concept is 252 kg. The mass possibilities were plotted on a graph, (Figure 3.9) to find the minimum required diameter of the heat shield.

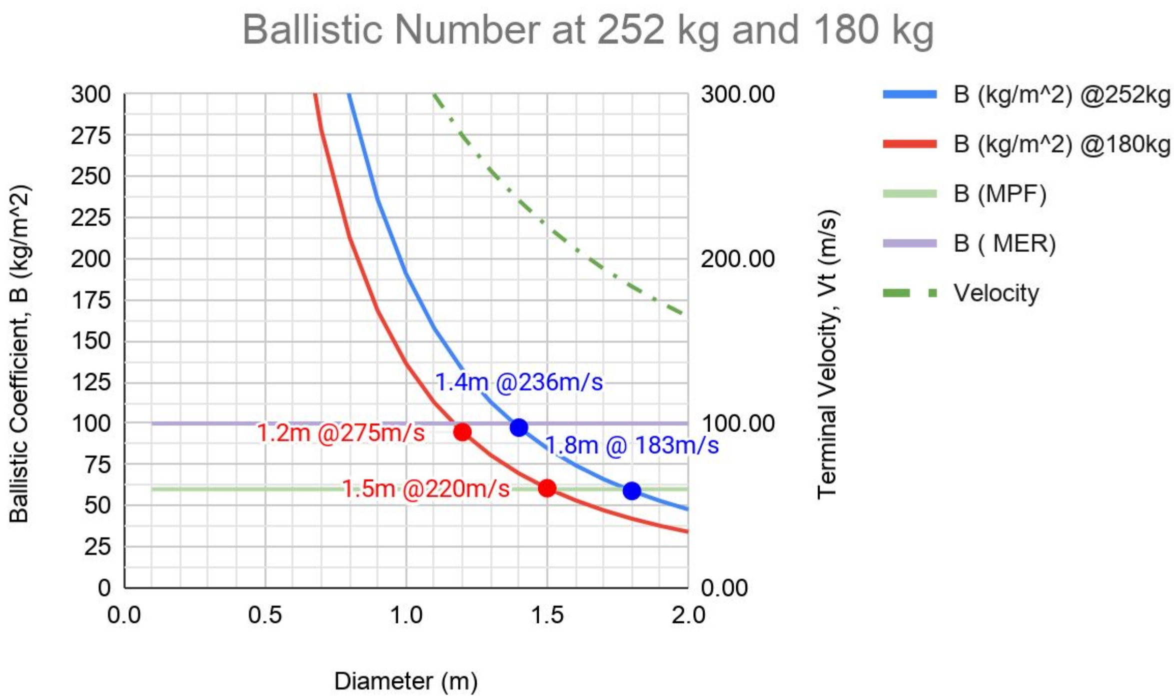


Figure 3.9: Ballistic Coefficient at a Varying Diameter.

A ballistic coefficient of about 60 kg/m^2 and 100 kg/m^2 is used as reference from MPF and MER [3]. Figure 3.9 was obtained using the ballistic coefficient equation (Equation 1) below [7], and the descent, or terminal velocity, equation, used in rocketry [8]. Essentially, the terminal velocity can be solved by equating Equation 2 and Equation 3 and solving for the unknown velocity. Knowing the terminal velocity is important to determine the speed at which the parachute will be deployed. By varying the diameter and reference ballistic coefficient, the graph shows the target diameter for the heat shield is a minimum of 1.2 meters.

$$BC = \frac{m}{C_d A}$$

Equation 1: Ballistic Coefficient equation. A drag coefficient of 1.68 is used for a 70 degree sphere cone shape [3].

$$F_D = \frac{1}{2} \times \rho \times C_d \times A \times v^2$$

Equation 2. Drag Force equation. Using Mars density of 0.013 kg/m^3 and an estimated drag coefficient of 1.75 for the parachute [9].

$$F_G = m \times g$$

Equation 3. Force of gravity. Mass of the spacecraft multiplied by the gravity on Mars.

$$D = \sqrt{\frac{8mg}{\pi \rho C_d v^2}}$$

Equation 4. Combination of Equation 1 and 2. Using an assumed circular area to find the diameter.

In Figure 3.9, the heat shield would need to be a minimum of 1.2 meters to achieve the target ballistic coefficient of previous mars missions. The reference ballistic coefficients are 60kg/m^3 and 100kg/m^3 for MPF and MER, respectively [3].

Even at the largest size of 0.9652 meters, a rigid shape would not meet the ballistic coefficient target of 100 kg/m^3. Therefore the team researched expandable or deployable technology that can deploy up to 1.2 meters, almost twice it's undeployed size of 0.60 meters. The heat shield of 1.2 meters in diameter, with a mass of 180kg, would achieve a terminal velocity of 275 m/s or about 0.8 mach speed as shown in Figure 3.1.

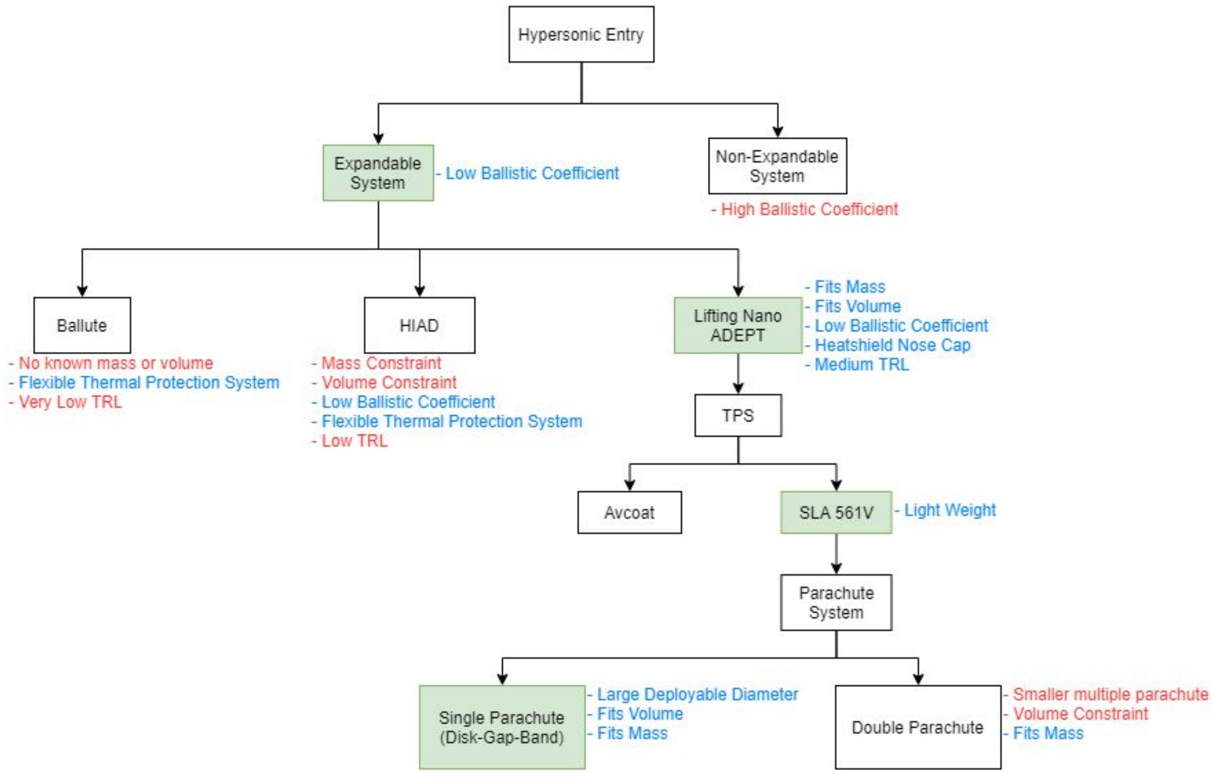


Figure 3.10: EDL Trade Study Flow Chart.

A flow chart shown in Figure 3.10 was created for various expandable or deployable technologies and the team finalized on choosing the Lifting Nano-ADEPT. The Lifting Nano-ADEPT has a medium Technology Readiness Level (TRL); compared to the Ballute and Hypersonic Inflatable Aerodynamic Decelerators (HIAD) technology with very low to low TRL [10]. In addition, the Nano-ADEPT is within the constraint of volume and mass. The HIAD came close to being chosen, however the current research and development proved too complex to scale within the project constraints.

A parachute would need to be deployed to further decrease this descent velocity. To size the parachute, a graph was plotted finding the terminal velocity while varying the diameter (Figure 3.11).

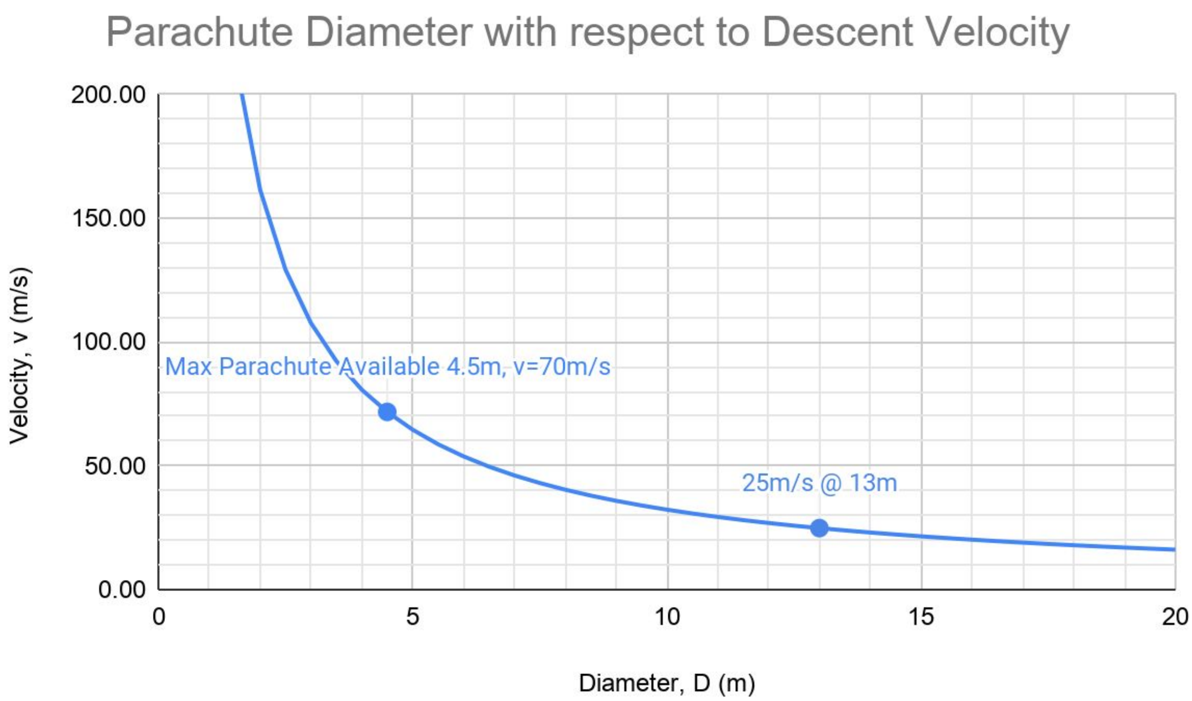


Figure 3.11: Terminal Velocity at Varying Deployed Parachute Diameters.

Safe touchdown landing is about 25m/s. Equation 2 and Equation 3 is used to find parachute descent calculations for rocketry [9]. By assuming a downward force of gravity, and an upward force of the drag force, the equation is equated to each other to solve for the deployed diameter of the parachute. In addition, Equation 4 can be used to solve for the descent velocity by varying the diameter.

A typical drag coefficient of 1.75 for parachutes was used as an estimate during the analysis [9]. Further on-site testing will be required to obtain a more accurate drag coefficient for the parachute. From Figure 3.11, the parachute would need to deploy with a minimum diameter of 4.5 meters. The target velocity of about 70 m/s is referenced from the previous Mars Pathfinder EDL graphic [3]. The target touchdown velocity is 25 m/s due to the strength of the airbags. If the volume was available, having a 13 meter deployed parachute would bring the EDL to a terminal velocity of around 25 m/s which is the target touchdown velocity for the airbags used on the MPF [3].

A descent velocity of 70 m/s after the parachute is deployed is still too fast for a safe landing. Before dropping the airbags, rockets are implemented on the backshell to reduce the velocity even more. These small rockets can be purchased from Apogeerockets for a low cost and are able to produce a max thrust of around 2000 Newtons [6]. Further testing will be needed to validate the amount of descent velocity reduced.

Airbags were implemented to ensure a safe landing for the payload during the impact. The rockets were added to further reduce the descent velocity of 70 m/s to 25 m/s. The airbag acts as the shock absorber for the final touchdown. The chosen airbags will absorb the shock of the landing and have been proven to successfully survive at a 25 m/s drop [3].

3.1.2. Subsystem Overview

The Nano-ADEPT uses a dual spring deployment system to expand twice its original diameter size. The expandable technology is best described as an umbrella with ribs, struts, actuators with guide rails, and avionic units to support the mechanism. To assist in deploying the mechanism, there are avionic units that include power, Inertial Measurement Unit (IMU), GPS, and solid memory. The avionic units will determine when to mobilize the actuators with guide rails and deploy the heat shield. The team can utilize the Nano-ADEPT's avionic system to decide when to separate during the EDL phase. Numerous tests have been conducted on the Nano-ADEPT such as the Sounding Rocket Flight Test and System-Level Arc Jet Test to further provide data of the technology.

The parachutes, rockets, and airbags are included to continue to reduce the velocity. Once the velocity reaches below mach speed, parachutes will be deployed similar to the Viking parachute descent system. The disk-gap-band parachute would be deployed using a mortar. Utilizing the IMU built in the Nano-ADEPT, the system will work together to determine when to deploy the parachute. Four rockets were chosen, placed on each corner of the backshell, to apply an equal amount of force. The rockets would be ignited using the same system included in the Nano-ADEPT. The airbags are implemented on the stationary lander similar to the petal lander on the MPF and MER. Airbags will deploy while in the air to fully encapsulate the stationary lander and will reach touch down at 25 m/s. Once landed, the airbags will be retracted back to give room for the stationary lander to operate the science instruments.

The materials chosen were used in past Mars missions. For the parachute, polyester and nylon were selected because of their durability, as well as Zylon bridles for tethers. Vectran was selected for the airbags also because of its durability and effectiveness in colder conditions, especially in comparison to Kevlar [11]. SLA 561V was chosen as ablative material for the Nano-ADEPT because of its successful past usage on Mars [12,13]. Table 3.1 shows the process of selecting materials.

TPS	Supplier	Nominal Density (g/cm^3)	Flight Qual/TRL	Max Heat Flux (W/cm^2)	Max Pressure (atm)	Mission Ready
Avcoat	Textron	0.51	Apollo	~1000	~1	Y
BPA	Boeing	0.48 - 0.96	TRL 3-4	~1000	~1	N
SLA 561V	LMA	0.26	Mars	<120 (<300)	<1	Y
SRAM	ARA	0.51	TRL 5-6	~300	~1	N

Table 3.1: Thermal Protection Materials Selection [14].

3.1.3. Dimensioned CAD Drawing of Entire Assembly

EDL

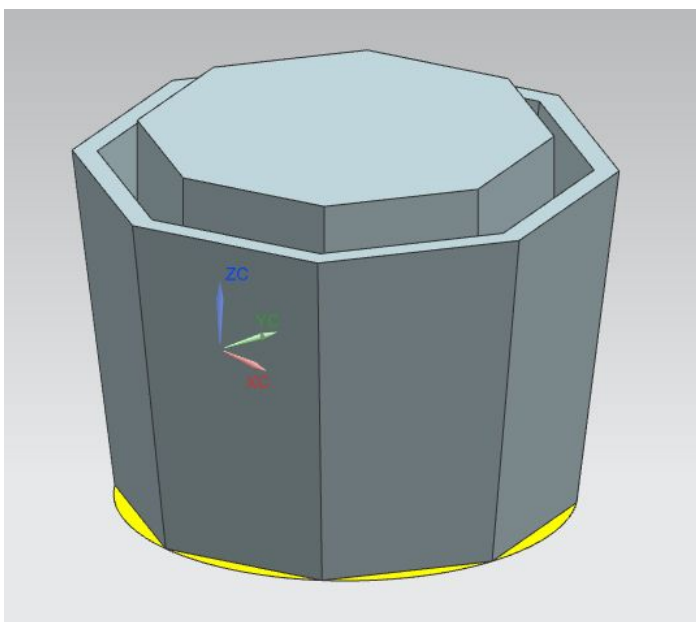


Figure 3.12: Heat Shield Stowed, Trimetric View.

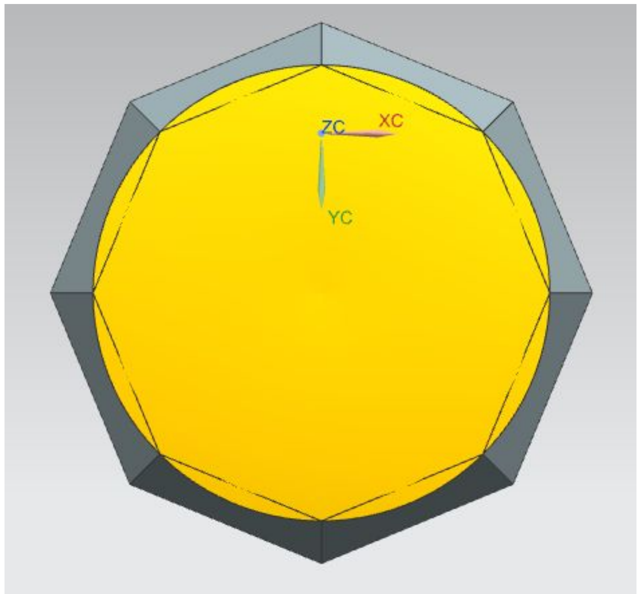


Figure 3.13 Heat Shield Stowed, Bottom View.

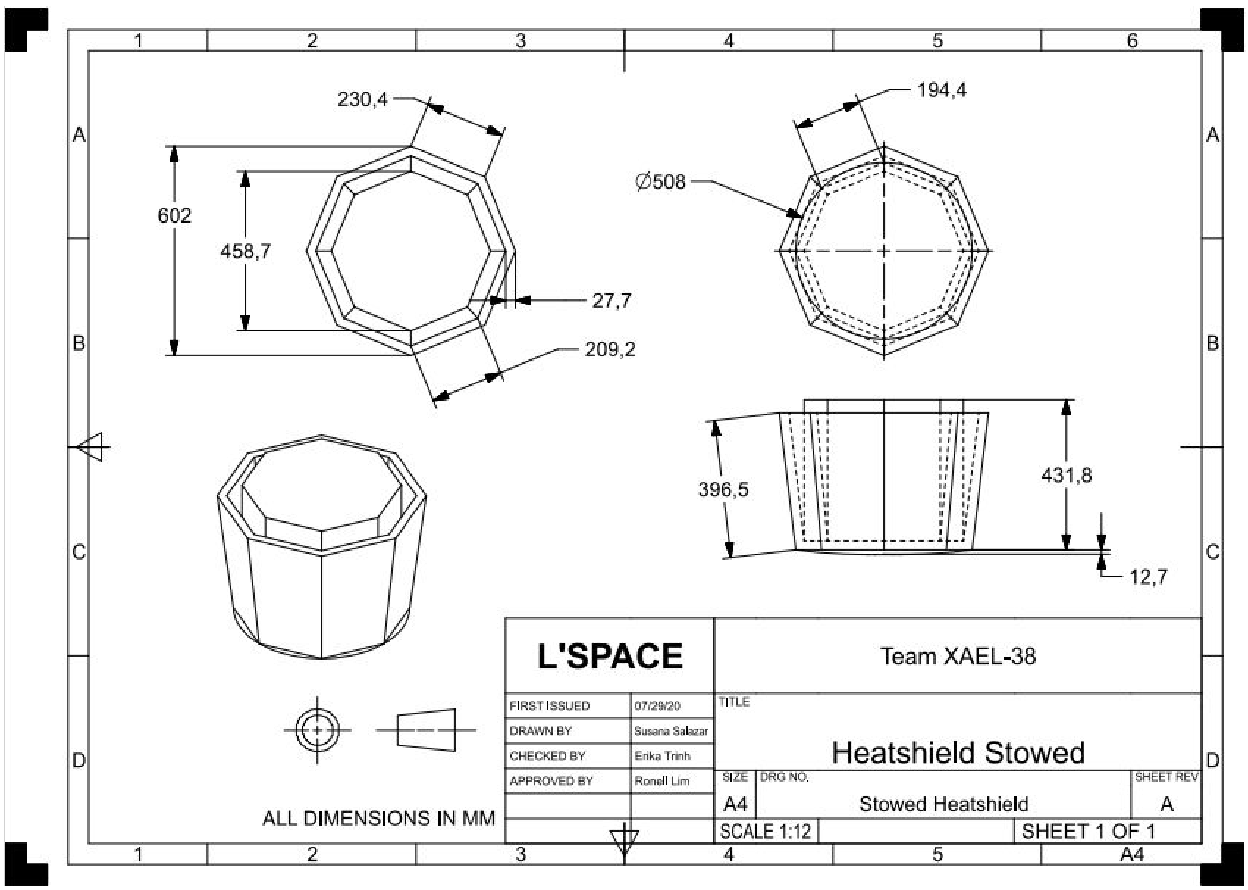


Figure 3.14: Heat Shield Stowed Drawing.

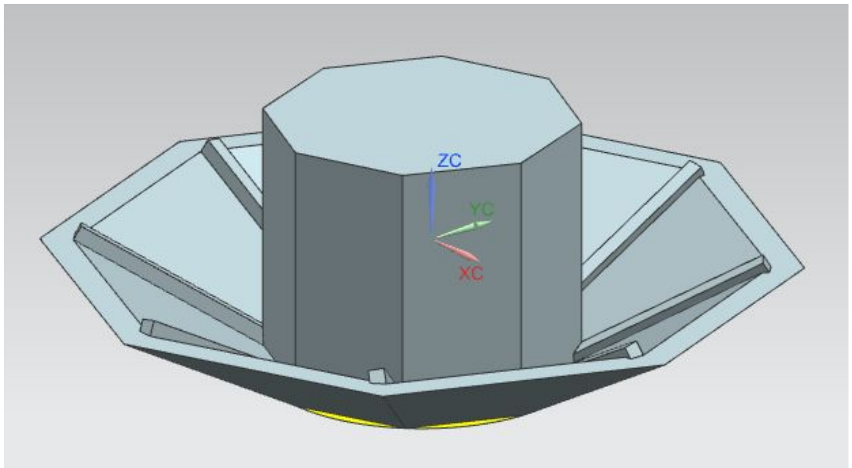


Figure 3.15: Heatshield Deployed, Trimetric View.

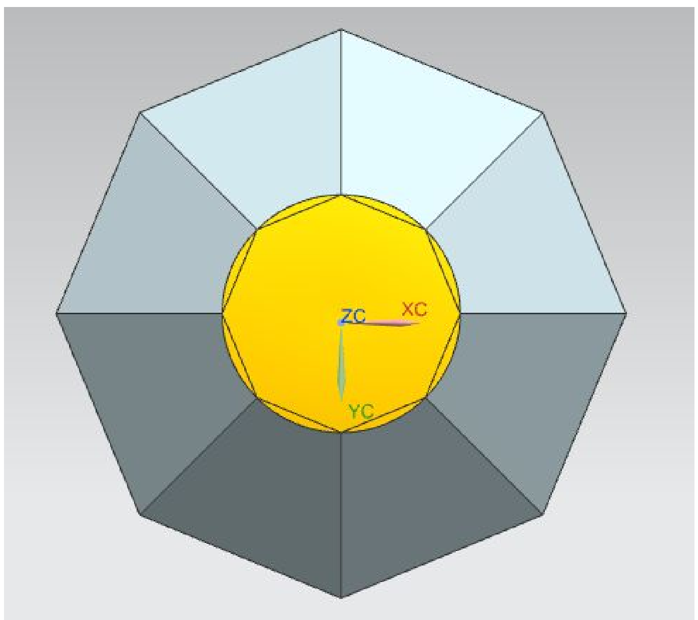


Figure 3.16: Heat Shield Deployed, Bottom View.

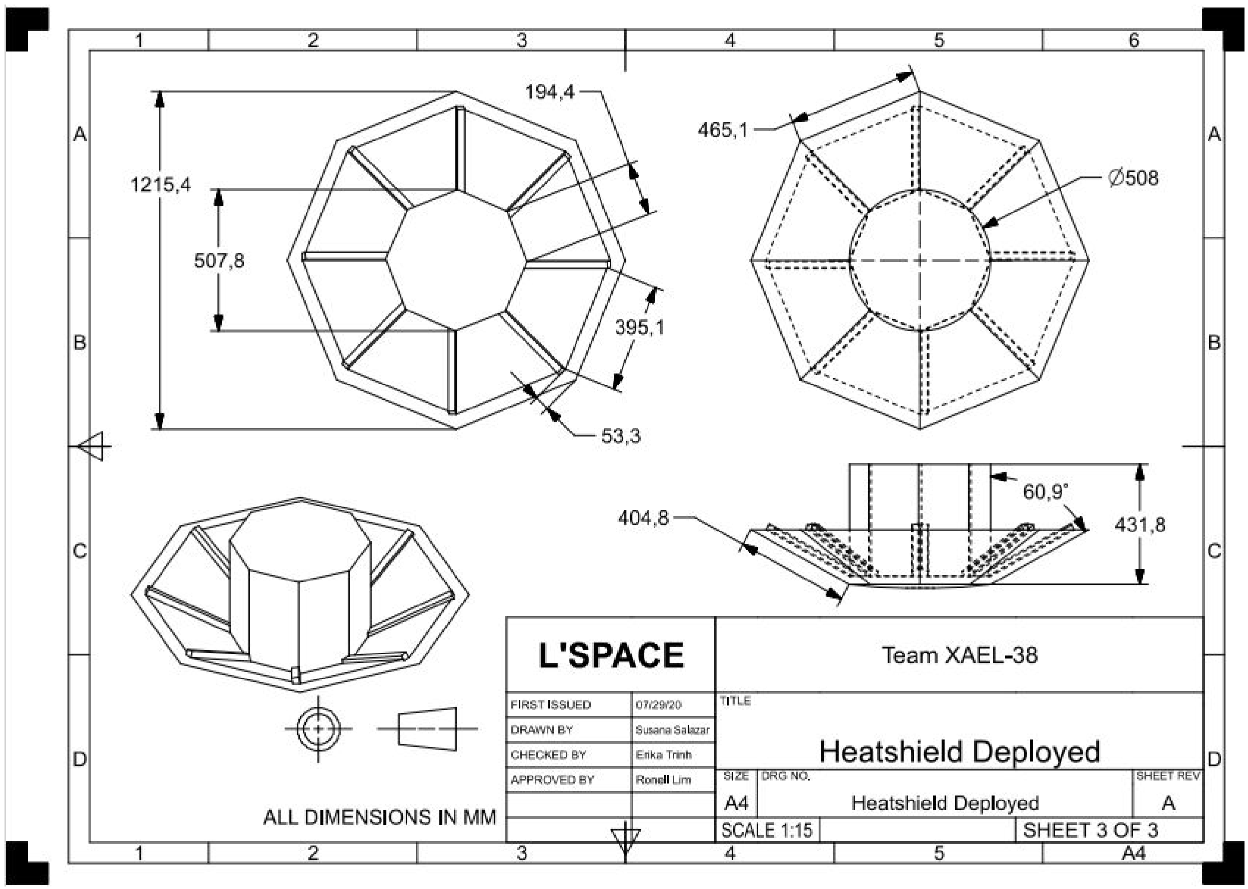


Figure 3.17: Heatshield Deployed Drawing.

As a note, the difference in the Heatshield Stowed (Figure 3.14) and the Heatshield Deployed (Figure 3.17) drawings are the Nano-ADEPT deployments. The dimensions of the two designs vary in wing length due to the inclusion of the ribs in the deployed version.

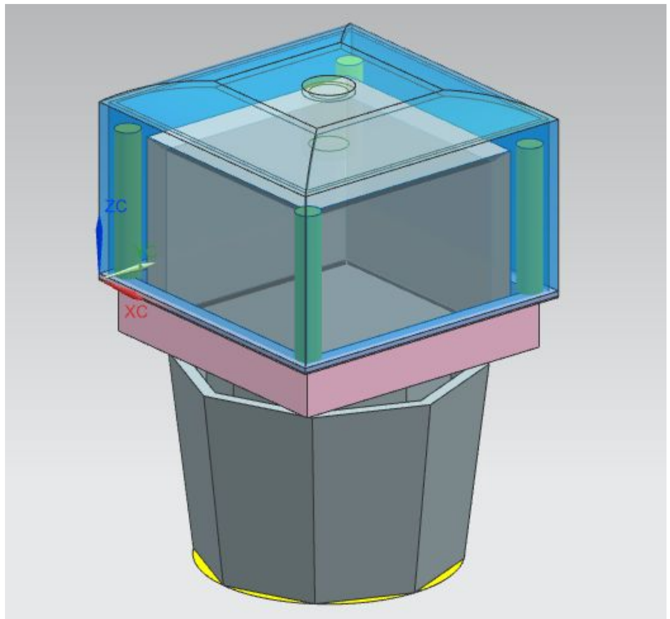


Figure 3.18: EDL Stowed, Trimetric View.

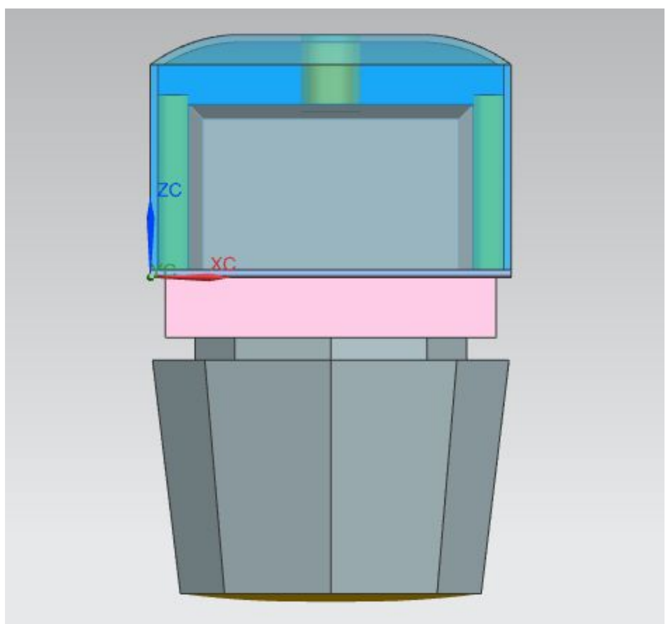


Figure 3.19: EDL Stowed, Left View.

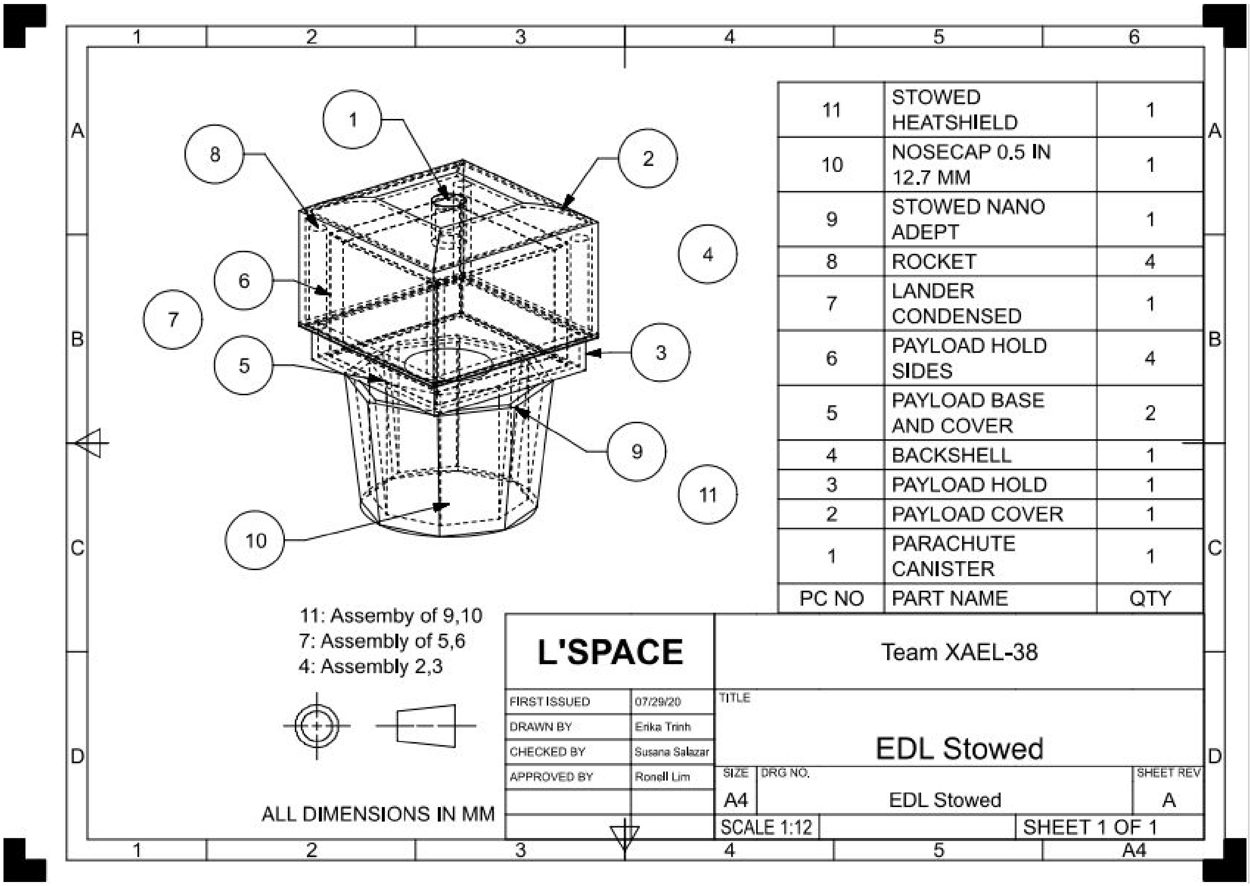


Figure 3.20: EDL Stowed Assembly Drawing, Trimetric View.

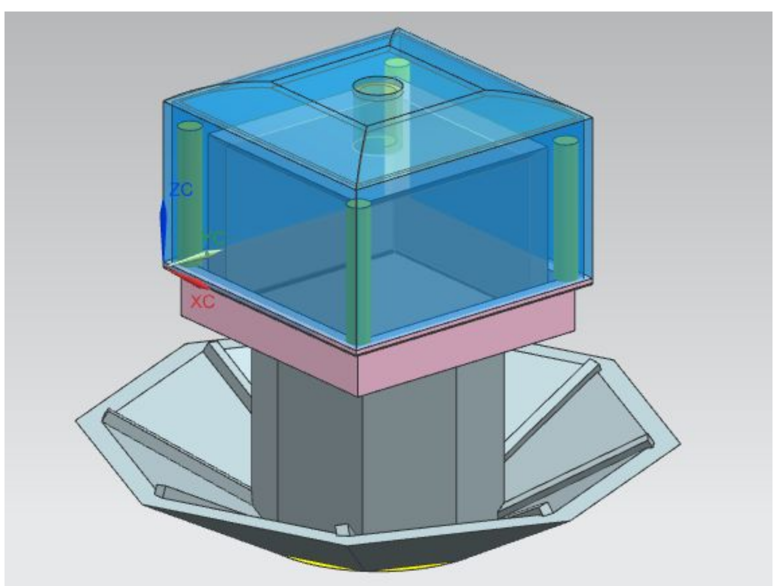


Figure 3.21: EDL Deployed, Trimetric View.

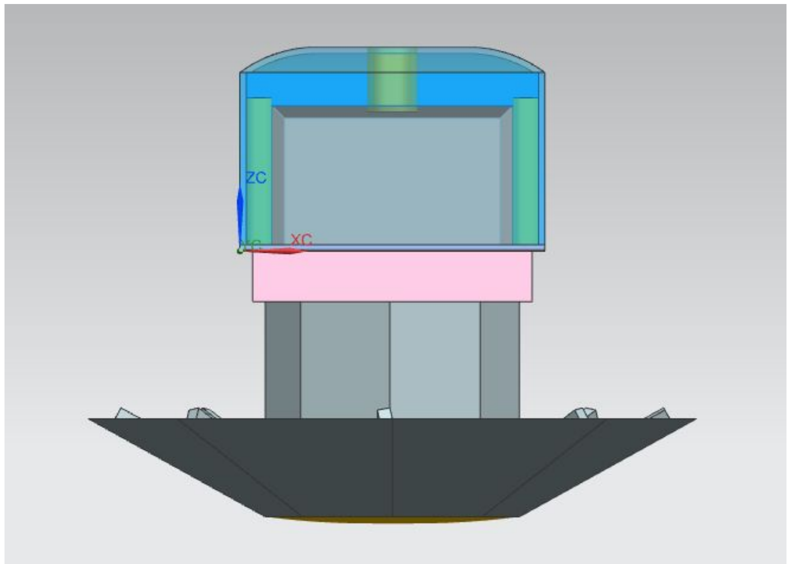


Figure 3.22: EDL Deployed, Left View.

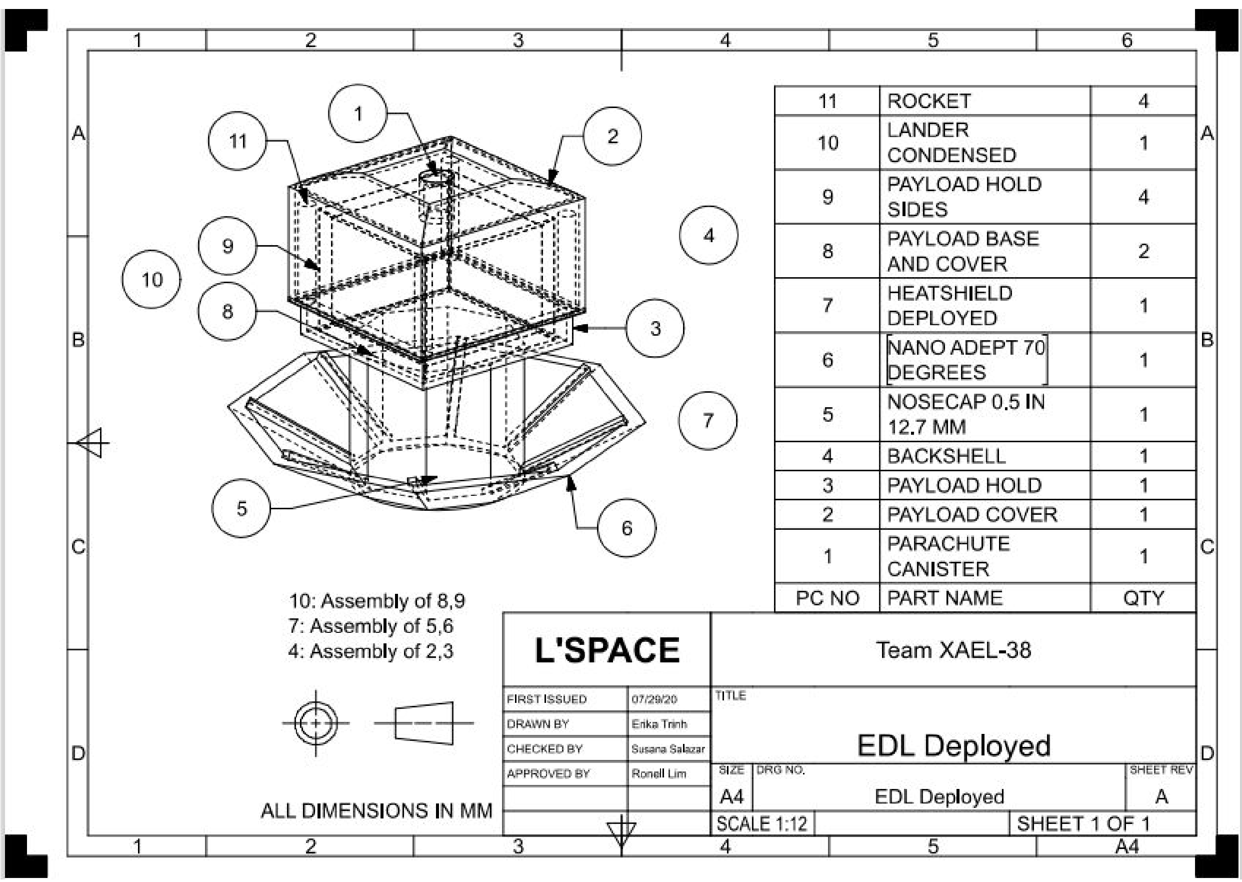


Figure 3.23: EDL Deployed Assembly Drawing, Trimetric View.

Similarly to that of the heat shield, the difference in the EDL Stowed (Figure 3.20) and the EDL Deployed (Figure 3.23) drawings are the Nano-ADEPT deployments. The numbers in the bubbles do not correspond between the drawings; however the bubbles in the same location between the drawings reference the same component of the assembly, aside from the Nano-ADEPT.

Lander

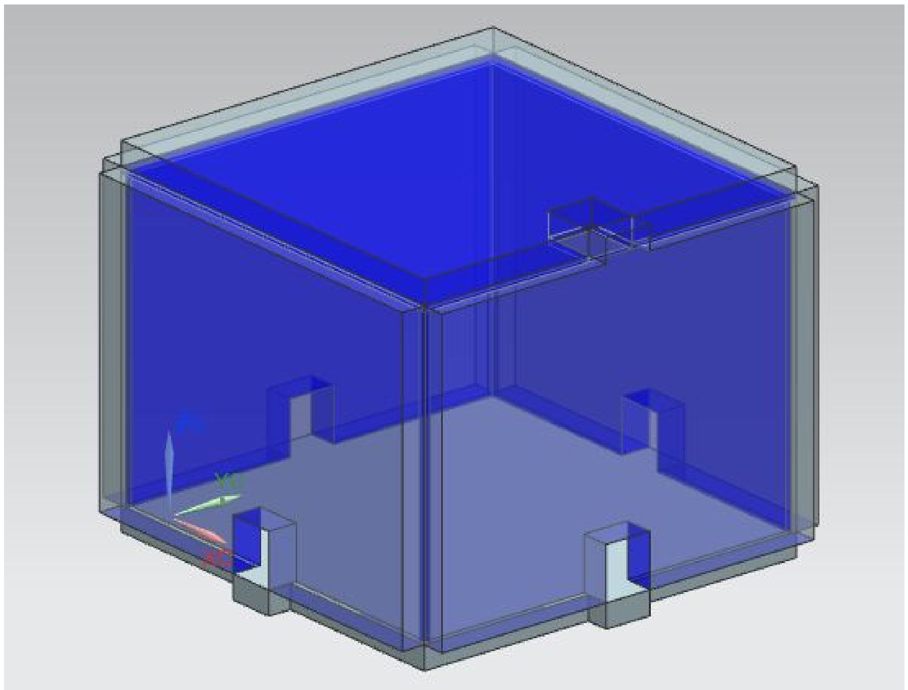


Figure 3.24: Lander Structure Stowed, Trimetric View.

The overall volume taken up by the lander is 0.4826 m by 0.4826 m by 0.381 m in its stowed position.

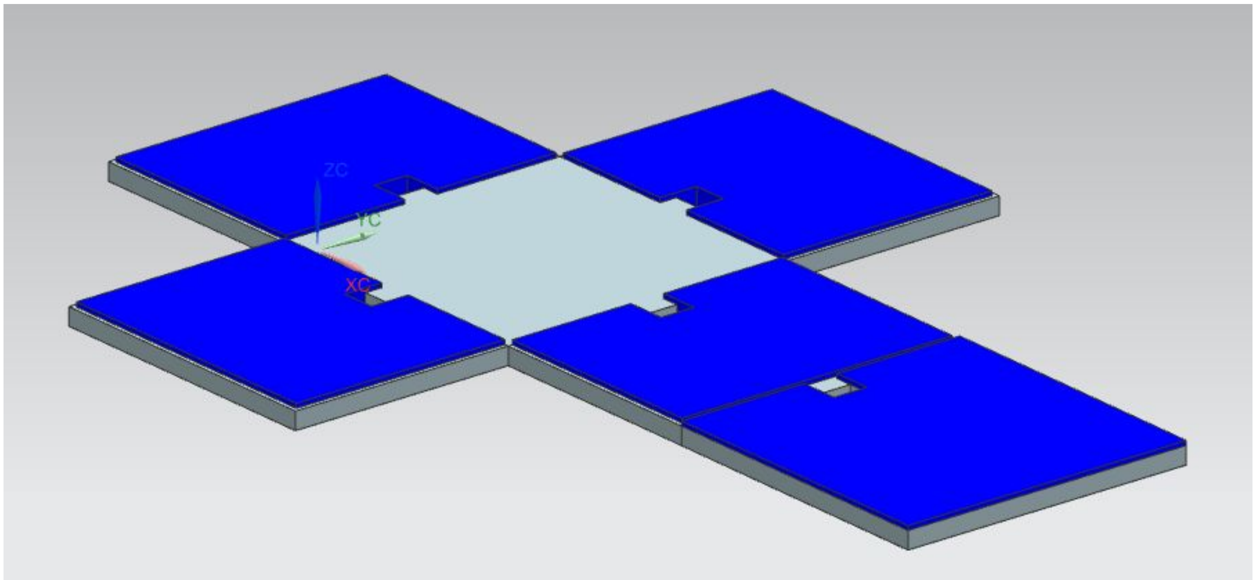


Figure 3.25: Lander Structure Deployed, Trimetric View.

A view of the lander's "petal" system in deployment is shown in Figure 3.25. The blue represents the solar panels attached to the interior of the lander. The notches in the lander provide a space for the motors for the means of expansion.

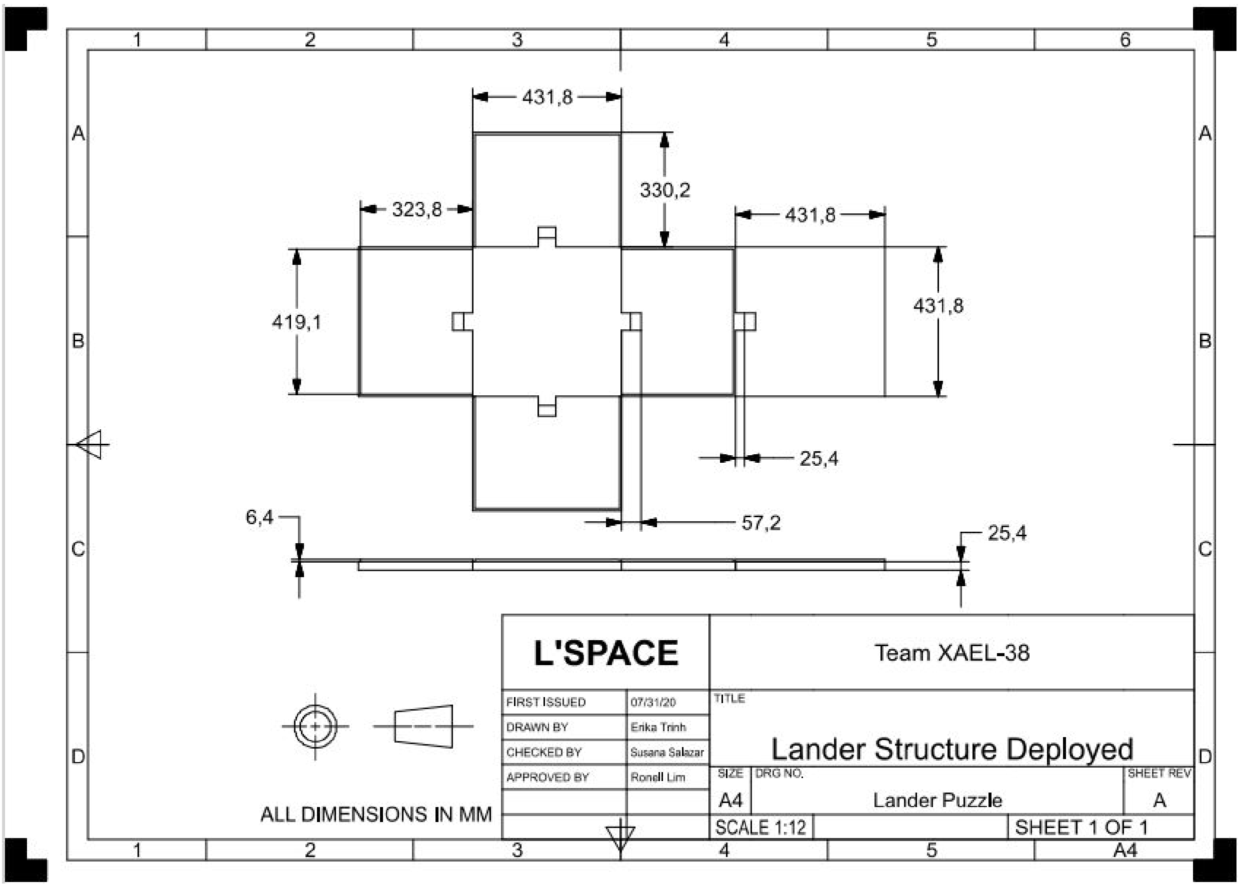


Figure 3.26: Lander Structure Deployed Drawing.

As a note, the slightly smaller dimensions of the lander sides, shown to the left of the connected base, are the dimensions of the solar panels. The component that is not directly attached to the base will have solar panels with the same length and width dimensions as that component. This is to allow proper stowing of the lander while maximizing the surface area of the solar panels.

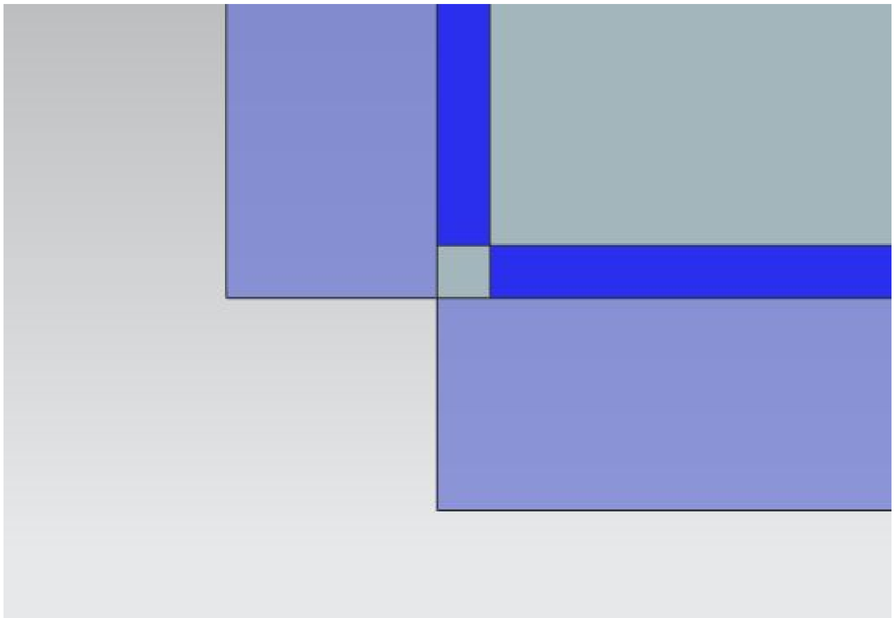


Figure 3.27: Solar Panel Orientation Between Two Sides, Top View.

Figure 3.27 shows how the solar panels of two sides would interact from the top view before the lander is fully closed.

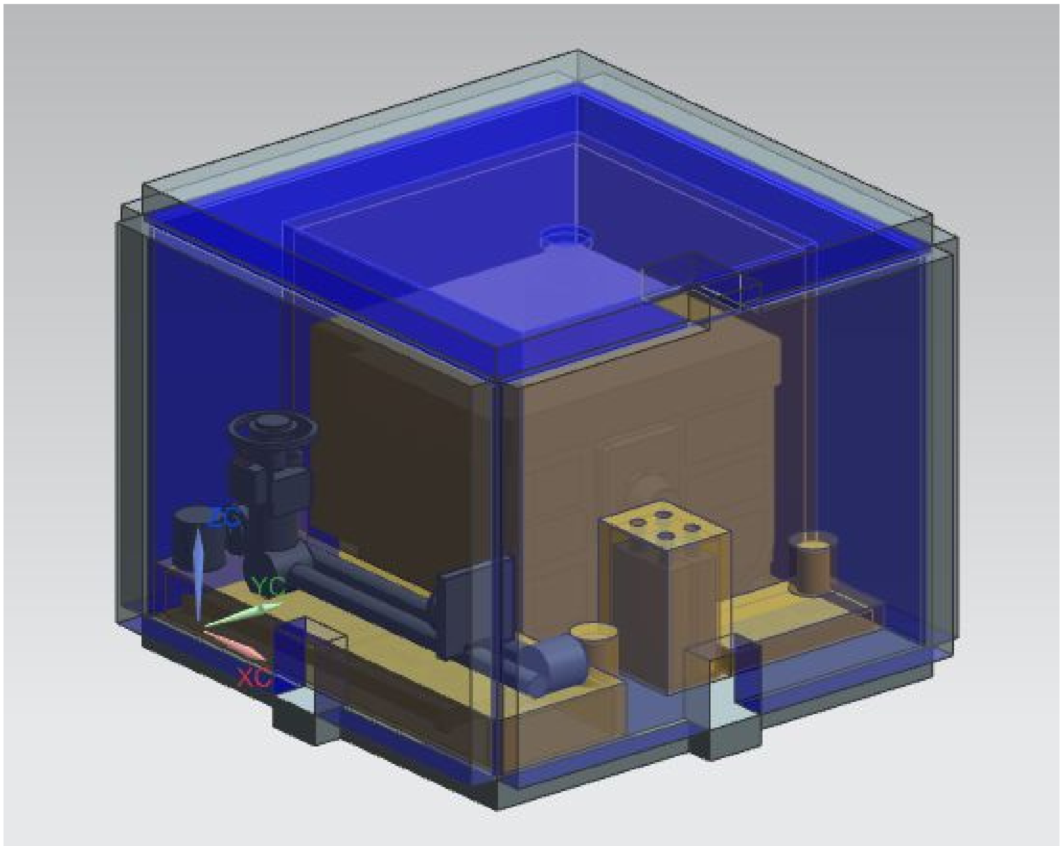


Figure 3.28: Lander and Instruments Stowed, Trimetric View.

This stowed view of the lander illustrates how the lander would land on Mars with all of the instruments encapsulated by the lander. The half-transparent dark gold casing around some of the instruments depicted is the thermal protection of Aerogel.

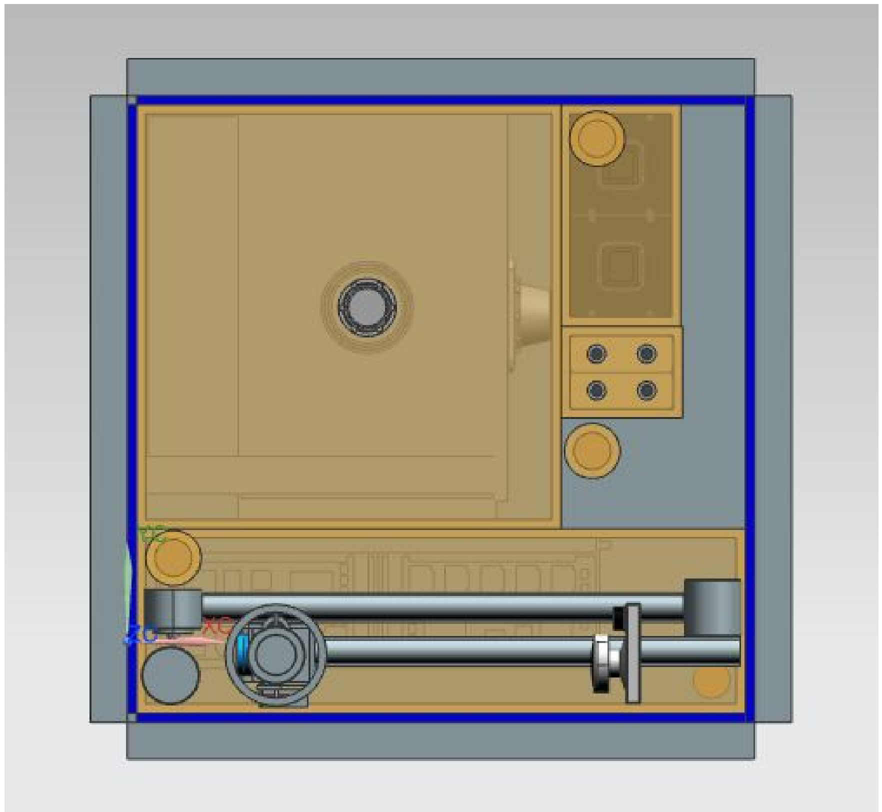


Figure 3.29: Lander and Instruments Deployed, Top View.

The top view of the stowed lander shows how the instruments are to be placed more clearly. Notice, there is some empty space on the right of Figure 3.29 that allows for rearrangement of the instruments if necessary.

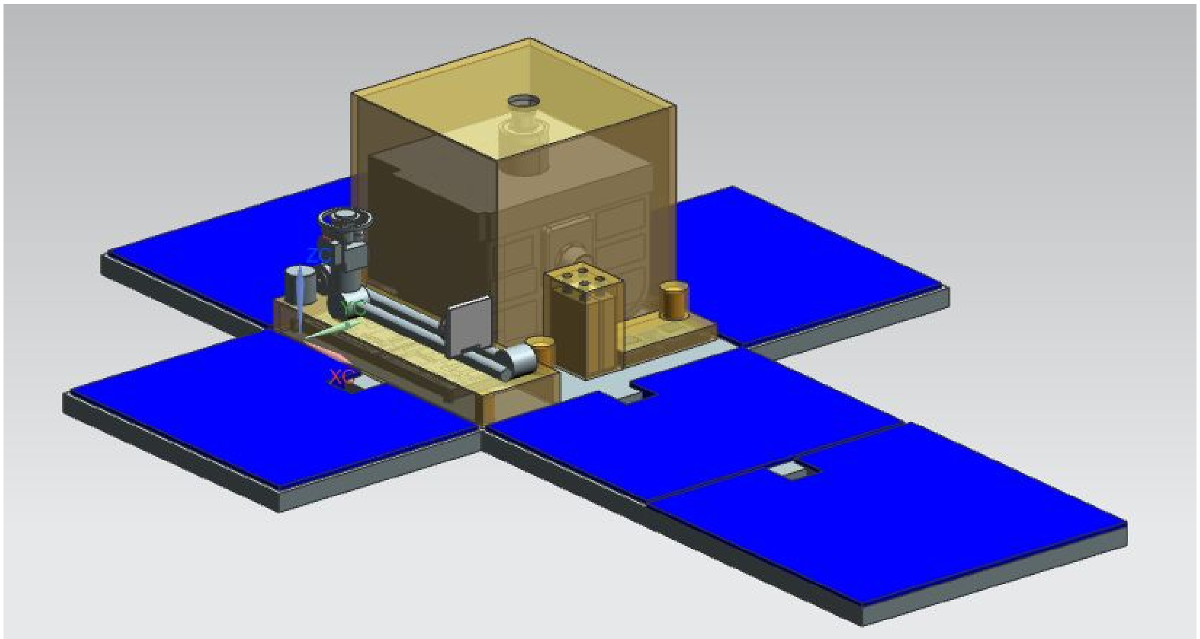


Figure 3.30: Lander and Instruments Deployed, Trimetric View.

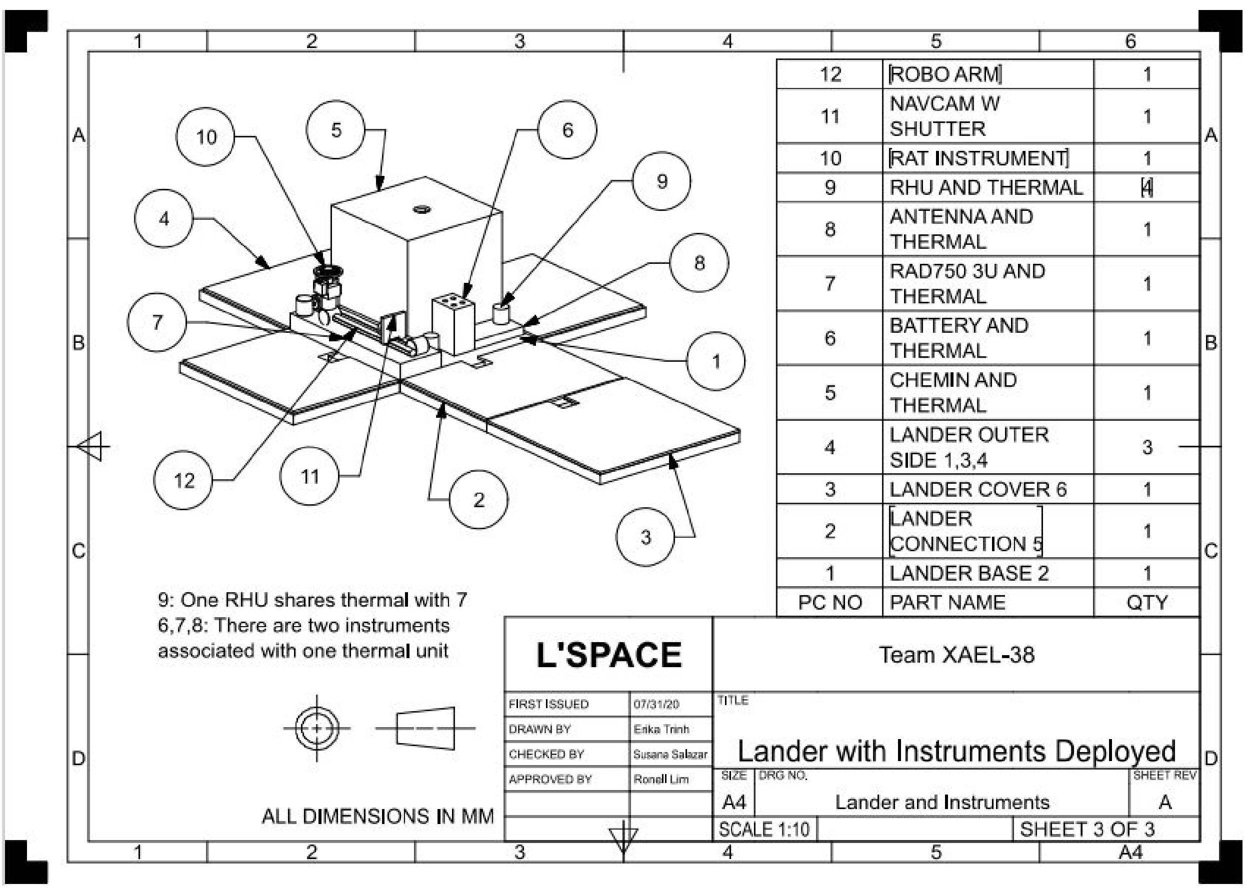


Figure 3.31: Lander and Instruments Deployed Drawing.

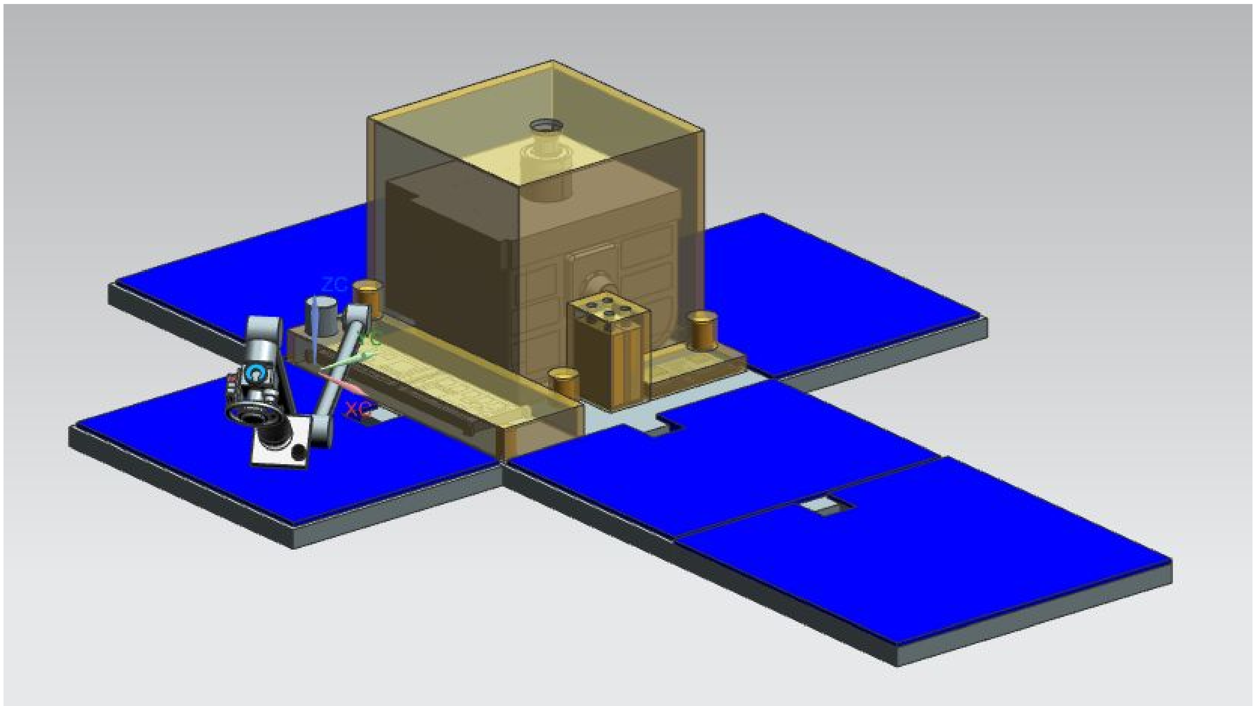


Figure 3.32: Lander and Instruments Deployed with Arm Extension, Trimetric View.

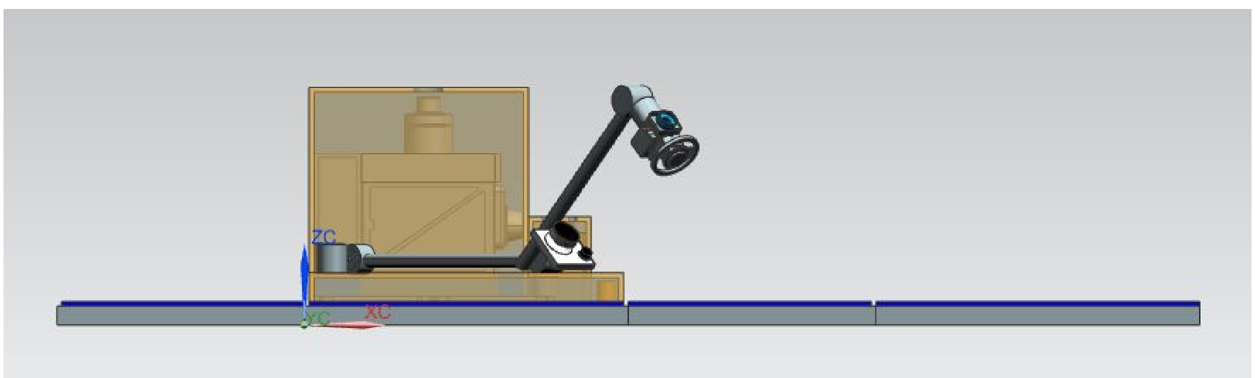


Figure 3.33: Lander and Instruments Deployed with Arm Extension, Left View.

Figure 3.30 shows the lander fully deployed with the instruments. Figures 3.32 and 3.33 show an extension of the arm.

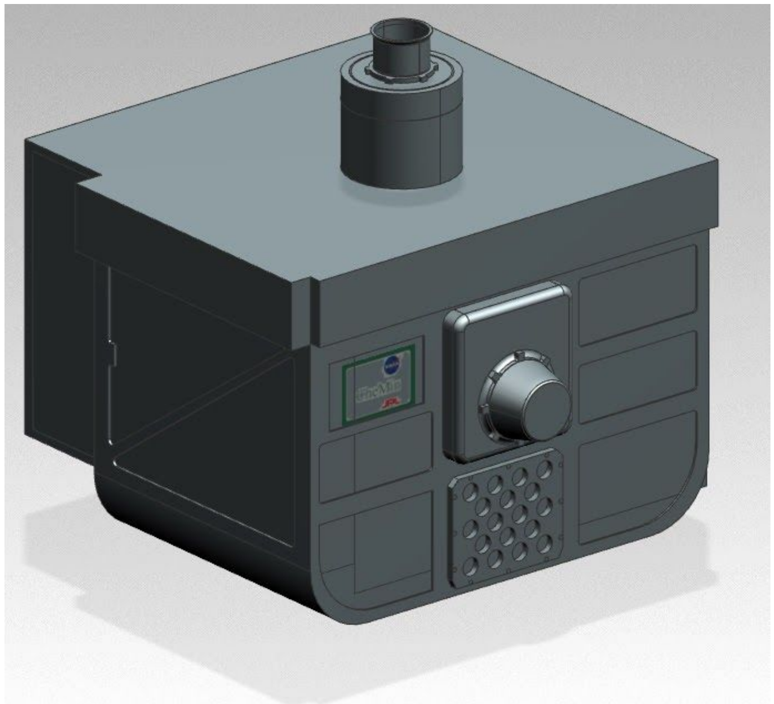


Figure 3.34: CheMin, Isometric View.

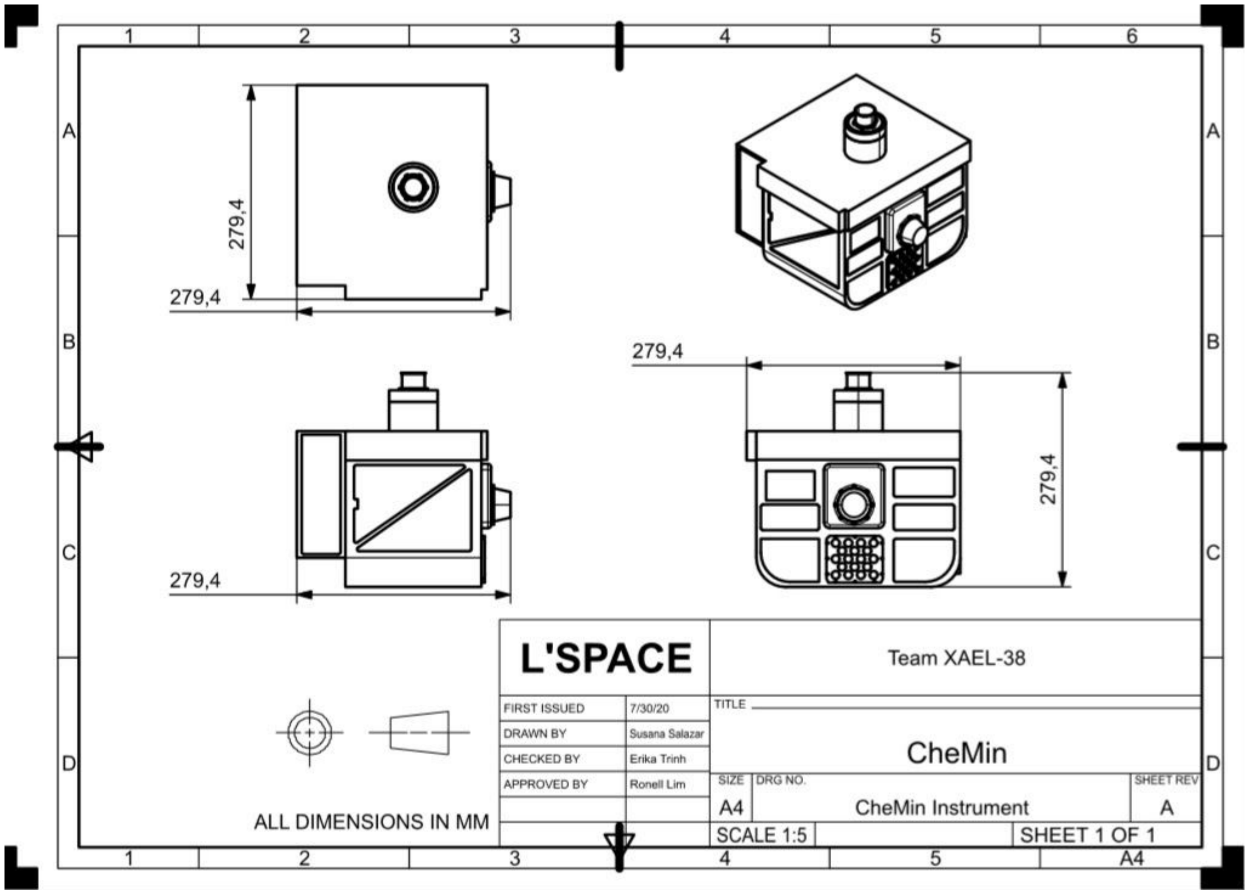


Figure 3.35: CheMin Drawing.

The CheMin had to satisfy a volume of 11 inch x 11 inch x 11 inch specifications, which was converted to millimeters in NX. The dimensions of the instrument itself was unspecified and was modelled in its likeness offered by the picture [15].

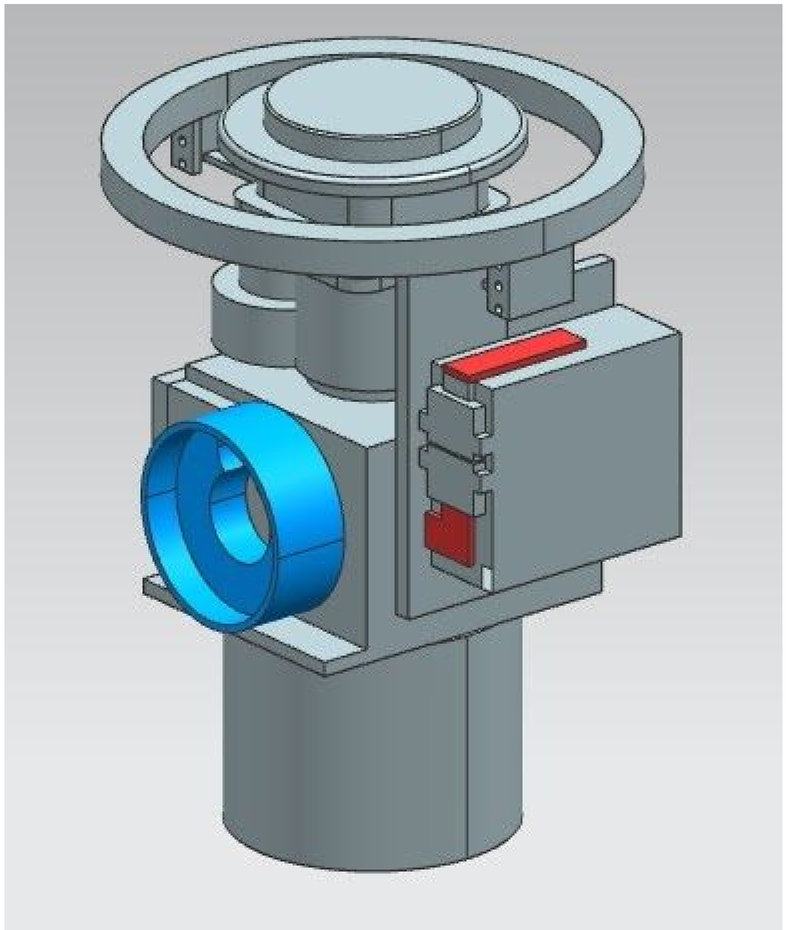


Figure 3.36: RAT, Trimetric View.

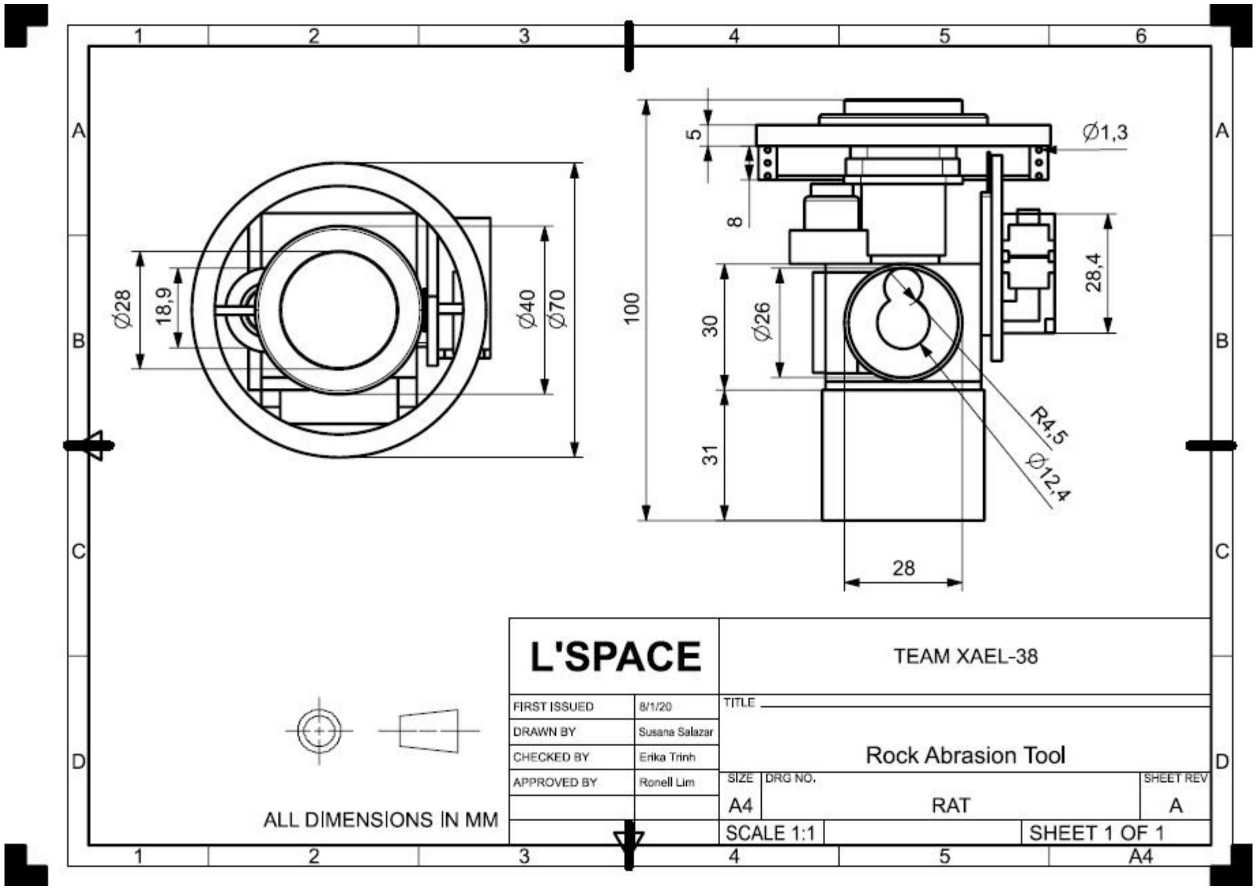


Figure 3.37: RAT Drawing.

The RAT must comply to a 70 mm diameter and a 100 mm length specifications, used on the MER [16].

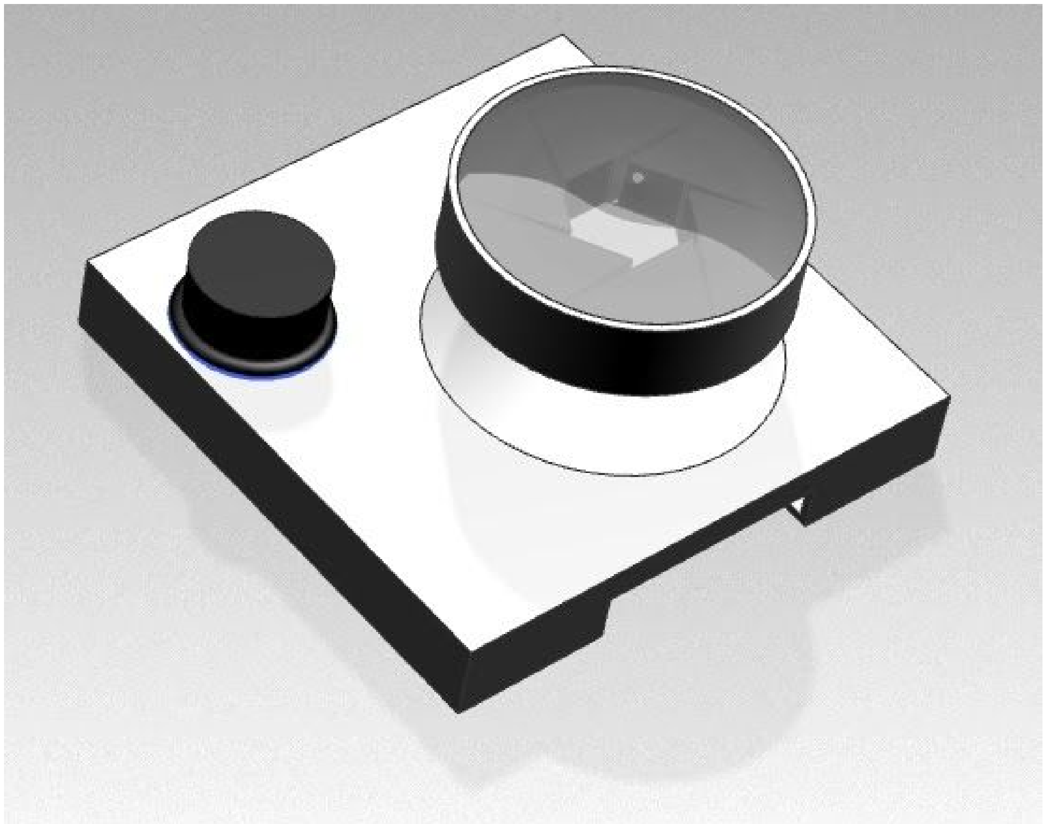


Figure 3.38: NAVCAM, Isometric View.

The shutter type was not specified in the reference photo [17], so a plausible shutter type was modelled for application and visual accuracy of the camera.

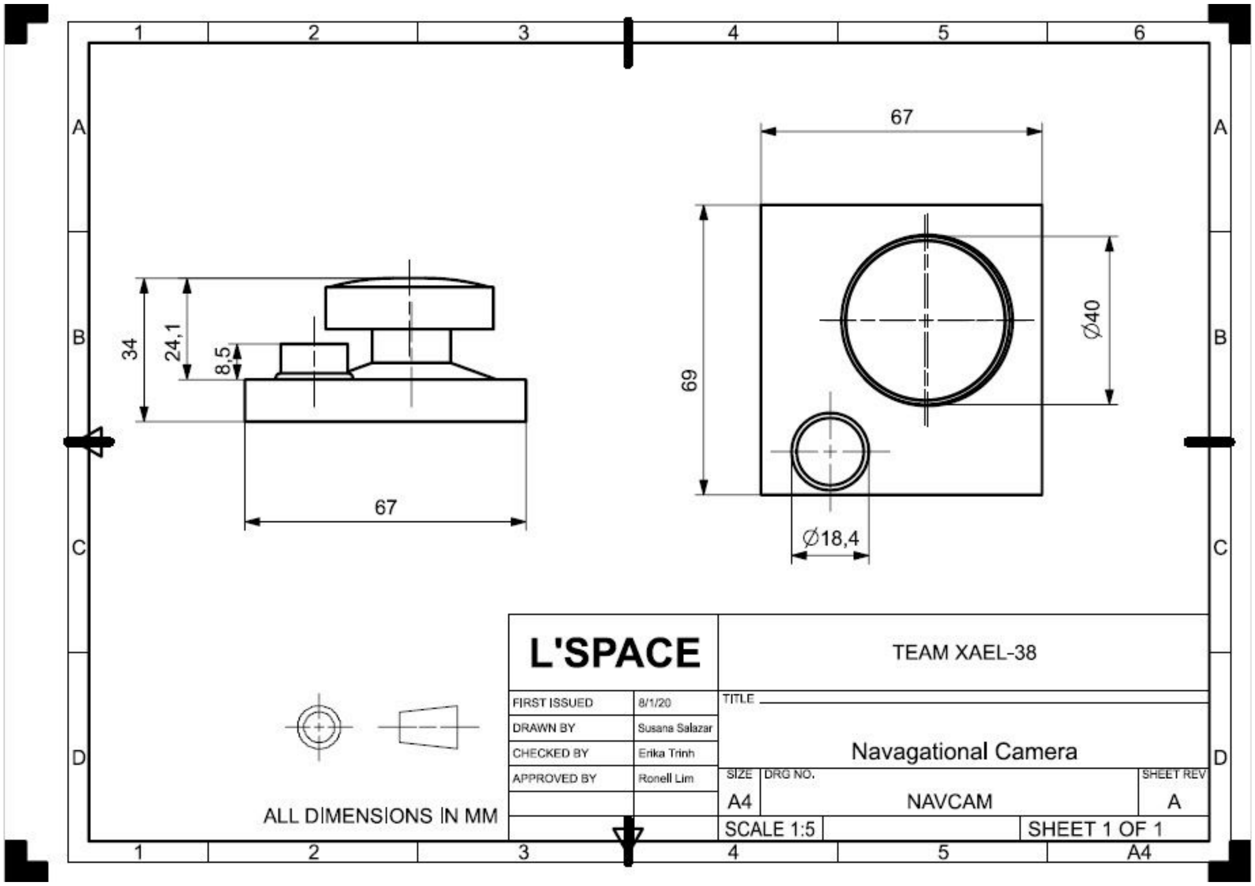


Figure 3.39: NAVCAM Drawing.

The Navcam had to suit 67 mm x 69 mm x 34 mm specifications [17].

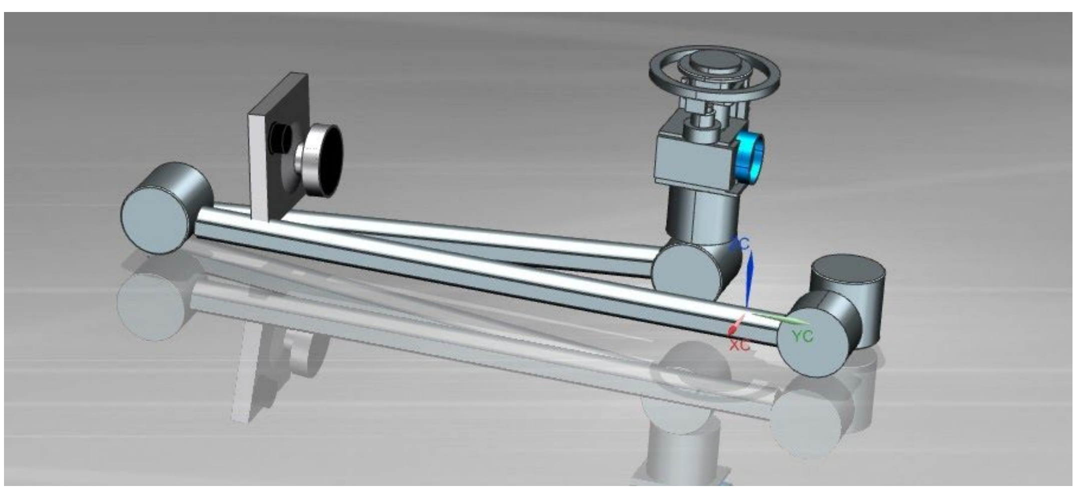
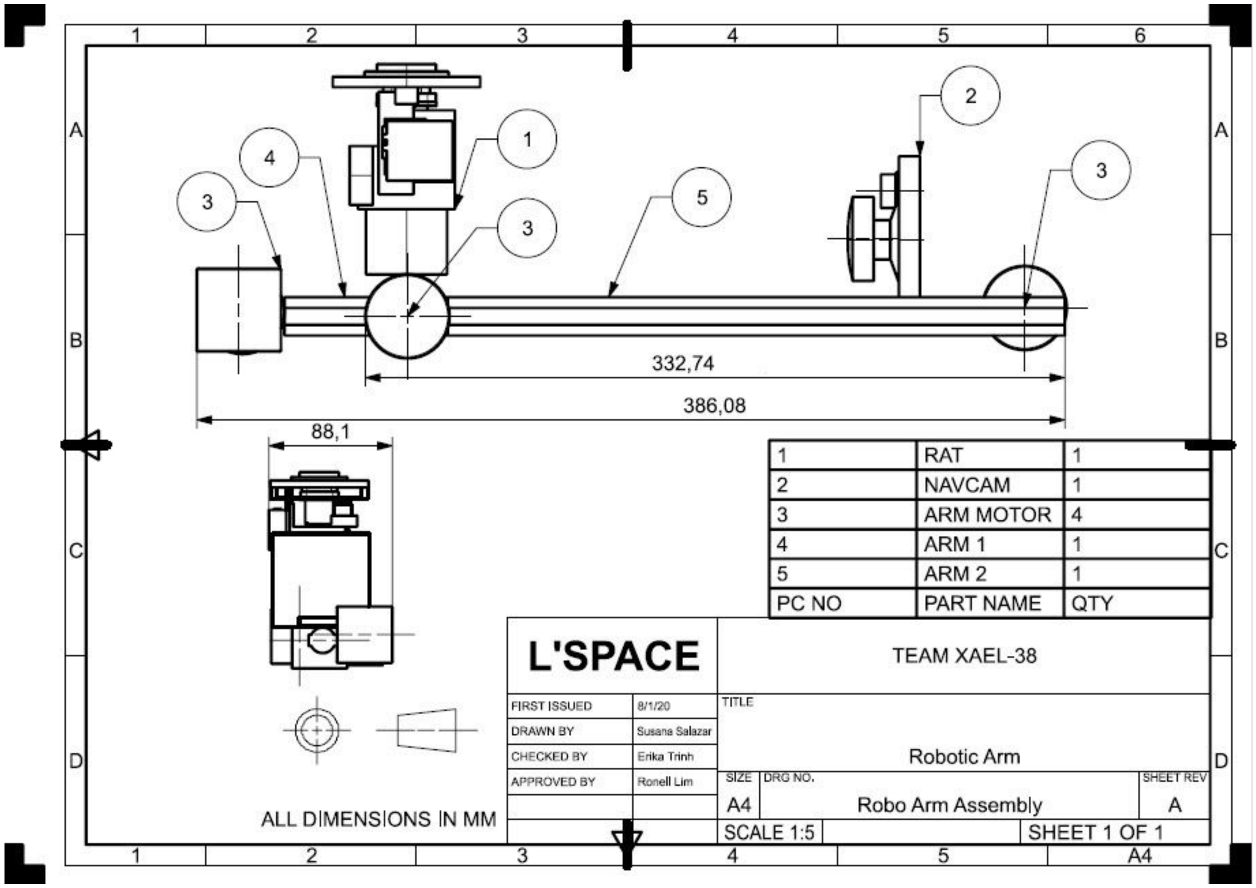


Figure 3.40: Robotic Arm, Unspecified View.

In Figure 3.40, the assembly of the robotic arm is shown. The RAT is attached to the end of the arm and the NAVCAM is positioned on the forearm.



PC NO	PART NAME	QTY
1	RAT	1
2	NAVCAM	1
3	ARM MOTOR	4
4	ARM 1	1
5	ARM 2	1

Figure 3.41: Robotic Arm Drawing.

The Robotic Arm had to suit the upper arm with a length of 367.08 mm and the forearm, housing the RAT and Navcam, with a length of 332.74 mm and a width of 88.1 mm to fit within the lander.

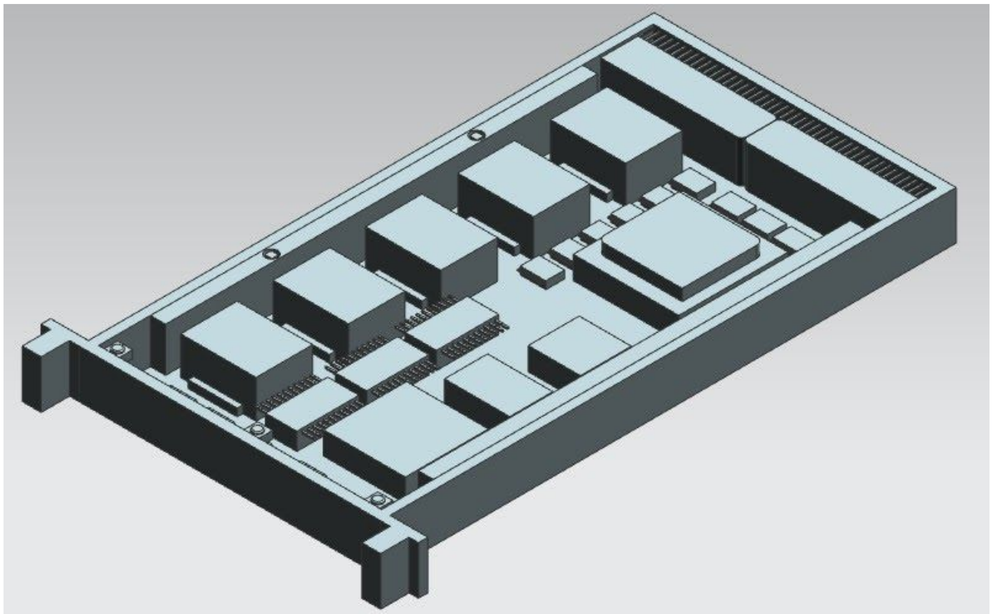


Figure 3.42: RAD750 3U, Isometric View.

The RAD750 3U was also modelled to match the reference visually [18].

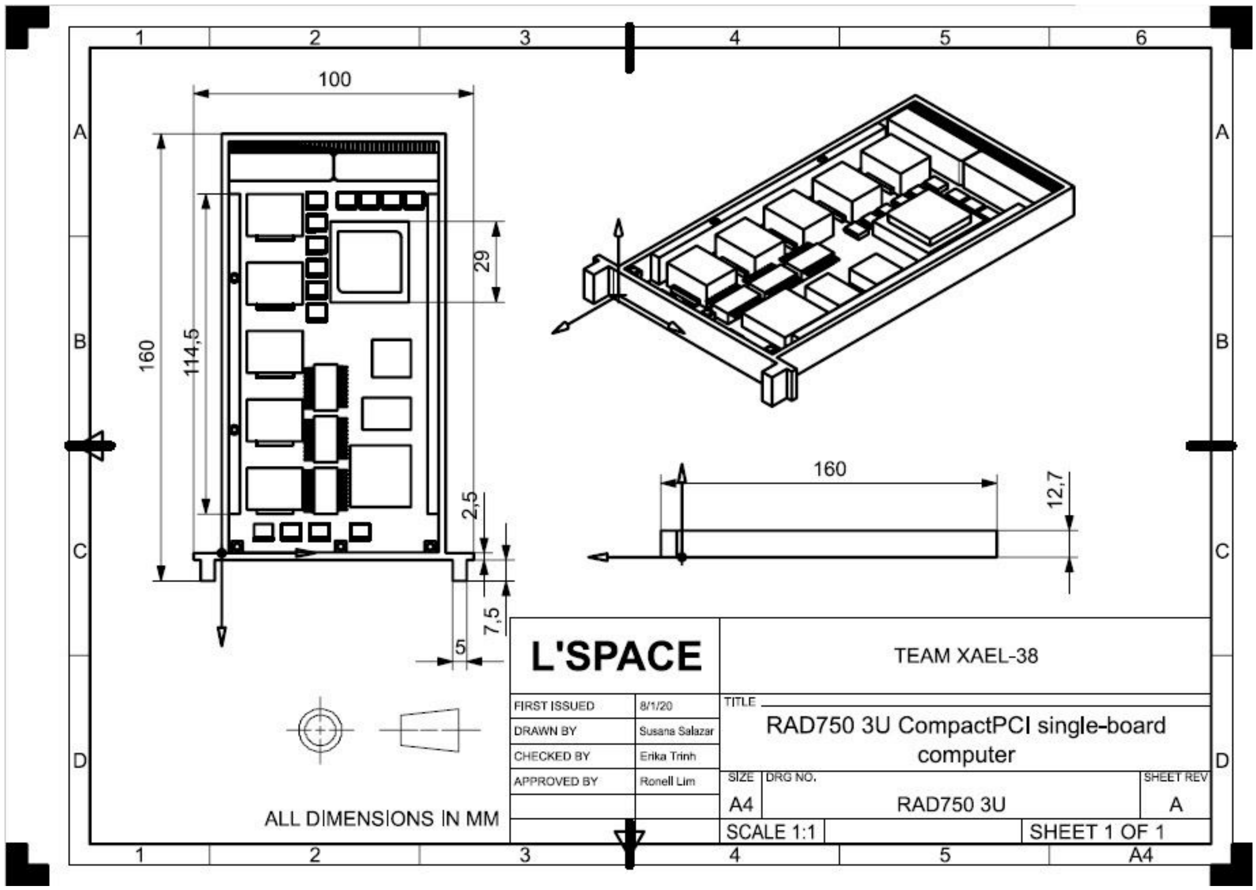


Figure 3.43: RAD750 3U Drawing.

The RAD750 3U was modelled 100 mm x 160 mm x 12.7 mm to match reference visually [18].

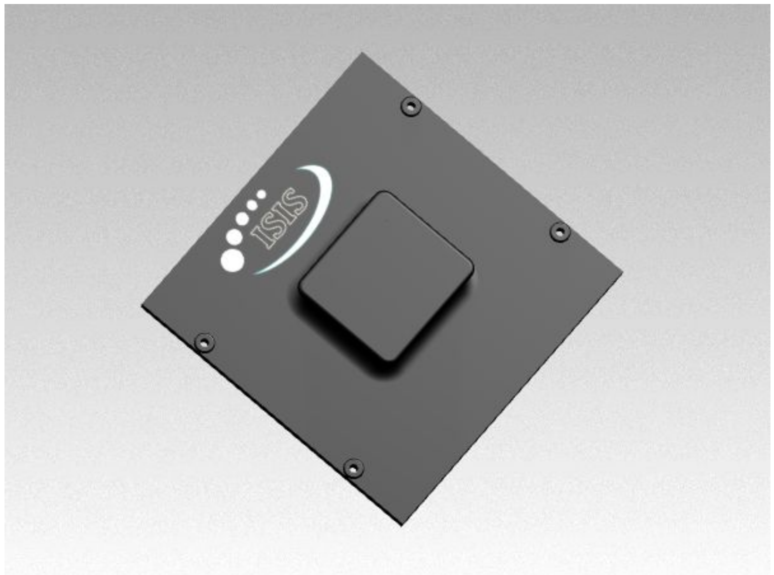


Figure 3.44: GNSS Patch Antenna, Unspecified View.

The specifications of 70 mm x 70 mm x 15 mm were referenced in the spreadsheet of the GNSS Patch Antenna provided by ISIS [19].

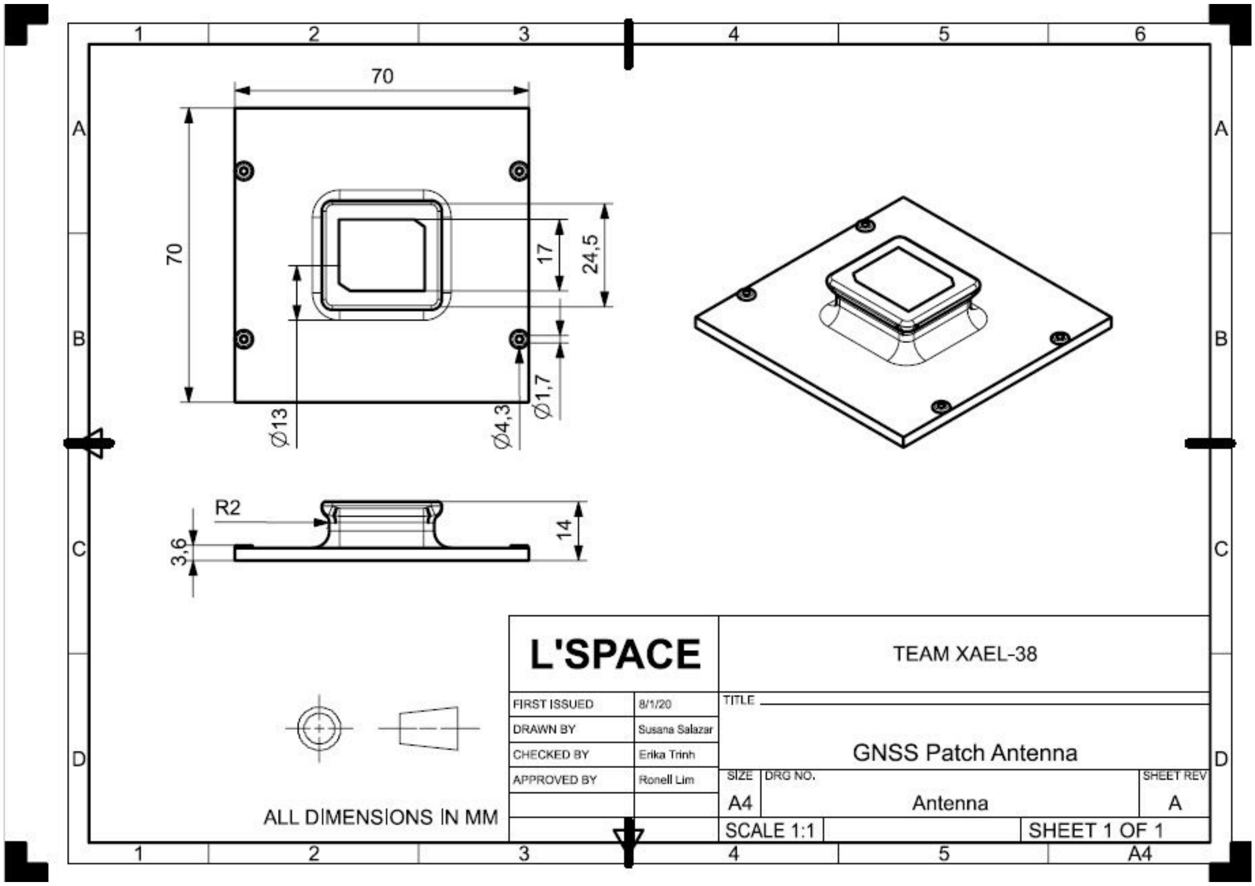


Figure 3.45: GNSS Patch Antenna Drawing.

The specifications of 70 mm x 70 mm x 15 mm were referenced in the spreadsheet of the GNSS Patch Antenna provided by ISIS [19].

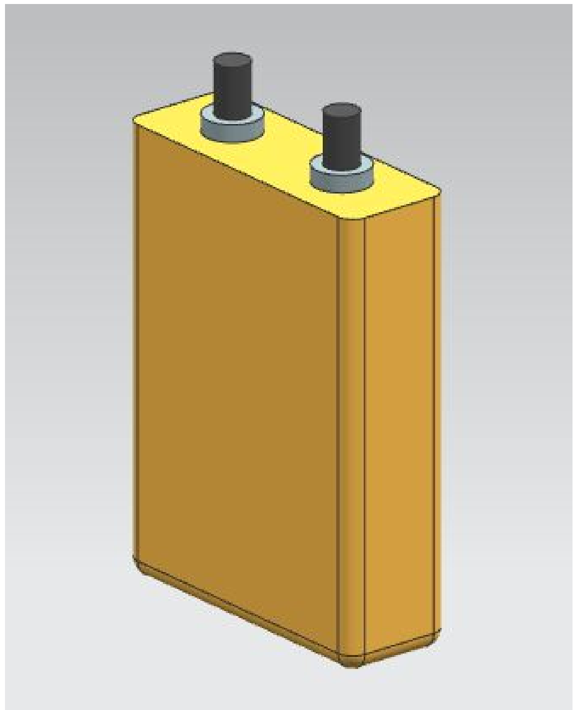


Figure 3.46: 12 Ah Space Cell Battery, Trimetric View.

The model shown in Figure 3.46 was simplified, with the exact dimensions defined in “12 Ah Space Cell” [20]. The Space Cell was modelled for visualization of its volume within the lander.

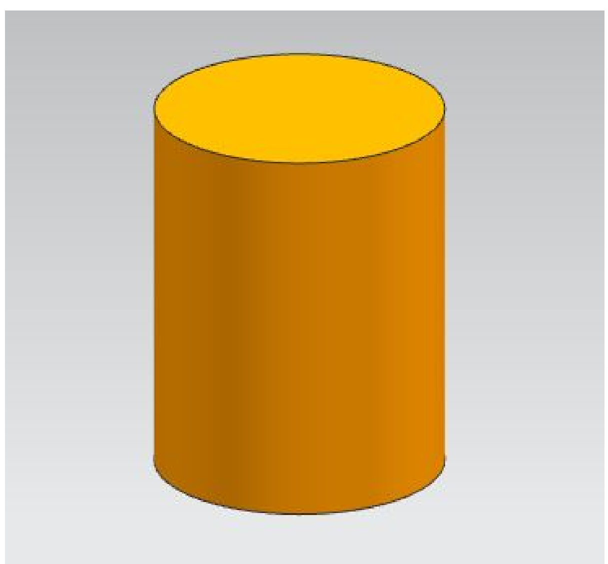


Figure 3.47: RHU, Trimetric View.

The dimensions are defined by “Radioisotope Heater Units” to be 25.4 mm in diameter and 33.02 mm [21] and simplified here.

The thermal protection around the instruments was decided to be 6.35 mm thick. The instruments were covered with the thermal protection individually. Redundant instruments, the RAD750 3Us, antennae, and space cells, were coupled together with the same thermal protection unit.

3.1.4. Manufacturing and Testing

For the EDL, lander, and instruments, NASA will be handling the manufacturing along with outsourcing to private companies. JPL will be the main source for assembly. Manufacturing is heavily reliant on the number of workers employed for such a mission. NASA has recently been in the market for using commercial parts rather than MIL-SPEC, or military defense standard parts, in order to reduce costs, obtain state of the art technology, and reduce production time [22].

According to Precision Castparts Corp Project Manager Lanel Wolff, the amount of time that it took to create backshells for airplane cast parts were typically around 2-3 months for their customers like Boeing and General Atomics [23]. Other parts that would be needed for the creation for the mission would be actuators, manifolds, reservoirs, and solenoid values. An aerospace company like Pneudraulics can typically make such products to customer specifications within 3-9 months depending on sizes [24].

As for the electronic components that are required for the EDL and lander, a company called HiRel Connectors is specialized in sending out numerous components and wirings in less than a month. HiRel Connectors has shown to be reliable as they have worked on NASA’s Orion space program in creating high density connectors [25]. To create the electronic components needed for our mission, the machinery department in HiRel uses a lapping room to create rubber inserts. Over 500 parts can be done in an hour. After inspection through scoping, the parts are sent to the Environment Assembly department for plasma treatment. The entire process for the plasma treatment for over 500 parts at HiRel can take about 1-2 hours. Cartilage clips can be produced in high quantities in a short amount of time. 3500 pieces can take about one hour to create into a roll and then another hour for removal. The assembly for 300 connectors can take about a month to complete.

This machine is additive manufacturing, essentially an industrial 3D printer. In order to reduce production time on large parts, using the EOS M 400 would be a good way to reduce time into production. The EOS M 400’s volume constraints are 400mm x 400mm x 400mm [26]. No tooling is needed while using this machine. It can reach up to four times more productivity than regular manned machinery. It can cut the time off of creating and manufacturing products.

There is not much public information to how manufacturing companies produce their products. As such, the government may have limited insight into how these parts are designed and does not control changes a manufacturer may make to a part's design or manufacturing process. Generally, information about commercial-grade parts is limited to published material and any other information the manufacturer is willing to release [27].

According to Mark Alder, Mars Exploration Rover Spirit Mission Manager, the time frame between conception and launch of Opportunity and Spirit rovers took 1163 days or about 3.2 years [28]. The EDL and lander being proposed are significantly smaller. With new technology like the EOS M 400, production time can be cut. An estimated time for overall production would be 2-2.8 years [28].

The critical systems to conduct a simulation or test here on earth are the EDL and stationary lander. The EDL has various components that require field testing to prove that the material and structure will survive the descent to Mars. Due to the small scaling of the Nano-ADEPT, or heat shield, a Sounding Rocket Flight Test using the scaled configuration will need to be conducted. A Sounding Rocket test here on earth can provide us data on the drag coefficient of the deployed state during the supersonic and subsonic descent. This will demonstrate the ability to deploy during the separation from its orbiter. The test will be conducted by attaching the Nano-ADEPT and Disk-Gap Band parachute onto a sounding rocket which will send the deployable heat shield into space and will fall back to Earth [29]. The data is collected by telemetry links which assist in transferring the data from the Nano-ADEPT to the ground control. The expected data are the drag coefficient of the Nano-ADEPT and parachute in order to find an accurate ballistic number during the descent. Current drag coefficient used in the Ballistic Number, Figure 3.9 of section 3.1.1, is 1.68, referencing the 70 deg cone like shape on MER, and a typical drag coefficient of 1.75 for parachutes [9]. Knowing an accurate drag coefficient will provide data about the ballistic coefficient, thus, knowing a more accurate estimated trajectory during the descent.

For the landing systems, the airbags will require a drop test to determine the deployability and durability of a rocky environment. This testing can be accomplished in the largest vacuum chamber in the Space Power Facility (SPF) at NASA's Lewis Research Center [30]. The vacuum chamber is essential to create a martian atmosphere for the impact drop test of the airbags and lander. Expected results are to know the durability and strength of the airbag and impact on the lander. The drop test is crucial in determining whether the Lander will survive the impact during the numerous amounts of bounces of the airbag.

For the stationary lander, testing of the deployment can be done in a sandy and rocky environment for a more accurate simulation. JPL's MarsYard is a replicated environment of the Mars landscape; the soils and rocks are characterized and placed to match images from previous Martian missions [31]. The lander will be tested on the MarsYard to determine how the deployment system will perform under a martian soil and rock sizes. To test the strength of each side during deployment, the lander will be placed on each side to cover all the potential landing possibilities. In addition, a vibration testing will verify if the payload integration on the Lander is strong enough to withstand the vibration during the bounces of the airbags. Expected performance is a successful mechanism to deploy the payload on any of the Lander's sides while still staying upright at the end.

3.1.5. Validation and Verification Plans

In the early phases,V&V plans are crucial in ensuring that the mission goes as smoothly as possible by validating and verifying that the systems can operate and complete what the system needs to do. Thus, V&V will help reduce any obvious failures that could occur within the system. Critical systems will undergo the V&V plans which include the EDL and Stationary Lander. Within these systems are subsystems that make up the system which will be analyzed below. The validation will include R&D to ensure the system will meet the requirements of the mission. The verification will assure the system will work a million miles away.

The V&V plans for the EDL will focus on the critical subsystems such as the deployment of heat shields, or the Thermal Protection System (TPS), parachute, rockets, and airbags. During the entry of Mars' atmosphere, the spacecraft will be engulfed with a massive heat load. To prevent failure due to heat, the TPS will be required to go through a rigorous testing to verify survivability in Mars Atmosphere. An important verification will include a heat simulation test in the Interaction Heating Facility (IHF) at Ames Research Center [32]. IHF will provide a heating simulation similar to the entry of Mars' atmosphere. This test will determine the durability of the material of the heat shield and the heat flow for the shape of the Nano-ADEPT. To verify that the heat shield will deploy millions of miles away from earth, an IMU will analyze the systems acceleration and orientation of the body. A solid memory will include all the steps for deployment, working alongside the sensors built in the Nano-ADEPT. The same subsystems will also verify the deployment of the parachute and airbags. The IMU will confirm the deployment of each system by observing a large reduction in acceleration. To validate the EDL, a prototype or scaled model will be developed and tested for the aerodynamic profile of the EDL configuration. This will help assure proper trajectory and velocity during the descent through Mars' atmosphere.

The parachute, rockets, and airbags will be validated through testing for durability and functionality. The parachute will need to be deployed at a high speed of 275 m/s, shown in Figure 3.9 of section 3.1.1. The speed at deployment will determine whether the parachute will tangle or deploy properly. The deployment test will also look into the durability of the parachute material. For the rockets, a vibration and activation test will be required to determine the force and deployment system. For the airbags, a verification would be to do the Sounding Rocket test,mentioned in Section 3.1.4. To validate that the system will deploy, an accelerometer integrated on the Nano-ADEPT will be used to initiate the deployment. A testing for the durability of the airbags will occur by dropping the airbags at various heights and velocity on a sharp or rocky landing environment. Providing these verifications are necessary to ensure proper deployment for the system.

3.1.6. FMEA and Risk Mitigation

Failure Mode and Effects Analysis Worksheet

Process or Product: All Components **FMEA Date:** **08/01/2020**
FMEA Team: Erika Szaldobagyi and Ronell Lim
Team Leader: Erika Szaldobagyi

FMEA Process

Line	Component	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Controls, (Prevention)	Current Controls, (Detection)	Detection	RPN	Recommended Action
1	Parachutes	parachute entangles	gets stuck	6	deploys wrong	2	parachute is well packed in the container.	electrical trigger	2	24	
		fails to deploy	speed increases	8	mechanical failure	4	correct programming	acceleration sensor does not decrease	3	96	
		parachute tears apart	hole in fabric	7	atmoshere dangerous	3	stronger fabric	acceleration sensor does not decrease	3	63	
		puncture	hole in fabric	5	sharp rock	2	durable material	pressure gauge	3	30	
2	Rockets	fails to deploy	not soft landing	6	mechanical failure	2	testing before mission	electrical trigger	3	36	
		stalls during ignition	slower landing	5	gets stuck	3	practice reactions	pressure gauge	3	45	
3	AirBags	fails to deploy	hard landing	8	mechanical failure	4	testing before mission	electrical trigger	4	128	run several simulations before mission
		tears apart	rough landing	7	due to weather	2	strong fabric	pressure gauge	4	56	
		punctured airBags	hole in fabric	6	due to impact	3	durable material	pressure gauge	4	72	
4	Nano-ADEPT	fails to deploy	could crash	9	mechanical failure	4	strong material and testing	avionic sensors	4	144	add stronger material for deployment
		punctured heatshield	heat up faster	7	materials bad	1	strong tested composite material, SLA 561V	avionic sensors	5	35	

Table 3.2: FMEA EDL Worksheet.

Failure Mode and Effects Analysis (FMEA) charts are used to determine the most critical components that need to be mitigated. Shown in Table 3.2 are the components for the EDL system. The chosen risk priority number (RPN) was 100 and up. Therefore, the critical component is the airbags and Nano-ADEPT. A failed deployment of the airbag is dangerous to the EDL system; the payload would crash and have no impact absorption. The recommended action is to run several simulations of the deployment system for the airbags. Numerous testing of this system will help reduce the failed deployment. Similar to the airbags, a deployed Nano-ADEPT is crucial in providing enough surface area during the descent. Therefore, a failed deployment for the Nano-ADEPT can potentially crash the whole spacecraft. A recommended action is to add stronger material for the deployment system or various deployment testing.

3.1.7. Performance Characteristics and Predictions

The performance characteristics are crucial in proving that the system can operate and survive under the Mars environment. The landing season will be during the Southern Hemisphere spring/summer During this season, various weather obstacles can occur on Mars that can be detrimental to the instruments or systems of the payload. These obstacles or conditions include the potential dust storms, like tornadoes, that could cover up the lander's solar panels with dirt [33]. Due to the low cost and low volume budget of the mission, the system has no system recovery for a dust storm. In the event that the solar panels are covered in dust, the rechargeable batteries will be utilized to provide enough power to turn on and off the system, and survive the dust storm.

In addition to the dust storms, the surface of Columbia Hills is rocky. To make sure the EDL lands safely, the airbags are tested and made of durable material to prevent any punctures during the impact landing. These airbags have been successful in landing small to medium sized rovers on missions such as MPF. The material chosen for the airbags are Vectran due to its durability and effectiveness in colder conditions [11]. This will ensure the material will survive in the temperature condition and landing impact of the rocky surface.

During the descent, temperatures can reach a high temperature and at night temperatures can reach to below freezing. To mitigate this temperature obstacle, the system will include thermal protection, aerogel and gold paint to protect from the extreme heat during the descent. During the freezing temperatures, the system contains a RHUs placed inside the lander system to radiate onto the systems, such as the antennae, and computer boards. The RHUs will keep the lander system warm to last the freezing night of Mars’ environment.

Mars' atmosphere is thinner than earth, so the EDL decent system is designed to maximize the surface area of the body to further reduce the terminal velocity at each deployment in the EDL phase.

The lander’s internal components must also not only be resistant to the harsh Martian environment, but also survive transit through a highly radioactive space environment. Both the RAD750 3U computer and the GNSS Patch Antenna are manufactured by third-party vendors with space deployment in mind. The RAD750 3U withstand a total radiation dose of >100 Krad (Si) before risking corruption. In addition, the model is advertised as latch-up immune, with general single event upset (SEU) of 1.9×10^{-4} errors per day from ionizing particle events. As this model family has been used extensively in previous successful NASA missions, this metric seems to be reliable [34]. On the other hand, the GNSS Patch Antenna, designed for CubeSats in Low Earth Orbit (LEO), does not list special radiation protection, but also does not have as sensitive components [19]. The risk of radiation damage to the antenna is negligible with radiation protection provided by the NASA satellite responsible for ferrying the payload to Mars, shielding the payload during the highest radiation exposure time in open space.

The RAD750 3U and GNSS Patch Antenna can operate safely in a range from −55°C to 70°C and −30°C to 70°C, respectively. Although the average temperature of Mars lies around −63°C, the lander will be kept within operational temperature by the thermal subsystem at all times. The internal temperature of system components will also be managed by the computer to ensure optimal working conditions and maintain system integrity [18].

The mission success criteria is broken down to the EDL, lander, and science mission criteria. The level of success for the EDL is to separate from the cruise separation, deploy the expandable heat shield, deploy the parachutes, survive the impact drop of 25 m/s, and make sure the payload is deployed on the upright position. The lander criteria is to confirm the lander has landed and deployed on the upright position. These criteria include knowing which way is down, commands to open the correct sides of the lander, and a confirmation using the NAVCAM to take pictures of the landing site. The science mission criteria is to confirm the data acquisitions meets the science objectives. The science objective is to obtain a controlled sample and compare its results to the new samples gathered on Mars.

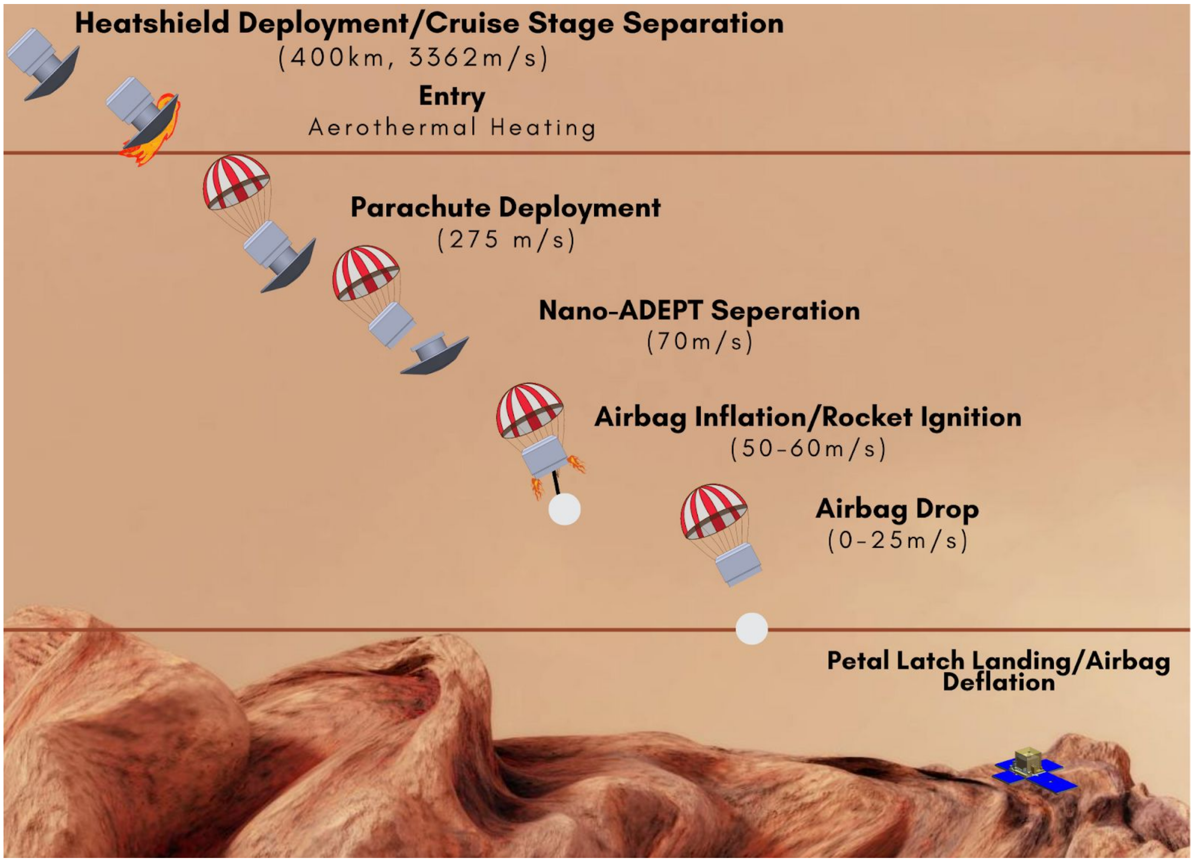


Figure 3.1: EDL Graphic.

The EDL begins at the cruise stage separation as shown in Figure 3.1, and shown again, above. Before the cruise stage separation occurs, the heat shield is deployed at around 400 km above Mars surface. This height will result in a speed of 3362 m/s or hypersonic speed. The heat shield will endure the entry with the Nano-ADEPT aerothermal heating system. As the payload reaches terminal velocity of 275 m/s, or at subsonic speed, the mortar will deploy a 4.5 meter wide parachute. As the payload descends to a descent velocity of 70 m/s, the Nano-ADEPT will separate. The airbags will inflate and tether. The rockets will ignite to further reduce the descent velocity to less than 25 m/s. Once the velocity has reached around 25 m/s,the airbag protecting the payload will be cut and dropped onto the surface of mars. The airbag will absorb the impact of the drop. As the airbag safely positions itself on the surface, the lander system will deploy the “petal” latches to expose the science instruments. Finally, once an image is taken by the NAVCAM and is sent to the COMM Package, the EDL and lander mission criteria will be complete.

3.1.8. Confidence and Maturity of Design

The designs changed according to the required science instruments needed to fulfill the science mission objective. The team's first designs consisted of a rigid EDL and a rover to obtain soil and rock samples around Columbia Hills. The rover would have had extendable legs with wheels to provide enough clearance during the surface exploration while being able to be compact. For the EDL, the initial design referenced the previous successful EDL systems such as the 70 degree sphere-cone aeroshells from Viking heritage [9]. However, the design needed to change due to the volume constraint; the rigid shape would not provide enough ballistic coefficient of 100 kg/m^2. Compared to the size constraint of Viking of 3.505 meters, DAEMONES would only have a rigid size of 0.9652 meters [1]. The significant decrease in size would require the utilization of new technology to provide a large heat shield. Therefore a mechanically deployable heat shield called Nano-ADEPT was chosen. The new design implemented the Nano-ADEPT with a backshell. The target deployment of 1.2 meters, shown again in Figure 3.9 for ease of reference, was determined by analyzing the relationship of the ballistic number and diameter using equations discussed in Section 3.1.1.

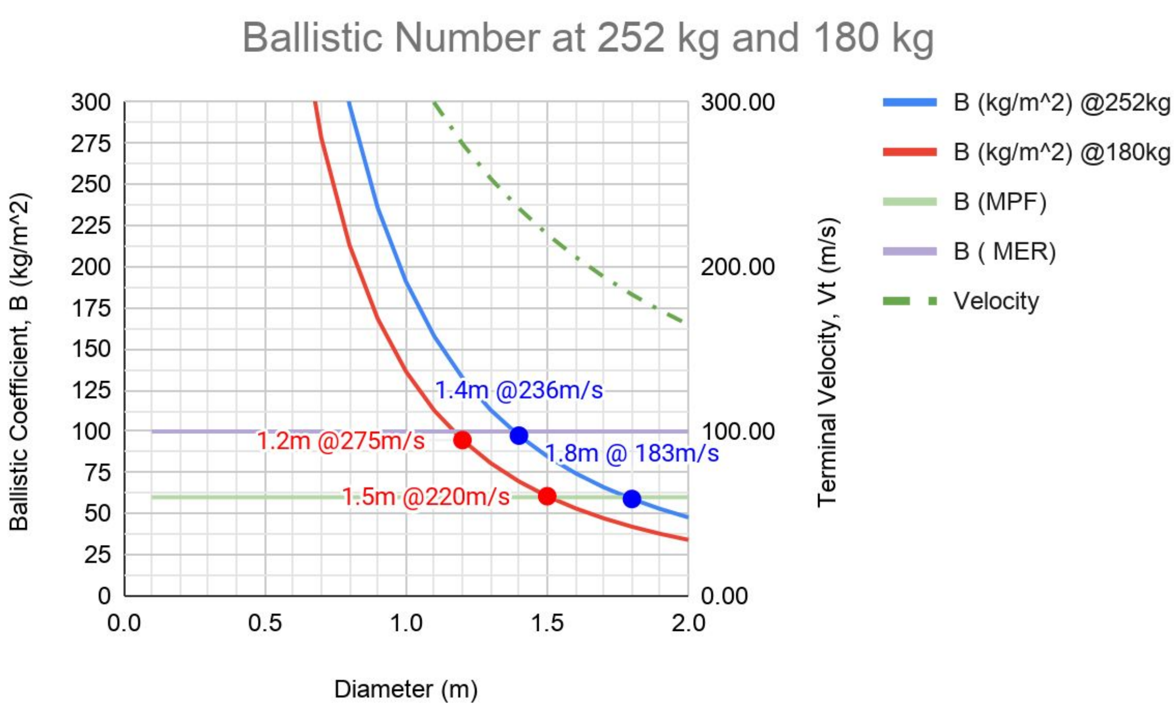


Figure 3.9: Ballistic Coefficient at a Varying Diameter.

Due to the Nano-ADEPT's consumption of half of the volume constraint and the size of the desired science instrument, the rover idea had to be reconsidered. The team discussed the idea of a stationary lander to maximize the remaining volume to implement the critical science instruments. A risk matrix, shown in Table 3.3, was created to make a reasonable decision between the science instruments and designs. The mission objective, design changes, time to implement changes, and unknowns of instrumentation were highly considered during the decision making progress. In the end, due to the critical need for the CheMin to complete the mission objective and time constraints, a stationary lander was decided as the best course of action. In addition, the decision was made due to the high percentage of completeness of the mission objective compared to the percentage of completeness of the rover and stationary lander designs. The alternative instruments that were considered were deemed to be too large or not unique enough compared to the previous rover mission, Spirit [15].

Risk	CheMin	Alternative Instrument
	L=1, C=1	L=2, C=3
Complete Mission Objective	Will complete the objective, no changes.	Have to alter objectives to fit in the new instrument.
	L=1, C=2	L=3, C=1
Design Changes	Will be able to fit with a stationary lander.	Depending on the alternative, a rover can be implemented.
	L=1, C=2	L=2, C=3
Time to Implement Changes	Less to integrate. To rework to a stationary lander means rover design is unnecessary.	More to integrate. Mission objectives will change. A rover design can be implemented in addition to a landing mechanism.
	L=2, C=2	L=2, C=2
Unknowns of Instrument	Research has been done on how the CheMin works and can be implemented with a stationary lander.	Some Research has been done on how alternative instruments work. Still need to figure out how to implement it.
Total	L=5	L=9
	C=7	C=9

Table 3.3: Risk Matrix for Choosing Between CheMin or Alternative Instrument.

In Table 3.3, “L” is the likelihood of the risk to be realized and “C” is the consequences or modification. A lower number for “L” and “C” means a higher chance of realization and little to no modification required, respectively.

Section 3.1.4, discusses the various simulation testing for the EDL. The important EDL simulation testing includes the sounding rocket to test the Nano-ADEPT and parachute deployment. This test is critical in finding the aerodynamic profile and drag coefficient. The Nano-ADEPT will also go through a heating stress test to find whether the heat shield will withstand the entry to Mars Atmosphere. Other tests mentioned are JPL's MarsYard environment to test lander deployment on the soil and rocky environment like Mars. To ensure the system will work in the conditions of Mars, each internal component of the lander will be put through rigorous functional and physical stress testing as mentioned in Section 4.1.4.

Especially sensitive components such as the computer and antenna will also undergo additional radiation and thermal checks to ensure they can survive the trip to Mars and properly operate on the surface. NASA is also expected to adequately test their transport satellite including its ability to provide compartmental radiation protection for the mission's lander payload. This process must also encompass the backup modules of the computer and antenna due to their importance in managing other subsystems.

3.2. Recovery/Redundancy System

Redundancy or a recovery plan is critical; in the case that one component fails, there is a back up component to recover the system. Due to the budget for cost, volume, and mass the payload will have a limited recovery or redundant system. Looking at the current payload, the most critical component is the communication system to ensure data is being sent back to mission control.

Redundancy and a recovery process for the computer and antenna had high priority due to their function in ensuring all other subsystems can operate. The RAD750 3U has built-in error handling to mitigate memory corruption or system level error. Upon detecting an error, if it could not be mitigated by the operating system, then a complete restart is initiated that will flush the cache and memory to correct the issue. An additional identical computer is fitted to replace the first iteration in the event of hardware failure. A monitoring service provided by a chip outside the computer will check for infinite loops or other fatal errors within the main computer, and send a signal to the failsafe switch (implemented as a logic gate) to redirect all internal wired communication to the backup computer. The same chip will also attempt to send an error code to the control center via the antenna to notify of failure. The lander includes two copies of the antenna, and its redundancy system is similarly designed. The GNSS Patch Antenna's compact form, low profile, and simple function makes it unlikely to be damaged from use or the Mars environment; however, another iteration of the antenna was included due to its importance in being able to contact the lander.

3.3. Payload Integration

The CheMin is placed in close proximity to the arm to allow samples collected by the RAT at the end of the arm to be moved and funneled through the CheMin inlet for analysis.

The decision was made to place the arm closer to the side of the CheMin to provide greater coverage of the visible surface area of Mars. In Figure 3.46 below, details the possible placements considered.

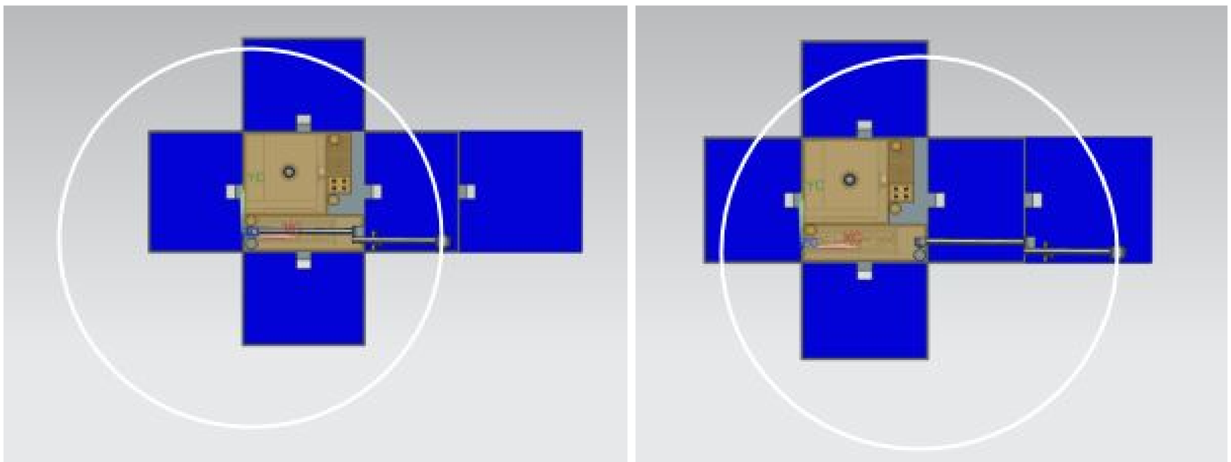


Figure 3.48: Arm Extension Radius.

Figure 3.48 shows the arm stationed on the left of the lander (left) and to the right of the lander (right). Here, the gray background represents the surface of Mars. The white circle illustrates the radial coverage of the arm fully extended. The surface of Mars encompassed by the circle indicates the area the arm is able to reach. Both positions have parts of Mars' surface obscured by the lander when it is deployed. However, the arm stationed at the right has an additional lander side that covers the surface and is unreachable by the RAT at the end of the arm. Therefore, the placement of the arm is made to the left of the lander for maximum coverage of Mars' surface for sampling.

The arm is placed on top of the thermal protection of the RAD750 3Us to allow for a greater ease of movement of the arm to collect samples.

There are four RHUs dispersed around the lander to produce heat to the instruments in Mars' cold environment. They are located by the RAD750 3Us, antennae, and space cells, with the last in the same thermal unit as the RAD750 3Us opposite the other RHU placement, further detailed in Figure 3.49 below.

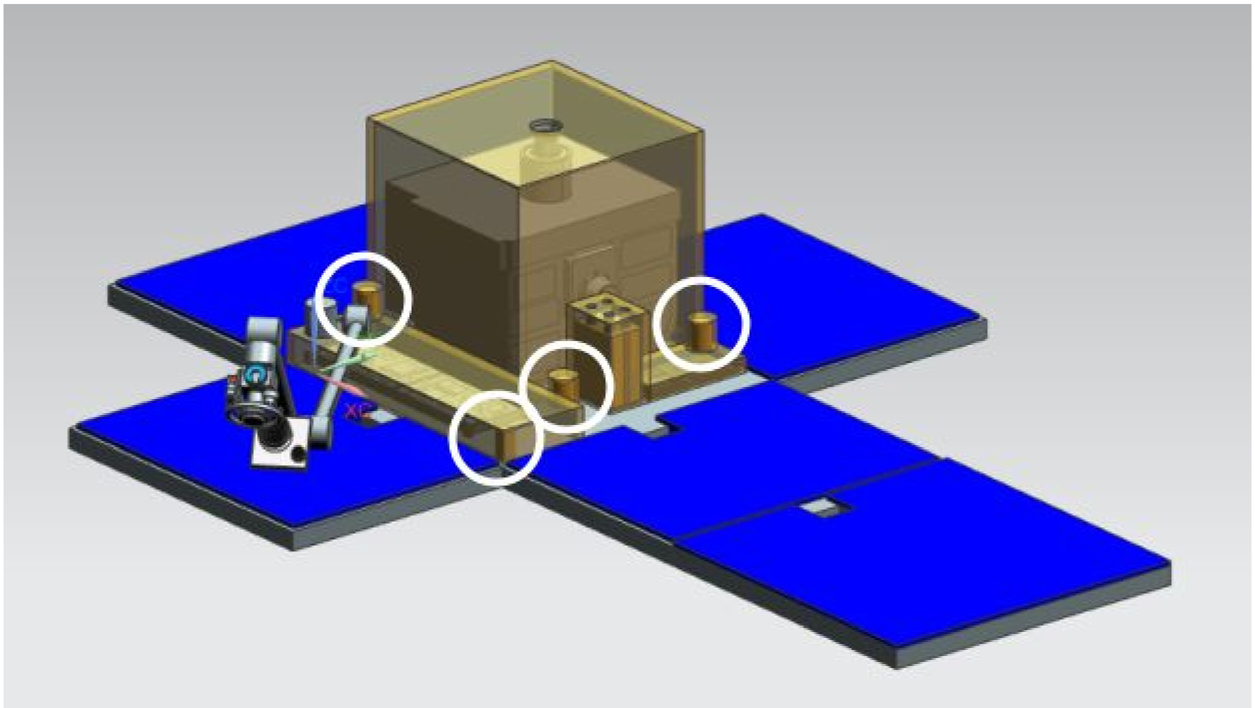


Figure 3.49: RHU Identification.

4. Payload Design and Science Experiments

4.1. Selection, Design, and Verification

4.1.1. System Overview - N^2 Chart

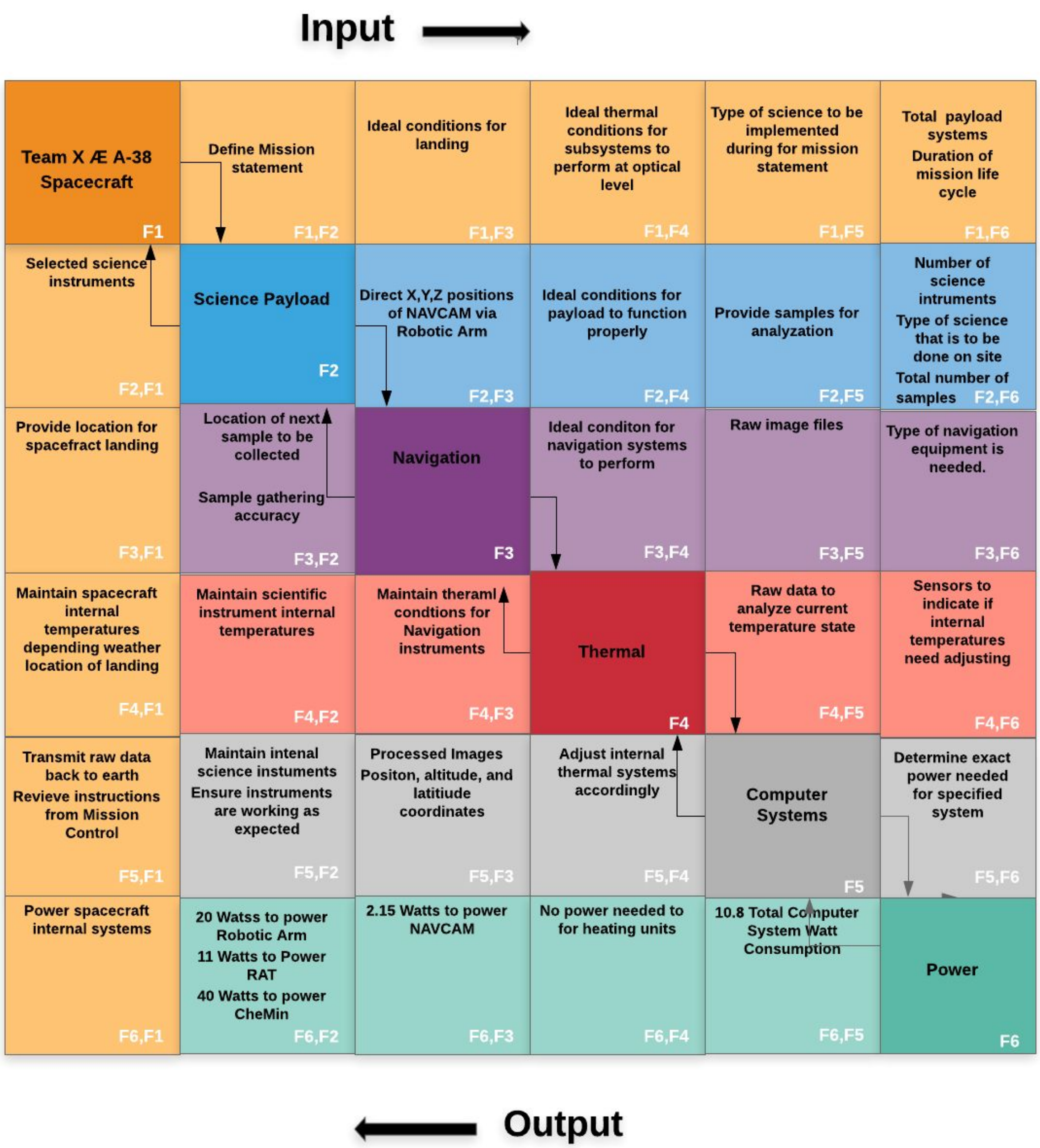


Table 4.1 is a detailed breakdown of the power consumption for each of the components onboard.

Component	Power Required (Watts)
CheMin	40
Electronic Thermometer/Heating Cables	50
GNSS Patch Antenna	0.07
Motors (9)	60
NAVCAM	2.15
RAD750 3U (2)	21.60
RAT	11
Transmitter Package	5
Total	189.82

Table 4.1: Instruments and Power Required.

Table 4.2 is a detailed breakdown of the power provided by each of the power generation components onboard.

Component	Power Provided (Watts)
Batteries (2)	106.02
Solar Arrays	90
Total	196.02

Table 4.2: Power Sources and Power Produced.

The lander's control systems include two RAD750 3U CompactPCI Single-Board computers and two Innovative Solutions in Space (ISIS) GNSS Patch Antennas. The antenna will work with the internal transmission package to receive commands from the control center by contacting a COMM package landed nearby on Mars. The on-board computer will execute received commands, manage and maintain subsystems, gather mission data, and initiate data upload back through the COMM package throughout its operation. The thermal and operational status of the instrumentation and robotic arm also fall within the computer's responsibilities.

The RAD750 3U computer board and GNSS Patch Antenna were chosen for having the best mix of functionality, resiliency, and costs for this mission. One of the driving factors in the controls system design was the ability to communicate with a COMM package landed directly on Mars near the lander. Previous Mars rovers needed powerful antennas with fast buses on the computer since they needed to transfer data directly to Earth or an orbiting satellite within a small available transmission window [34]. The lander did not need as much data transmission speed since, instead of brief liaison with a satellite or Earth passing overhead as Mars rotates through its day, it has uninterrupted contact with the nearby COMM package at all times. Thus, the PCI 2.2 (computer bus built-in on the RAD750 3U) and GNSS Patch Antenna capabilities, while not extensive, balanced power and space consumption with required functionality, and made the smaller, lighter, and less power intensive RAD750 3U the best fit for the constraints of the lander. In addition, both components were specifically engineered to withstand the harsh thermal fluctuations and radioactivity of space [18] [19].

Both third-party sourced components are designed and rated for space environments, however in the event of hardware failure, the extra copy of each critical systems component can continue to provide functionality.

4.1.2. Subsystem Overview

The lander system is centrally managed by one RAD750 3U CompactPCI Single-Board computer produced by BAE Systems. The computer's attributes include a 132 MHz processor providing 2.1 MIPS, 128 MB SDRAM, 256 kB SUROM, and PCI 2.2. This PCI is rated for up to 264 MB/s data transfer, adequately handling subsystem commands in conjunction with the data upload capabilities of the antenna. The RAD750 3U can withstand the harsh radioactive environment of space in transit and landed on Mars, withstanding temperatures between −55 °C and 70 °C and total radiation exposure of greater than 100 Krad (Si) with built-in hardware error verification [18]

The computer is initially booted within orbit of Mars to avoid unnecessary operational wear and power draw in transit. After a systems verification check, the computer enters normal operational mode in which it can actively manipulate wired subsystems as needed for automatic maintenance or through manual control with signals from the control center on Earth. As part of development's programming, the computer would ideally never be powered down completely unless facing a critical OS error or power outage, but the computer may enter hibernation mode during dark periods on Mars' surface when power generation is limited.

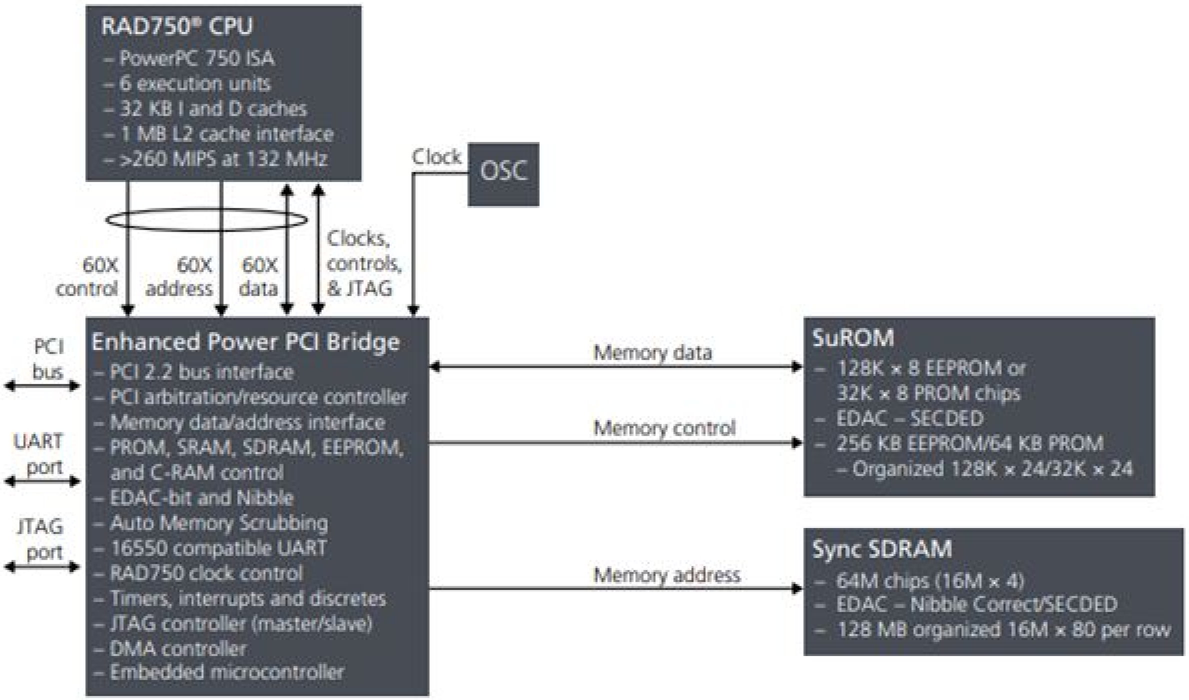


Figure 4.1: RAD750 3U Internal Schematic Layout.

Communication with the lander is facilitated by one GNSS Patch Antenna produced by ISIS. The antenna features 5.5 dBi antenna gain and 34.5 dB signal gain operating at 1575 Mhz (Ultra-High Frequency). While the GNSS Patch Antenna is originally designed to receive GPS signal on CubeSats in LEO (<2,000km) from Medium Earth Orbit (MEO) (>20,000km) [popular orbits 101 replace number], the antenna can be employed to receive data within an atmosphere at a reduced range. With appropriate configuration and deployment location of the COMM package, the lander can establish a strong connection for Earth-Mars communication. The total distance limit will depend on the NASA provided COMM Package’s antenna power.

Parameter	Typical Value	Units
Environmental Characteristics		
Operational temperature	-30 to +70	°C
RF Characteristics		
Frequency Range:	1572- 1578(GPS L1 / GALILEO E1)	MHz
Signal gain (active circuitry)	32.5	dB
Antenna peak gain	5.2 (1575 MHz)	dBi
Axial ratio	< 3	dB
Return Loss	> 15	dB
Bandwidth	6	MHz
Polarization	RHCP	-
Physical Characteristics		
Mass	18	g
Dimensions (H x W x T)	70 x 70 x 15	mm
Connector type	MMCX (for both RF and power line-female)	-
Antenna material	Ceramic	-
Electrical Characteristics		
Supply voltage	3 - 5	VDC
Current consumption	9.5 (at 3.5 V)	mA

Table 4.3: GNSS Antenna Specifications [19].

	Strength	Corrosion/Weather Resistance	Durability
Aluminum 2195	2	2	3
Aluminum 2024	4	3	4
Aluminum 7075	5	4	5
AS4C	4	4	4
AS4D	5	4	4
AS7	5	4	4
HM63	5	5	5

Table 4.4: Lander Materials Decision Matrix.

The materials for the structure of the lander need to be strong, durable, and particularly weather/corrosion-resistant, due to the extreme weather conditions on Mars. Aluminum 7075 was chosen as the supportive material for the beams of the lander, due to its high strength and wide use in aerospace structures [35]. The face panels of the lander are made of a HM63 carbon fiber-HexPly 8552 composite material, with both components supplied by Hexcel. The HexPly 8552 matrix and HM63 carbon fiber were chosen because of their combined strengths and use in aerospace [36, 37]. The process of selecting lander materials is summarized in Table 4.4.

Power Supply and Management

The lander is powered using a combination of solar panels and batteries. The lander includes 5 medium-powered solar panels capable of generating 70 Watts of power during the day. Each solar panel has a layer of glass to protect it from the radiation in space. The solar panels are 1.3 cm thick with a total area of 0.7 m^2.

Besides the solar panels, the lander is equipped with two 12 Ah lithium-ion rechargeable Space Cell batteries specifically designed for Mars landers. These batteries are capable of providing 192 A of max current and 106.02 Watt-hours of energy. These batteries are hermetically sealed and they are enclosed in a stainless steel case, capable of operating in range of -20 to 60°C [20].

Thermal Management

Similar to the human body, the lander cannot function well under excessively hot or cold temperatures. In order to survive during all of the various mission phases, the lander’s "vital organs" must not exceed extreme temperatures of -40°C to +40°C. Due to the great temperature variation on Mars, the central unit needs to be protected from these variations using two general methods. The first method involves two layers of insulation. One layer is a gold paint layer to protect the unit from radiation and help with the insulation. The second layer is an Aerogel Silica Tile. Consisting of 99.8% air, Aerogel is an effective and light material in insulating the heat generated by the components of the lander and preventing the cold air from getting inside [38].

Other than the insulation methods, the lander relies on heat generation mechanisms. This mechanism involves four Radioisotope Heating Units (RHU), heating cables, and the heat generated by the batteries and the electrical components [39]. The RHU is capable of generating 1 Watt of power, and each unit contains a Pu-239 fuel. The other source of heat is from the heating cable that has been implemented inside the main unit. This heating cable is controlled by the computer on-board. A digital thermostat is used to measure the temperature and based on the temperature the program on board will decide if there is a need to turn on the heating cable. There is a total of 15 feet of cable inside the unit and the heating cable is capable of providing a maximum power of 55.5 watts.

This automated process ensures that the central unit will be within the operating temperature. The power management software is capable of activating the heating cable and varying the current through the cable based on readings from the thermometer.

CheMin - Chemistry and Mineralogy Spectrometer

CheMin was chosen for this mission because of it's a highly volatile equipment. Meaning, this machine will be able to perform a variety of tests and analysis of different types of experiments. Specifically, for this mission, it will be able to analyze the composition of rocks and be able to search for past signs of water and microbial activity. However, in order to perform analysis, it must obtain a physical sample to be placed on to it. Additionally, this sample must be in powdered form in order for the CheMin to perform analysis. To accomplish this, the RAT has been selected. It will be mounted onto the end of the robotic arm in order to reach the Martian surface. The RAT will be able to produce rock powder by grinding into the Martian rocks and carrying powder samples into the CheMin via the robotic arm. The robotic arm will be controlled by mission control back on Earth and will rely on the NAVCAM for visual support.

Using its x-ray diffraction and x-ray fluorescence capabilities, the CheMin will be able to identify elemental compositions of rocks. Inside the CheMin is a sample handling wheel system (shown in figure 4.2) made of cells to store samples. Sitting on top of the CheMin is a funnel containing a 1-mm mesh screen to filter out larger than expected powdered grains from entering CheMin. This funnel will be exposed to the environment and is where samples will be able to enter the instrument and be transported into the cells. The sample handling wheel will be able to store up to 27 reusable samples. For the powdered samples to correctly enter the sample cells, the funnel has a piezoelectric vibration system that will act as a guide for the samples to successfully enter the cells. Each sample will approximately have a diameter of 8 mm and be within 175 μm of thickness. This sample will be bounded by an about 6 μm thick Mylar Kapton window. A wavelength of ~50μm in diameter X-ray beam will illuminate the center of this sample. These cells are engineered inside a dual-cell assembly, known as the “tuning fork”.

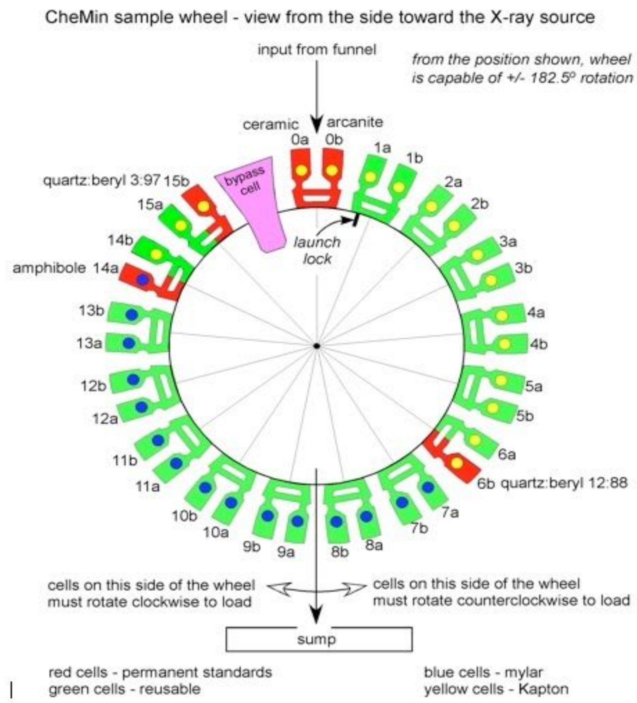


Figure 4.2: CheMin Sample Wheel.

An x-ray sensitive charged-couple device (CCD) imager is positioned on opposite sides of the cells and directly detects X-rays diffracted by the sample. This CCD imager is a 600 x 600 pixel EV2 CCD-224 frame transfer imager operated with a 600 x 582 array data collection area. It's position within the CheMin is placed on opposite sides of the cells so that mineral phases with big spacings can be detected. A 150 μm aluminum film supported on a ~2,000-Angstrom polyamide film cooled to a temperature of 60°C is placed in front of the detector to prevent the CCD from being exposed to the X-ray induced optical fluorescence (photons in the visible energy range) during analysis. The fluorescence detector is mounted on the tube side of the sample cell, placed in a reflection geometry where X-ray fluorescence chemical analyses can be obtained.

RAT - Rock Abrasion Tool

To gather powdered samples and have it delivered to the funnel system of the CheMIn requires a scientific tool that will be able to accomplish these tasks. For this, the RAT has been chosen. Mounted onto the end of the robotic arm, it will be able to gain access to the interior of Martian rocks by grinding a 5-mm deep and 45-mm diameter hole onto the surface of the Martian rock. It is primarily made from Alvernet, steel, and titanium to prevent dust from entering into the interior of the instrument. It will be able to perform independently once placed near the surface of the rock and would not require any input of the rover's instrument deployment device. During the grinding phase, the RAT will be able to collect powdered samples into a clean tube to be later dispensed onto the funnel of CheMin using vibrational mechanisms. Additionally, the RAT is made of three motors with each one serving a distinct motional function.

The grind motor consists of two shafts that are equidistant from the center of the housing and centerline of the RAT and placed at the bottom unit where the grinding wheel and the rotating brush are placed. It operates with 27 V as its set parameter that rotates the grinding wheel at about 3000 rpm. During activities during mid-day, it can be expected to have between 28 V and 34 V running through the grind motor. The second motor is the revolve motor that supports the two rotating shafts to rotate about a common center point so that the grinding wheel can complete a full 45 mm diameter circle. Its speed is inversely proportional to the grind motor current voltage. The Z-axis motor moves the lower section of the RAT in a linear fashion. It has a magnetic detection brake built within the upper section of the motor that prevents the Z-axis from migrating during launch and landing. The lower section of the RAT consists of a butterfly mount and two butterfly wings that will act as a preloading structure. Preloading the ground structure of the RAT against the rock will significantly increase the overall stiffness of the design for grinding activities.

Robotic Arm

Mounted to the side of the stationary lander is the robotic arm. With 4 degrees of freedom and back-hoe design, it will carry two additional scientific instruments. The robotic arm will be controlled by mission control back on Earth by a combination of software executing on the lander computer and firmware resident in the robotic arm electrical equipment. The robotic arm is essential for this mission by providing support for the NAVCAM and the RAT. By providing support to these two instruments, experiments involving the CheMin will be achievable. The NAVCAM will be mounted onto the forearm on the robotic arm and the robotic arm will be able to position itself to allow the NAVCAM to take images of the surface properties at the touchdown site. Additionally, suitable rock samples will be detected with the combitional support of the robotic arm and the NAVCAM.

The robotic arm is made up of a low-mass graphite-epoxy composite and the joint actuators consist of DC motors with 2-stage speed drivetrain. It is equipped with a wide range of arm motion commands that provide for coordinated joint motion as well as Cartesian motion of a selected tool, such as the RAT. The interior of the robotic arm also consists of RA Electronics containing two PC boards that provide power conditioning to the motor and heater drive circuit. The four degrees of freedom mentioned earlier are the three translation coordinates in addition with the angle that the RAT approach vector makes with the plane of the Martian surface.

NAVCAM - Navigational Camera

In order to navigate the robotic arm for it to accomplish its required tasks, it must be remotely controlled by Mission Control back on Earth. For this, having a visual view of the scientific instruments and the Martian environment is crucial. The NAVCAM has been chosen to accomplish this task and will be mounted onto the forearm of the robotic arm. It will be equipped with a f/12, 14.67-mm fixed-focal length lens that will provide a 45 x 45 degree field of view with a pixel scale at the center of the field of view of 0.82 mrad/pixel and will be able to provide scientists with a 45 degree angle of view with a 2.1 milliradians per pixel and a focal length about 10 centimeters to infinity [40]. The lens will come equipped with a one time removable lens cover that will protect the lens from dust and debris upon landing.

4.1.3. Precision of Instrumentation, Repeatability of Measurement, and Recovery System

The CheMin will be able to detect minerals with an atomic number greater than 12 (Mg) that are present at and above the 3% level which is known as the Minimum Detection Level (MDL). The precision of the instrument when the mineral is in a quantity greater than 4 times the MDL (12%) is ±10%. In terms of accuracy for minerals present at or above 4 times the MDL, the CheMin could detect the absolute amount present ±15%.

Tables 4.5 and 4.6 depict two separate tests of the quantification of Beryl and Quartz [41]. The data gathered in Table 4.5 is the sequential analysis of a 65 mm^3 aliquot of beryl: quartz mixture. Sample homogeneity over time was tested under Mars atmospheric pressure. The data gathered in Table 4.6 is of a 45 mm^3 aliquot mixture of Beryl and Quartz tested in the same manner under the same Mars atmospheric conditions. The values gathered in the first test are reasonably similar to its corresponding data in the second test indicating that the instrument is fairly accurate at taking measurements.

Cumulative Analysis time	Beryl %	Quartz %
30 minutes	90.6 ± 1	09.4 ± 1
60 minutes	87.6 ± 1.2	12.4 ± 1.2
90 minutes	88.2 ± 1.2	11.8 ± 1.2
120 minutes	89.8 ± 1	10.2 ± 1
150 minutes	90.6 ± 1	09.4 ± 1
Average		10.64
Std. Dev.		1.39
Rel. Accuracy		11.33 %
Rel. Precision		13.05 %

Table 4.5: CheMin Quantification Test 1.

Cumulative Analysis time	Beryl %	Quartz %
30 minutes	87.7 ± 1.2	12.3 ± 1.2
60 minutes	87.2 ± 2.6	12.8 ± 3.3
90 minutes	88.4 ± 2.6	11.6 ± 2.6
120 minutes	89.3	10.7
Average		11.85
Std. Dev.		0.79
Rel. Accuracy		1.25 %
Rel. Precision		6.66 %

Table 4.6: CheMin Quantification Test 2.

The recovery system for the data starts with data being stored in a RAD750 3U. The RAD750 3U has a data cache in which data is temporarily stored until it can be moved to another storing location on Earth at a NASA center. This data can then be stored into Hadoop for data analysis, either manually by scientists or using computation software. In order to avoid any data loss from background radiation when transmitting information, data will be sent twice. This is so that any data points that were not properly sent the first time can be recovered.

4.1.4. Validation and Verification Plan

It is imperative that a validation and verification plan is in place to prove the success of the mission by ensuring that the onboard science payload will survive launch, entry, and environmental factors. The V&V plan will help the engineering and science team recognize any potential risks regarding the safety of the onboard equipment and attend to these potential risk factors. Given the nature of the mission, V&V Tables 4.7, 4.8, 4.10, and 4.11 will provide a summary of the expected tests to be done on the scientific instruments prior to launch.

CheMin V&V	
$CheMin_{1\text{-}1}$	1.1.1 Payload Random Vibration Testing
	Random vibration testing is to be done to ensure CheMin survives launch and sensitive internal compenents remain caliberated
$CheMin_{1\text{-}2}$	1.1.2 Payload Landing Test
	Ensure that CheMin would be able to withstand landing event
$CheMin_{1\text{-}3}$	1.1.3 Payload Thermal Testing
	Ensure external environmental thermal fluctuations won't tamper or contaminate the data processing stage.
$CheMin_{1\text{-}4}$	1.1.4 Assembly and Analysis Test
	Ensure that sensitive interanl components responsible for analysis of selected samples work as expected by doing on-field testing on terrain similar to that of Mars

Table 4.7: CheMin Validation and Verification Plan.

CheMin has gone through several prototypes to ensure it will survive environmental factors on the surface of Mars and will perform as expected given the conditions. Initially, employment of the CheMin was not feasible because access to powder sample preparation remained a difficult task to accomplish. Additionally, this required huge power supplies to power its high-power X-ray tubes and complicated mechanical motions. Early CheMin prototypes were tested at NASA Ames Research Center in 1992-1997 and proved to not meet expectations. The third prototype of the CheMin resolves this issue by improving the X-ray CCD detectors and implementing small X-ray tube technology. Furthermore, with the implementation of a sample vibration system, it removed the dependency for fine-grained powder samples. Rigorous on field-testing has been done at Death Valley, California to ensure the success of this instrument.

Vibration testing will be done to ensure calibration standards are met prior to launch and minimize any damage to internal systems. In addition, the vibration testing will be done on the CheMin to verify that it will survive the launch and landing phases. The cells built into the sample handling wheel inside of the CheMin are bounded by Kapton windows which are extremely durable under intense vibrations and are shown to not be susceptible to acid attacks during testing. However, there is a small diffraction interference at ~6-7° of 2θ in diffraction peaks from some clay minerals [42]. To ensure success on Mars, further testing using Flight Models and Development Models will be done.

The surface of Mars consists of an atmosphere of primarily carbon dioxide which serves as a conductive and convective load on the CheMin. If operated under conditions that are too cold, the cooler and detectors will freeze. Thermal conditions on Mars can range between -130°C and +50°C. Therefore, the CheMin must maintain thermal conditions between -40°C and +50°C. To maintain these thermal conditions, the CheMin will only operate during the evening of Mars when ambient temperatures are at a minimum.

Calibration Testing will be done on the CheMin to ensure sensitive internal data gathering systems will work as expected. Demonstration models and various testbeds will be performed to analyze quantitative X-ray diffraction calibration. Different types of materials across a broad spectrum will be tested to ensure the CheMin will be able to distinguish the composites of various types of minerals that will be found on the surface of Mars. Prior to launch, the development model will be used to test algorithms, establish calibrations, develop operations scenarios, and characterize Mars analog samples.

RAT V&V	
RAT_{2-1}	1.2.1 Payload Random Vibration Testing
	Random vibration testing is to be done to ensure RAT survives launch and complex internal moving mechanisms stay caliberated
RAT_{2-2}	1.2.2 Payload Landing Test
	To verify that all the internal gears, mechanisms, and tools suvive landing event.
RAT_{2-3}	1.2.3 Payload Thermal Testing
	Verification that internal structures will perform as expected throughout internal and external thermal fluctuations.
RAT_{2-4}	1.2.4 Assembly and Analysis Test
	Sample testing of rocks similar in structure to those found in Mars will be done to ensure the RAT will perform as expected.

Table 4.8: RAT Verification and Validation Plan.

During initial testing of the development of the RAT, it had not been realized that the rate of the grinding wheel wear had decreased 5-fold when being compared under the same conditions on Earth. In order for the RAT to effectively grind the rocks on Mars, a desirable cutting material with sufficient power and force is crucial. For this, various synthetic diamonds had been tested to examine the most effective cutting material. However, testing had revealed that after various grinding sessions, the diamond grinds had essentially developed flat spots. This came to a surprise to scientists because diamond is much harder than the basalt that was used during testing. To resolve this issue, the ability for a diamond abrasive to sharpen itself was needed. Additionally, the resin diamond wheel would be designed to use very little down force.

To ensure that the RAT will meet grinding expectations during the extreme temperatures of Mars, four prototypes of the RAT have been designed to withstand a series of tests that will be performed. By implementing “worst-case scenarios,” such as operating at 0°C on basalt, these tests will allow scientists to examine rock compressive strength and topology and analyze force requirements. Figure 4.3 examines the operational conditions at this temperature [43]. The horizontal x-axis represents the “worst-case” motor current during grinding and the vertical y-axis represents the corresponding torque on the motor.

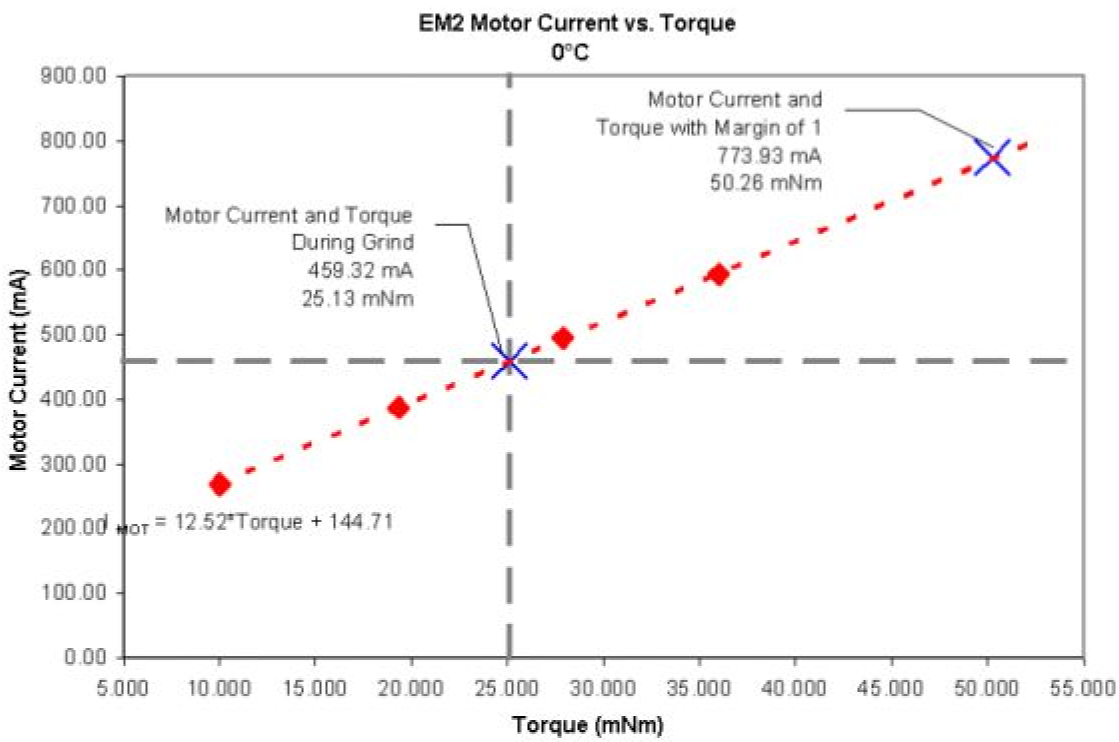


Figure 4.3: Motor Current vs. Torque at 0ºC.

Thermal testing will be done on the RAT to ensure this tool can operate under various temperature fluctuations on Mars as well as to analyze internal heating of the RAT during operation. The Z-axis motors have been found to overheat when running in voltage mode at 8 V and at temperatures below -55°C with a load of 30 N. To avoid this issue, the Z-axis motors will only operate between 4 V and 6 V and with a load less than 6 N. However, the grind motor is the most susceptible to overheating issues as researched in Table 4.9. Overheating on the grind motor is based on two variables, which are the motor current and its surrounding temperature on the Martian surface. Temperature limits on the grind motor are +110°C for the rotor and +85°C for the case. However, overheating issues start to occur within 28 minutes of an internal temperature of +55°C. Thermal testing analysis has determined that +35°C will be the maximum internal temperature that the motor will safely operate with four hours of continuous grinding.

Temp. (ºC)	Grind Current Margin of 0 (mA)	Grind Current Margin of 1 (mA)	Time to Overheat (min) for Margin of 0	Time to Overheat (min) for Margin of 0.5	Time to Overheat (min) for Margin of 1
+55	378.7	696.6	28	23.67	9.33
+35	396.3	710.77	Infinite	43.67	14.67
+23	400.83	704.27	Infinite	140.67	20
0	459.32	773.96	Infinite	Infinite	22
-20	471.37	779.3	Infinite	Infinite	31.67
-40	510.65	782.79	Infinite	Infinite	48
-55	539.5	844.45	Infinite	Infinite	41.67
-70	567.98	868.08	Infinite	Infinite	47.67

Table 4.9: Grind Motor Thermal Margins.

Robotic Arm V&V	
Robotic $Arm_{3\text{-}1}$	1.3.1 Payload Random Vibration Testing
	Random vibration testing is to be done to ensure the Robotic Arm survives launch
Robotic $Arm_{3\text{-}2}$	1.3.2 Payload Landing Test
	To ensure that the Robotic Arm will be able to withstand landing phase and internal gears and motors stay caliberated.
Robotic $Arm_{3\text{-}3}$	1.3.3 Payload Thermal Testing
	Thermal testing will be done to ensure that any thermal fluctuations will not damage any gears and/or motors within the robotic arm.
Robotic $Arm_{4\text{-}4}$	1.3.4 Assembly and Analysis Test
	Testing will be done on terrain similar that of Mars to ensure success. Robotic Arm is expected to withstand exteranl factors such as weather and dust.

Table 4.10: Robotic Arm Validation and Verification Plan.

To be able to withstand the intense vibrations during launch and landing phases, the robotic arm will be included in the Random Vibration Tests to simulate launch and landing phases. Upon landing, these instruments must show that they are able to operate under the environmental circumstances of the Mars environment. For example, dust will inevitably come in contact with these instruments, and therefore, one way to demonstrate that the robotic arm will be able to withstand Martian dust is to implement testing here on Earth and analyze how the gears and motors of the robotic arm operate when in contact with dust.

Thermal testing will be done on the robotic arm to ensure that it will be able to withstand the harsh environment on Mars. To analyze the performance of the robotic arm, testing operations will be done in temperature ranges of 183 K to 293 K with expected voltages.

In addition, testing for calibration will be done as well to verify that the instrument will work as expected. Calibration of the arm position sensors will be done by moving the robotic arm at different angles and movements and measuring the location of the end of the arm using a system of highly accurate sensors. Analyzing the data acquired by these sensors will help us in minimizing the mean error over measured poses.

NAVCAM V&V	
$NAVCAM_{4-1}$	1.4.1 Payload Random Vibration Testing
	Random vibration testing is to be done to ensure that the NAVCAM survives launch and raw image processing components stay caliberated.
$NAVCAM_{4-2}$	1.4.2 Payload Landing Test
	Ensure that the NAVCAM will endure the landing phase and internal systems will not distort image processing.
$NAVCAM_{4-3}$	1.4.3 Payload Thermal Testing
	Various thermal testing to ensure that thermal fluctuations will not distort image quality
$NAVCAM_{4-4}$	1.4.4 Assembly and Analysis Test
	Software testing will be done by implementing code which will analyze two images to ensure camera is able to differentiate between them.

Table 4.11: NAVCAM Validation and Verification Plan.

Additionally, the NAVCAM will go under the Random Vibration Tests, as well as thermal testing to ensure calibration remains intact during launch and landing phases and to confirm that it will be able to withstand the extreme environments of Mars. We will also need to verify that it is able to differentiate one image from another upon these events. To demonstrate this, code representing the Mean Squared Equation will be implemented into the software to take two images upon touchdown. The first image will be taken before the shutter opens and a second image will be taken after the shutter opens. The following Mean Squared Equation will demonstrate this task [44]:

$$MSE = \frac{1}{m\,n}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2$$

Equation 4.1: Mean Squared Equation.

```
1. diff nvcm (image A, image B)
2. diff = np.sum((imageA.astype(“float”) - image.astype(“float”)) ** 2)
3. diff /= float(imageA.shape[0] * imageA.shape[1])
4. Return diff
```

Program 4.1.2: Python Equation Conversion.

We can examine Program 4.1 code representing Equation 4.1 line by line. Line 1 represents the nvcm function that takes two arguments in its parameters which are image A and image B. Line 2 converts all unsigned 8-bit integers into floating points for better accuracy. Next, the difference between the two images are taken by subtracting the pixel intensities. Afterwards, the squares of these differences are taken and summed up. Line 3 will calculate the mean of the Mean Squared Error by dividing the sum of squares by the total number of pixels in the image. Lastly, line 4 simply returns the result of the function. Using this equation, we can analyze if the camera is functioning as expected.

The V&V plans for the “petal” subsystem will include scaled models and simulation testing. The main objective of the petal subsystem is to deploy the payload upright. In addition to the testing on the MarsYard, as mentioned on the previous section, scaled models or prototypes will be used for motion testing before the final build. The main test will include the motors used on each side of the lander to deploy the petals one side at a time. More than likely, a gearbox will be required to apply the proper torque and speed during the opening of the sides. In order to verify that the lander opens the correct side first, an accelerometer will be used to measure the pull of gravity. With this measurement, we know which way is down, and then the computer commands the correct side to open and pushes the rover in the correct position. After the rover’s position has been fixed, the other sides will open accordingly.

Validation of the RAD750 3U’s design is provided by BAE Systems as part of the third-party’s product guarantee; however, in-house testing will be performed to verify the integrity of the two instances implemented on the lander. The computer instances will first undergo thermal and vibration stress tests. In regards to function, both copies of the computer will undergo identical stress tests in which the computer must produce the marketed 132 MHz clock speed, detected through Open Hardware Monitor, an open source hardware monitoring utility. The software can also be used to track voltage, temperature, and fan speed under load. Diagnostics will also be run on built-in memory to avoid corrupt units in addition to the computer board's own error handling procedures.

During lander operation, verification of successful computer operation is critical, as this component is responsible for overseeing every other system on the lander. Each subsystem controlled by the computer will return an unsigned integer indicating status such as receiving a command successfully, finishing execution of a command, or finding some error in operation. The computer will be programmed with responsive action to each coded integer to initiate a recovery protocol, resend the command, and notify the control center, along with any other appropriate response. Since each subsystem and the computer are pre-programmed with an encoding of integer signals, the computer will be able to efficiently handle operation of the whole lander with reduced speed requirements for data transfer, due to a couple bytes of integers being very easy to handle. Thus, the control center will be properly notified on command execution status, general operation, and error states.

Validation of the GNSS Patch Antenna's resilience in a space environment is also provided by the manufacturer, ISIS. The antenna will undergo thermal and vibration tests along with the rest of the lander. The antenna's functional validation will involve field testing in a large flat field by testing communication between two transmission units at varying distances. A flat field with little elevation change is the best option for a test environment since the Columbia Hills landing site is of similar topology. One unit will be fitted with the GNSS Patch Antenna, RAD750 3U main and backup computer, transmission package, and a power supply. The other unit will be the complete COMM package provided by NASA. The capabilities of the antenna can then be tested by transmitting bytes of data at varying distances until finding a distance limit or determining that adjustments need to be made to either unit.

Verification of antenna functionality is challenging because lack of functionality (no signal reaching the control center) could in fact be a result of a multitude of different scenarios. For example, the lander may be in a communication dead zone on the opposite face of Mars or the computer may no longer send signal codes due to a malfunction. In order to address the most scenarios, the computer will attempt to send data to the control center through an antenna up to five times. If no response is received from the control center within a certain time frame after the fifth attempt, then the computer will redirect data to the other antenna. This process ensures that if one antenna is damaged and cannot receive an acknowledgement from Earth, then the remaining antenna will be used instead until both antennas are truly inoperable.

The V&V for the power management system includes simulation testing in different temperatures to capture the harsh conditions of Mars. The main objective of the power management system is to provide energy to the instruments onboard, the heating system, and keeping the lander “alive.” The main tests will include testing the batteries, to provide the energy needed in different temperatures with a varying combinations of instruments working, and the charge and discharge rates in those temperatures. A similar testing mechanism will be done for the solar panels. The power provided by the panels in daylight, nighttime, with different levels of dust on the panels, and different operating temperatures need to be tested.

The V&V plans for the thermal system include testing the automated software onboard in various temperatures, the heating coils, the insulation mechanisms, Aerogel and gold paint, and the digital thermometer. The testing for the insulation includes heating up the inside of the central unit and measuring the temperature inside as the outside temperature varies to verify the effectiveness of insulation. The heating coils' reliability and heat generation mechanism should be tested in very low temperatures. For each subsystem, the operating temperature range has been determined and validating that the thermal system is capable of keeping the temperature within the safe zone is another important aspect that needs to be verified.

4.1.5. FMEA and Risk Mitigation

Failure Mode and Effects Analysis Worksheet											
		Process or Product:	All Components					**FMEA Date:**	08/01/2020		
		FMEA Team:	Erika Szaldobagyi and Ronell Lim								
		Team Leader:	Erika Szaldobagyi								
FMEA Process											
Line	**Component**	**Potential Failure Mode**	**Potential Effects of Failure**	**Severity**	**Potential Cause(s) of Failure**	**Occurrence**	**Current Controls, (Prevention)**	**Current Controls, (Detection)**	**Detection**	**RPN**	**Recommended Action**
1	RAT	can't scoop	no data collected	8	mechanical failure	4	N/A	camera, visual	5	160	add additional scoop mechanic
		gets stuck	no function	6	electrical issues	3	strong material for grinding teeth	camera, visual	5	90	
2	Navigational Camera (NAVCAM)	lens break	cannot see mars surface	8	dust storms / rocks	4	camera protective shutter	camera picture	3	96	
		can't capture data	no data collected	6	electrical issues	3	N/A	camera data	4	72	
3	RAD 750 3U	power issue	no function	9	electrical issues	4	backup, redundancy	data received	2	72	
		electrical component fails	no data collected	7	mechanical failure	3	backup, redundancy	data received	4	84	
4	GNSS Patch Antenna	can't read signal	no data collected	8	electrical issues	3	backup, redundancy	data received	2	48	
		electrical component fails	no function	7	mechanical failure	2	backup, redundancy	data received	3	42	
5	Petal System	doesn't deploy	no mission	8	mechanical failure	3	strong motors	camera, visual	5	120	add sensors for deployment
		breaks	no data collected	6	electrical issues	2	strong material, aluminum	camera, visual	7	84	

Table 4.12: FMEA Lander Worksheet.

Table 4.12 is the FMEA for the lander system which includes the RAT, NAVCAM, RAD 750 3U, GNSS antenna, and petal system. The chosen critical RPN is 100 and higher. After analysing the potential failure modes, the most critical failure mode to mitigate is the deployment for the petal system and the RAT. The RAT will need to be able to collect the soil or rock data to deposit to the CheMin. The RAT is one of the first steps in completing the science mission objective—not being able to collect data is highly severe. The recommended action is to add an additional scoop mechanism. This will help ensure a backup for the system. The petal system is also critical to deploy. The deployment of the petal system enables the science instruments to collect data on the upright position. The recommended action is to add more sensors for deployment to ensure deployment of the petals is occurring.

4.1.6. Performance Characteristics

During any season on Mars, small dust storms, nicknamed Dust Devils, can occur, which can pose a hazard of covering solar panels on the lander, removing a potential source of energy, and also destroying and creating projectiles from the material on Mars [45]. However, specifically on Columbia Hills, the probability of these types of storms subside during Southern Hemisphere spring as the peak storm frequency shifts to the Northern Hemisphere during Northern Hemisphere autumn and winter seasons, as presented in Figure 4.4 below [46]. The whole-planet dust storms encompass all of Mars and can last an average of 30 days. Due to the dust storms, the stationary lander is at risk of getting damaged. However, the probability of dust storms occurring in the Southern Hemisphere in this season is equal to or less than 1.6% [47]. Specific to the instruments' ability of data collection in this particular environment, factors, such as temperature and distance, also provide a less strenuous environment for the lander to collect data.

Month number	Ls range (degrees)		Sol range		duration (in sols)	specificities
1	0	30	0.0	61.2	61.2	Northern Hemisphere Spring Equinox at Ls=0
2	30	60	61.2	126.6	65.4	
3	60	90	126.6	193.3	66.7	Aphelion (largest Sun-Mars distance) at Ls=71
4	90	120	193.3	257.8	64.5	Northern Hemisphere Summer Solstice at Ls=90
5	120	150	257.8	317.5	59.7	
6	150	180	317.5	371.9	54.4	
7	180	210	371.9	421.6	49.7	Northern Hemisphere Autumn Equinox at Ls=180 Dust Storm Season begins
8	210	240	421.6	468.5	46.9	Dust Storm Season
9	240	270	468.5	514.6	46.1	Perihelion (smallest sun-Mars distance) at Ls=251 Dust Storm Season
10	270	300	514.6	562.0	47.4	Northern hemisphere Winter Solstice at Ls=270 Dust Storm Season
11	300	330	562.0	612.9	50.9	Dust Storm Season
12	330	360	612.9	668.6	55.7	Dust Storm Season ends

Figure 4.4: Mars Calendar at Different Solar Longitude (Ls) Degrees [46].

During the Southern Hemisphere spring and summer seasons, the ground is very accessible (along with the rocks present that the CheMin will analyze) and not frozen over. The instruments are capable of handling the ground environment. At 270 degrees, Mars and the Sun are closest together, known as Aphelion. This provides an abundant amount of sunlight for the instruments to work, given that a dust storm doesn't occur. Figure 4.5 shows the possible maximum and minimum temperatures at Ls 270 degrees. The science instruments begin malfunctioning at 273 K. However, at Ls 270 degrees, temperatures come close to 300K, well above 273K, providing a sufficient temperature range for science and data collection without problems with instrumentation.

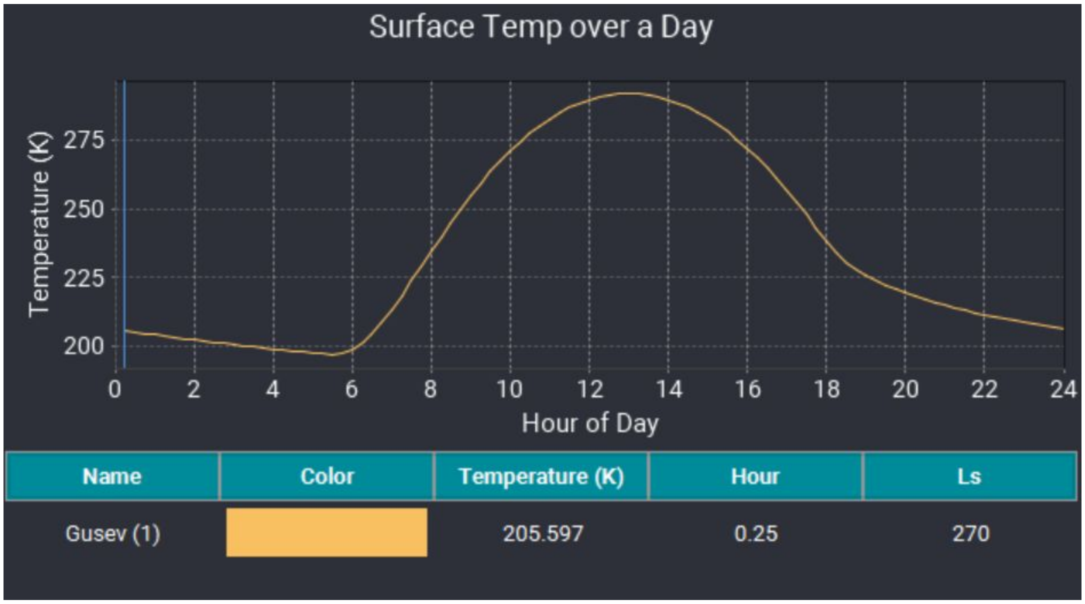


Figure 4.5: Temperature at 270 Ls Degrees.

Before placing instrumentation in the actual conditions on Mars, the Jet Propulsion Laboratory (JPL) offers a facility called MarsYard II that duplicates conditions on Mars [31]. To make sure that the instrumentation works, it can be placed in the JPL facility and the experiments can be executed in the same manner that it would on Mars. More specifically, some of the resources they offer to ensure proper data collection by the instrumentation is providing specific soil and rocks that can be analyzed just like samples would be analyzed on Mars. JPL also has an In-Situ Instrument Laboratory (ISIL) that holds a Mars-like environment with artificial light with the same intensity as on Mars. ISIL also has a surface similar to Mars to closely mimic and address stability and balance of instrumentation [48].

Figure 4.6: MarsYard II [31].

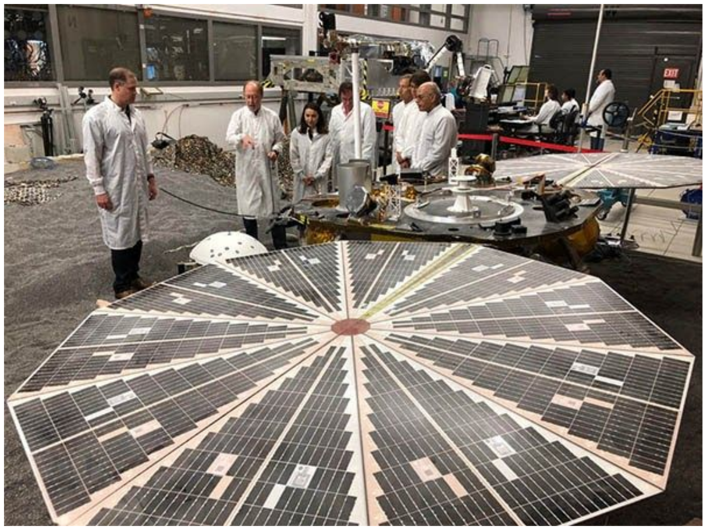


Figure 4.7: In-Situ Instrument Laboratory (ISIL) [48].

4.2. Science Value

4.2.1. Science Payload Objectives

The science objective chosen by the team is to collect more information on Mars' past environment, and use that analysis to determine the existence of past carbon-based life on Mars, and project the habitability of the environment for humans in the near future. These objectives have been chosen as they are highly pertinent to the data being sought in most celestial bodies: to find signs of life. However, the team is taking this a step forward by finding evidence of primitive life that can determine whether life has ceased to exist or if there are other reasons behind the lack of finding life – not just signs of life.

Some of the data being sought from the samples on Mars are evidence of peptidoglycan and chitin, as those are defining characteristics of bacteria and fungi, which are primordial. With evidence of peptidoglycan and chitin on Columbia Hills, it opens up a gate to a new understanding of the composition of Mars. The use of the CheMin is also novel as this instrument has not been used to find this type of data before.

4.2.2. Creativity/Originality and Uniqueness/Significance

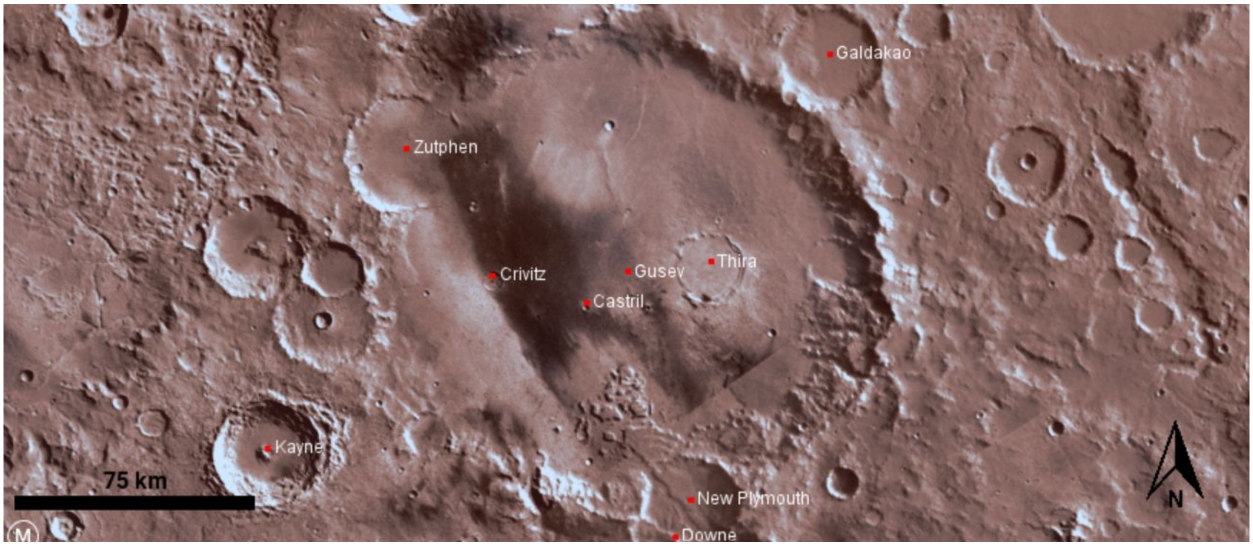


Figure 4.8: Gusev Crater.

Due to its location within Gusev Crater, Columbia Hills is the ideal candidate for our mission because of its lack of obstructions and the level elevation that the crater provides. In Figure 4.9, it is apparent that Gusev Crater maintains a uniform green color indicating that all areas are close to the same elevation with very minimal deviation. The elevations around Columbia Hills range from an estimated -1950 meters to -1850 meters based on the information given in the JMARS tool [49].

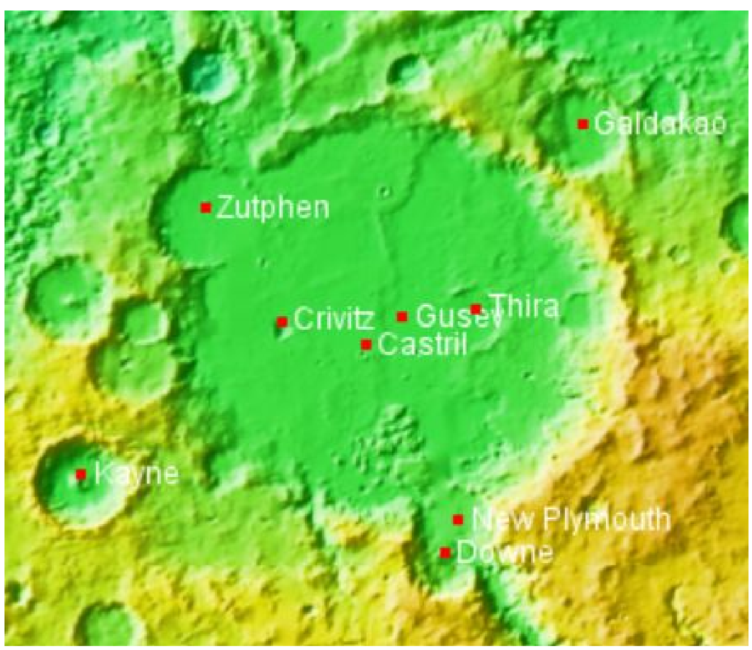


Figure 4.9: Gusev Crater Elevation.

The area within Gusev Crater, specifically at Columbia Hills, is very abundant in its amount of rock, as seen in Figure 4.10. The green and light blue areas within the map contain at most 30% rock with the purple and dark blue areas containing about 5-15% rock based on information from the JMARS tool [49]. Since part of our mission requires the study of the rocks and sediments, Columbia Hills' high abundance of rocks makes it a fitting location for our studies and experiments.

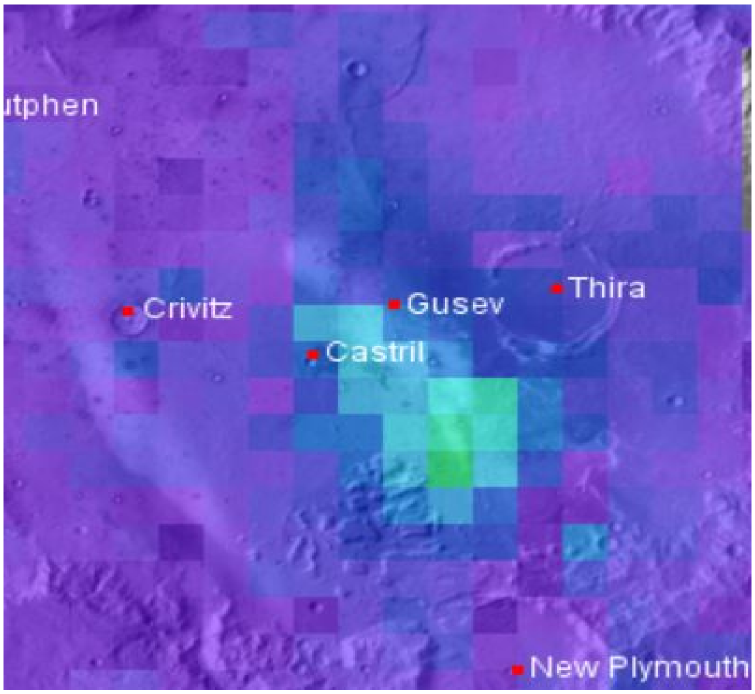


Figure 4.10: Gusev Crater Rock Abundance.

The team's design utilizes CheMin and RAT. The CheMin will identify and quantify minerals in the rocks and soil samples taken from Mars which will aid in the search for potential bio-signatures, energy sources for life, or indicators of past habitable environments. The RAT can also provide information on the samples taken from our site such as the rock's physical properties and when the amount of material removed is known, the team can derive the required energy per unit volume of the material. The RAT can also distinguish the hardness of a rock based on the fracture strength and that information can be compared to rocks on earth. Based on the Attewell and Farmer's rock hardness classification, rocks range from a hardness of 10 to a hardness of 320, the rocks can be classified as very weak, such as sedimentary rocks to very strong, such as dense sedimentary rocks like quartzites and basalts.

4.2.3. Payload Success Criteria

The data collected by the CheMin and the RAT can provide a myriad of novel information on Mars. By acquiring data on microbial activity in ground samples on Mars' surface, it furthers the goal to find life outside of Earth and shows the potential of finding life anywhere with the presence of certain organic material [50]. Finding remnants of biological components on Mars' surface would lead to the beginnings of more direct signs of life. Currently, the indication of the presence of water on Mars is the largest sign of any presence of life on Mars. However, this is an indirect assumption as the presence of water does not necessarily mean that life exists but rather that it at one point could sustain life. With the presence of DNA remnants and other fossilized biological components, this would mean that life actually did exist at some point and is therefore a direct sign.

Bacteria are very primitive forms of life that, on Earth, started the diversification of early forms of life. If bacteria and/or its parts can be found in the ground samples, it shows potential for the same process to occur on Mars and/or a halt to this process due to hostile environments.

4.2.4. Describe Experimental Logic, Approach, and Method of Investigation

The CheMin was chosen for this mission because it will be able to answer and fulfill the mission objectives. It will be able to examine if a particular area of interest had past signs of water as well as detect if there was once microbial activity. It will accomplish this task by using x-ray diffraction and fluorescence beams [51]. It will acquire rock powder samples through its funnel systems. The RAT was selected to collect these powdered rock samples. It will be able to grind rock into powdered samples from the surface of Martian rocks and collect it with a clean tube. Afterwards, it will be transported to the funnel input system of the CheMin. The transfer system will be the robotic arm and it will be responsible for transporting the RAT back and forth from the CheMin to the Martian surface to gain access to samples. To navigate the robotic arm, the NAVCAM was chosen to provide visual support. Through the NAVCAM, scientists will have a clear view of the environment and manually maneuver the robotic arm to its desired locations. The entire system is dependent on one another to complete the mission requirements.

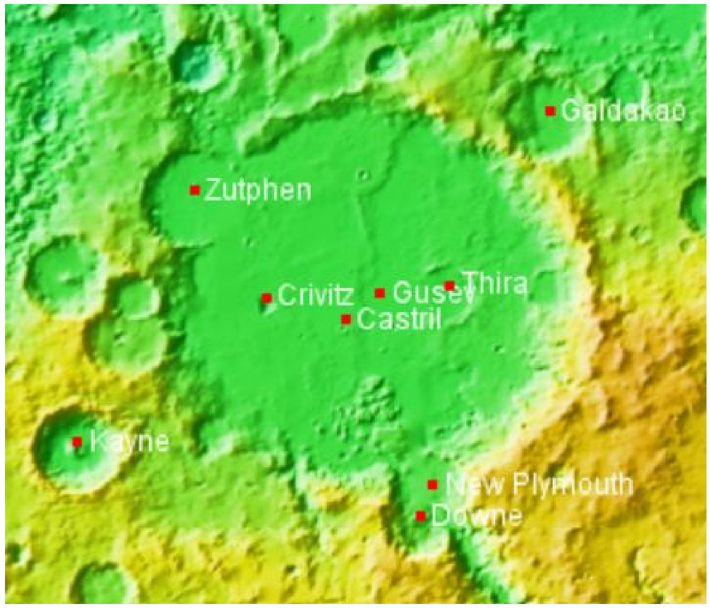


Figure 4.10: Gusev Crater Elevation.

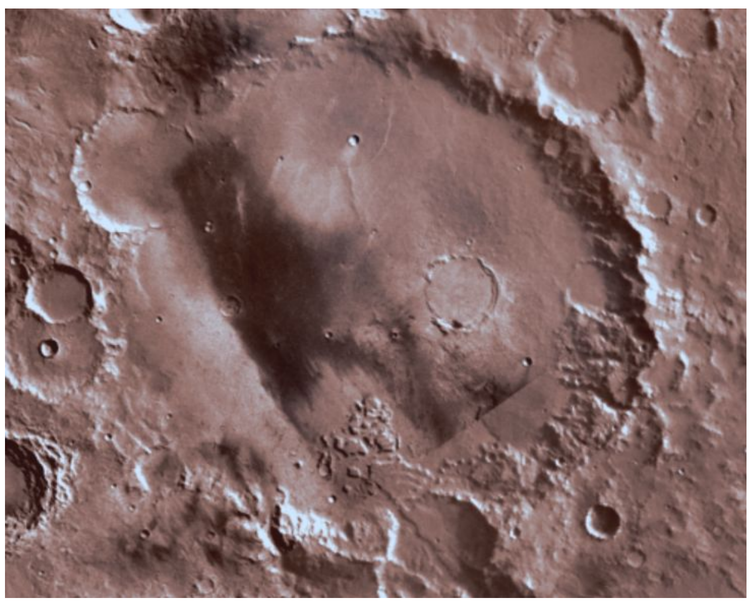


Figure 4.11: Gusev Crater.

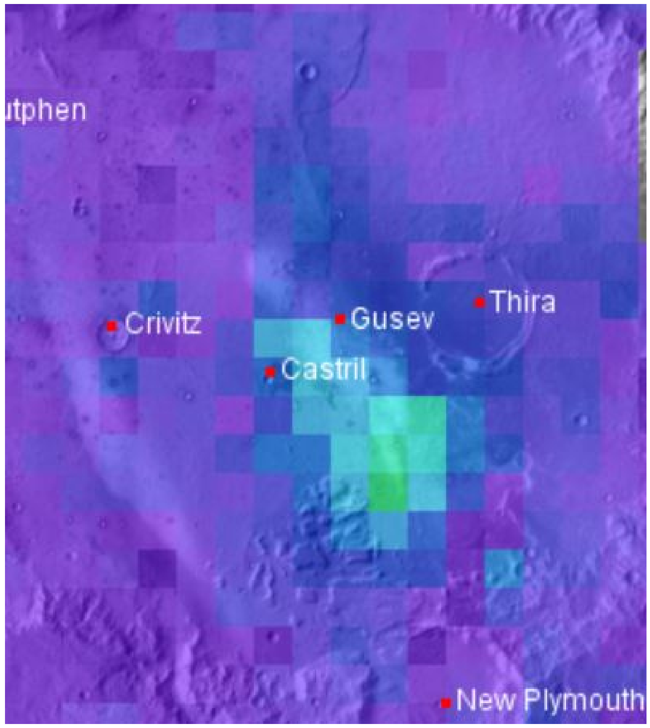


Figure 4.12: Rock Abundance.

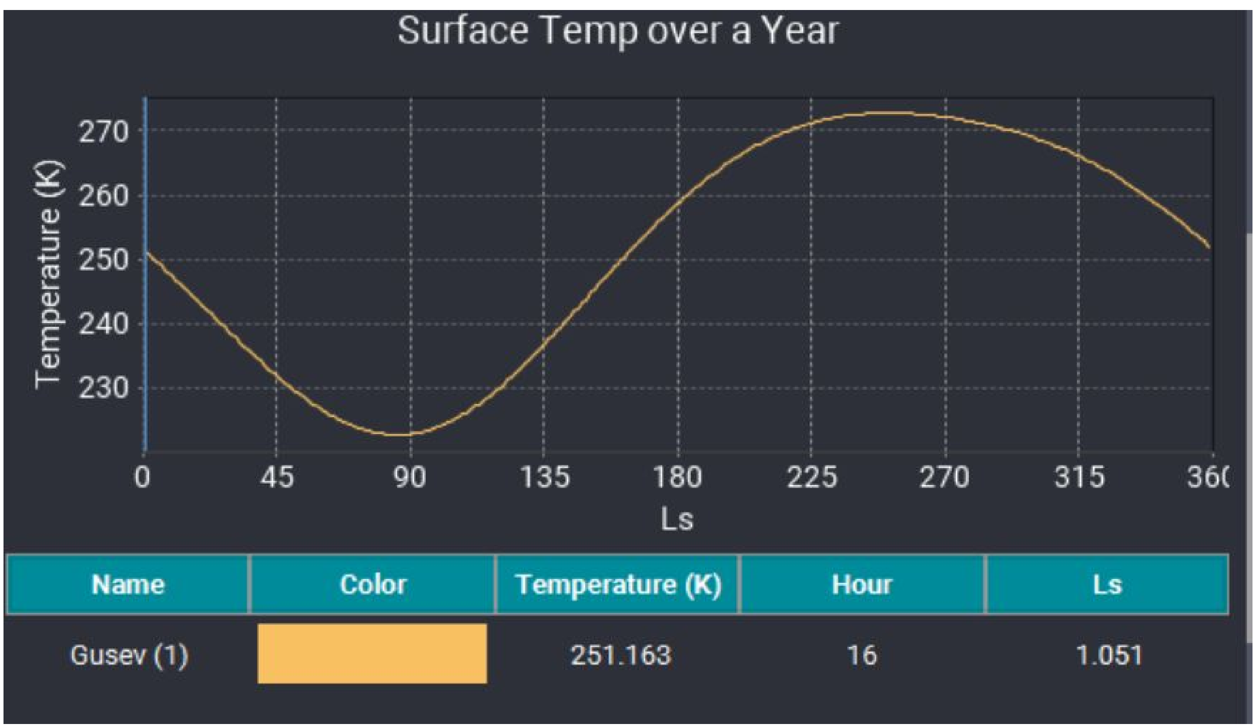


Figure 4.13: Surface Temperature Over Year in Gusev Crater at 1 Ls Degree.

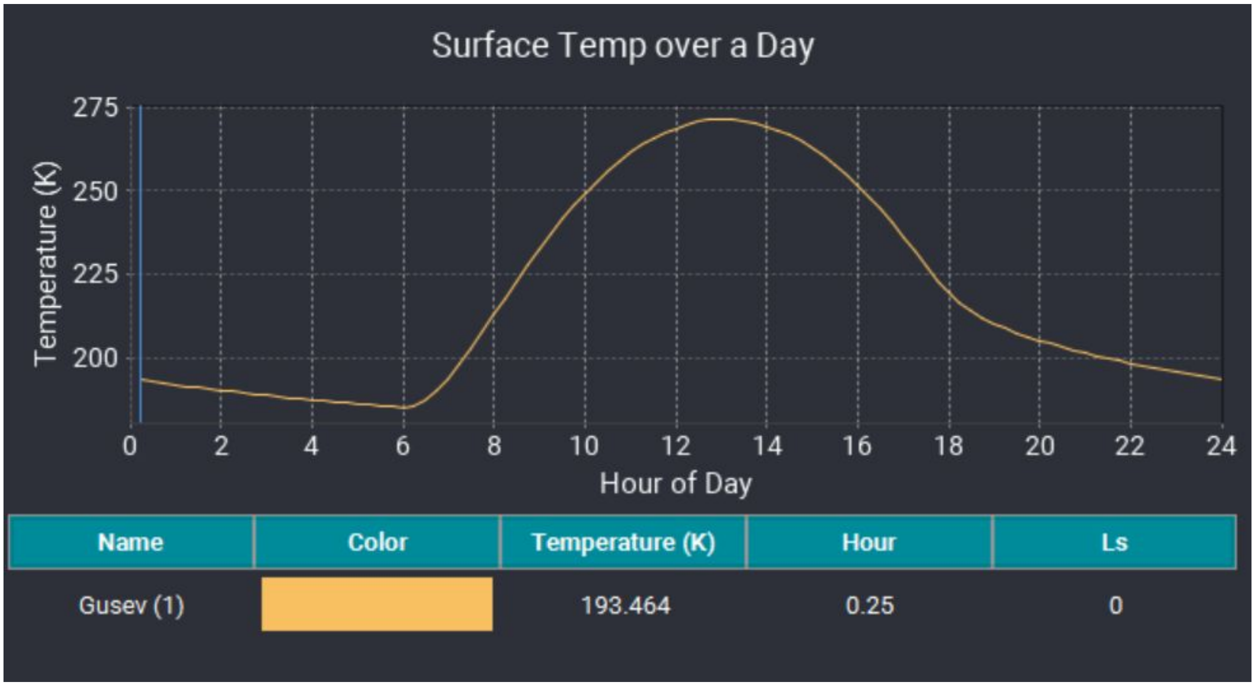


Figure 4.14: Surface Temperature Over Day in Gusev Crater During Landing Season at 0 Ls Degrees.

4.2.5. Describe Testing and Measurements, Including Variables and Controls

In order to make sure that the science instruments are working, the instruments must go through preliminary tests before starting testing on ground samples from Mars. The CheMin will first analyze a known sample to determine if it can distinguish the proper characteristics of the sample. This determines that the instrument is collecting proper data and not processing data with false negatives or false positives. In this specific case, a false negative would be the lack of recognizing components that the instrument is set to notice and a false positive would be detecting remnants of biological matter without any present. Afterwards, any of the samples taken from Martian soil can be compared to the data from the known sample to see if there are any differences. These differences should be from any potential evidence of peptidoglycan and chitin and should determine any evidence being sought out, as stated by the science objectives for this mission. Presence of peptidoglycan would mean that there is evidence of the existence of bacteria as peptidoglycan is the substance forming the cell wall of bacteria. Presence of chitin would mean evidence of the existence of fungi as chitin is what makes up the cell wall of fungi

Some of the control variables in the experiments stem from a lack of biological components in the sample. In the original known sample that the CheMin processes, the biological components, such as DNA remnants, peptidoglycan, and chitin, are not present. In the ground samples from the surface of Mars, however, these biological components may be present. The control variables assist in the identification of the biological components in the ground sample, derived from the data provided by the instrumentation.

Data collection will only occur in the daytime due to the risk of instrument malfunction at nighttime. Under 273 K, the instruments are expected not to collect data as well as it would at temperatures above 273 K. This also increases the risk of receiving false negatives and false positives from instrument malfunction. Temperatures in the daytime average between 280-300 K, as stated in Figure 4.4 from Section 4.1.6, higher than the 273 K needed for adequate function of instrumentation.

4.2.6. Show Expected Data & Analyze (Error/Accuracy, Data Analysis)

CheMin - Chemistry and Mineralogy Spectrometer

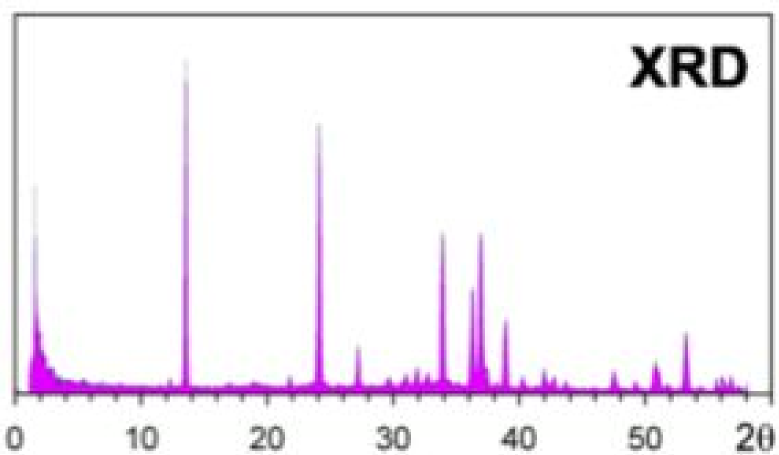


Figure 4.15: X-Ray Diffraction Plot [52].

Figure 4.15 depicts a plot that sums the diffracted protons from the Kα line of the X-ray source. Using the diffraction pattern from Figure 4.15, the minerals present and their abundances can be determined similar to that of the Energy-Dispersive Histogram (EDH) in Figure 4.16. Since each minerals diffraction pattern is unique it can be compared with standard diffraction patterns of known natural and synthetic materials.

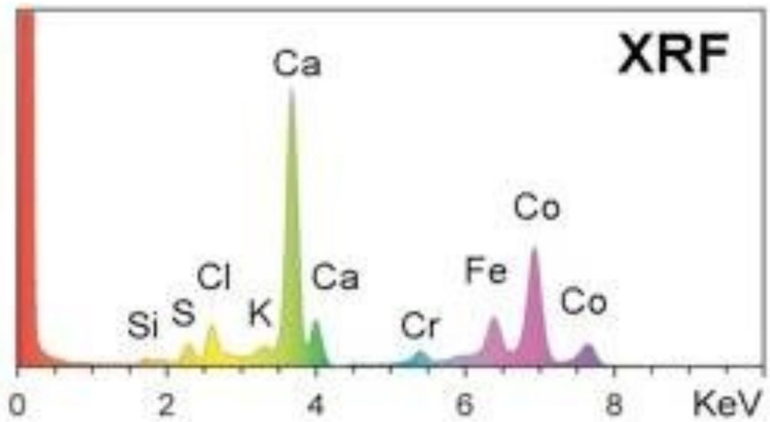


Figure 4.16: X-Ray Fluorescence Plot [52].

The CheMin is able to identify and quantify minerals present in rocks and soil after analyzing samples taken from the landing site. Using the EDH in Figure 4.16 as an example, the team can see that the sample contains various abundances of silicon, sulfur, chlorine, potassium, calcium, chromium, iron, and cobalt. This graph depicts the X-ray fluorescence spectrum obtained by summing all of the X-ray photons detected by a charge-coupled device.

Based on the data from Figure 4.16, it can be concluded that with the high levels of calcium and low levels of silicon this sample could possibly contain gypsum. Gypsum is a sedimentary rock made of calcium sulfate with bound water. It is also found with deposits such as limestone, sand, shale, anhydrite and sometimes rock salt. Gypsum is one distinct mineral combination associated with volcanoes. Examples of other mineral combinations related to volcanoes are poly-hydrated sulfates and a smectite-zeolite-iron oxide mixture. With this information, it is reasonable to say that this sample indicates the possible presence of water in the past Mars environment and volcanic activity in glacial environments.

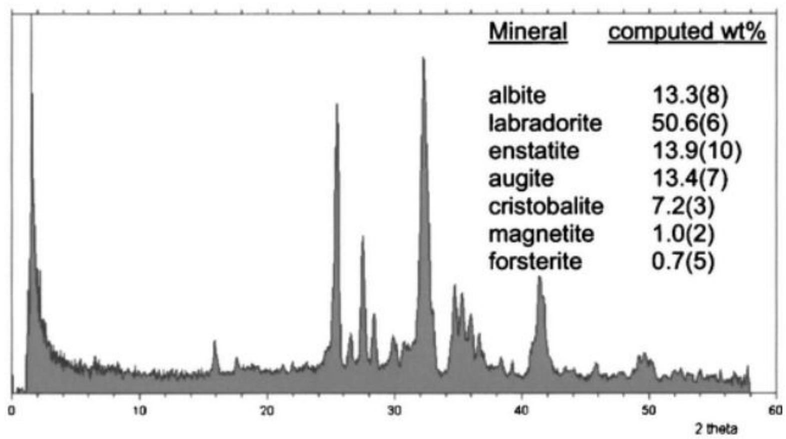


Figure 4.17: Mineral Composition of Andesite [53].

Using the composition of minerals in Figure 4.17, it was determined that the rock sample was andesite. This sulfur free rock can be classified as a type of volcanic rock that is formed by fractional crystallization of ferro-basalt magma. It can be concluded that with evidence of andesites, there is evidence of volcanic activity and potential evidence of water due to lava eruptions which occur where ice lays close to the surface. The magma melts the ice, releasing steam and possibly floods of water. This leaves deposits consisting of ash and small rocks on the Martian floor.

CheMin can only detect minerals that are present at a level of 3% and above. When minerals are present at 4 times the minimum detection level of 3% or above CheMin can accurately state the absolute amount present ±15%. CheMin has a precision of ±10% when measuring quantities of 4 times the minimum detection level [53].

RAT - Rock Abrasion Tool

Temp. (ºC)	Grind Current Margin of 0 (mA)	Grind Current Margin of 1 (mA)	Time to Overheat (min) for Margin of 0	Time to Overheat (min) for Margin of 0.5	Time to Overheat (min) for Margin of 1
+55	378.7	696.6	28	23.67	9.33
+35	396.3	710.77	Infinite	43.67	14.67
+23	400.83	704.27	Infinite	140.67	20
0	459.32	773.96	Infinite	Infinite	22
-20	471.37	779.3	Infinite	Infinite	31.67
-40	510.65	782.79	Infinite	Infinite	48
-55	539.5	844.45	Infinite	Infinite	41.67
-70	567.98	868.08	Infinite	Infinite	47.67

Table 4.13: Grind Motor Thermal Margins.

The grind motor is the most likely to overheat, and thus limits, the RAT functionality. Table 4.13, previously shown in Section 4.2.6, was derived from entering the current and its corresponding ambient temperature into a RE25 motor thermal model [43]. The information of the table indicates that at 55ºC the motor overheats in 28 minutes. The next lowest temperature 35ºC does not overheat, therefore making it the maximum turn-on temperature. All other temperatures tested did not have the problem of overheating based on the information given in the table.

Temp (ºC).	Maximum Motor Current (mA) at 3V, 150 mNm	2X Maximum Motor Current (mA) at 3V, 150 mNm	Overheat (min)	Maximum Motor Current (mA) at 6V, 150 mNm	2X Maximum Motor Current (mA) at 6V, 150 mNm	Overheat (min)
+55	34	68	Infinite	35.8	71.6	Infinite
+35	34.3	68.6	Infinite	36.9	73.8	Infinite
+23	36.1	72.2	Infinite	37.5	75	Infinite
0	35.8	71.6	Infinite	40.6	81.2	Infinite
-20	41.3	82.6	Infinite	53.1	106.2	Infinite
-40	67.7	135.4	Infinite	71	142	Infinite
-55	89.4	178.8	Infinite	74.6	149.2	Infinite
-70	142.1	284.2	Infinite	152.9	305.8	Infinite

Table 4.14: Revolve Motor Thermal Margin.

Rather than using the measured torque of the revolve motor, the torque margin was based on a no external load motor current as depicted in Table 4.14 [43]. When the revolve motor was run in velocity mode to simulate the required speed to operate during a grind (0.35 rad/sec), the thermal test points were analyzed, resulting in the no load motor current that was used to find the torque margin. The thermal margin was determined while running the revolve motor in voltage mode. By doubling the current, it was determined that the revolve motor does not overheat at any of the temperature points or voltages that were tested.

Temp (ºC).	Maximum Motor Current (mA) at 4V, 30N	2X Maximum Motor Current (mA) at 4V, 30 N	Overheat (min)	Maximum Motor Current (mA) at 8V, 30N	2X Maximum Motor Current (mA) at 8V, 30 N	Overheat (min)
+55	46.6	93.2	Infinite	43	86	Infinite
+35	41.4	82.8	Infinite	39.1	78.2	Infinite
+23	40.2	80.4	Infinite	46.3	92.6	Infinite
0	46.1	92.2	Infinite	52.2	104.4	Infinite
-20	56.7	113.4	Infinite	73.7	147.4	Infinite
-40	100.9	201.8	Infinite	137.8	275.6	Infinite
-55	127.8	255.6	Infinite	172.7	345.4	24.33
-70	167.4	334.8	Infinite	285.1	570.2	2.75

Table 4.15: Z-Axis Motor Thermal Margin.

Each of the thermal test points were tested by running the motor in velocity mode to simulate the required speed it needs to operate during a grind (0.05 mm/sec), resulting in the average motor current. The thermal margin was determined and the peak motor current had to be calculated and was doubled to determine transient heating of the motor at all thermal test points. It was found that the Z-Axis motor only overheated at –55ºC and below when run at a voltage of 8V as depicted in Table 4.15 [43].

Robotic Arm

Parameter	Value	Comment
Degrees of freedom	4 rotary joints - shoulder yaw (azimuth), shoulder pitch, elbow pitch, wrist pitch.	Back-hoe design.
Reach	2-m radius sphere	
Max Cartesian velocity	0.07m/sec	Configuration dependent.
Mass	5 Kg.	Includes electronics (868g).
Materials: Upper Arm and forearm link Scoop Blade Secondary Blades	 Graphite-epoxy tubes. 6Al-4V Ti STA Tungsten Carbide, GC015	
Actuators	DC motors with 2-stage drive train (planetary gear plus harmonic drive).	Wrist has bevel gear for 2nd stage instead of harmonic drive.
Accuracy and repeatability	1 cm and 0.5 cm, respectively.	
End-effector force capability	Configuration dependent; typically 80 Newtons.	
Thermal environment: Non-operating: Shoulder, upper Arm, elbow Forearm, scoop, wrist Operating: Shoulder, upper Arm, elbow Forearm, scoop, wrist	 173 K to 308 K. 153 K to 308 K 193 K to 308 K 168 K to 308 K	Heaters used when necessary to bring actuator temperatures up to 208K before operation.
Scoop volume	TBD	
Power	42W peak during heavy digging, 15W average during free space motion.	Load dependent. Values include 5W for electronics.
Joint parameters	See Table 2.	

Table 4.16: Robotic Arm Parameters

$$I_{nl} = I_0 T + a e^{-bT} (V/V_{max})$$

Equation 4.2: No-load Motor Current.

$$t=K_a (I-I_{nl})$$

Equation 4.3: Joint Torque.

The robotic arm has an accuracy within 0.5 cm to 1 cm and it can operate in thermal temperatures within 193 K to 308 K [54]. Ideal non-operational thermal conditions fall within 173K to 308K. The no-load motor currents were computed by Equation 4.2, while the joint torques were computed from Equation 4.3, where I_{nl} is the no-load motor current, I_0 is the no-load current at 293 K, and a and b are constants. The actuators are capable of producing 26, 91, 53, and 10 Newton-meters of torque at the joint output during normal operation for joints 1 through 4, respectively. Peak limits are approximately 50% higher.

Based on the data, it can be concluded that the robotic arm will only be able to operate on the surface on Mars during midday hours to prevent overheating issues. However, to prevent dropping internal temperatures too low, heating systems (RHUs) will be put in place to provide heat during night hours. Given its accuracy, the robotic arm will be able to collect samples as expected with the support of the NAVCAM to provide additional visual support.

NAVCAM - Navigational Camera

Table 4 MSL Engineering Camera optical properties

	Navcam
Pixel scale at the center of the FOV	0.82 mrad/pixel
Focal Length	14.67 mm
f/number	12
Entrance Pupil Diameter	1.25 mm
Field of View (horizontal × vertical)	45 × 45 degrees
Diagonal FOV	67 degrees
Depth of Field	0.5 meters–infinity
Hyperfocal Distance	1.0 meters
Spectral Range	600–800 nm

Table 4.17: MSL Engineering Camera and Optical Properties.

Table 5 MSL Engineering Camera configuration summary	
Property	Navcam
Stereo baseline	42.4 cm
Stereo co-alignment difference	<1 degree
Boresight Pointing Direction	0–360 degrees, azimuth −87 through +91 degrees, elevation
Height above Martian Surface	1.9 meters (exact value depends on elevation of RSM head)
Mass (per camera)	220 grams
Dimensions (per camera)	67 × 69 × 34 mm (electronics) 41 × 51 × 15 mm (detector head)
Power (per camera)	2.15 Watts

Table 4.18: MSL Engineering Camera Configuration Summary [55].

The NAVCAM will be providing visual support to coordinate and maneuver the robotic arm as well as to select desirable samples. According to the data, the NAVCAM has a range from 0.5 meters with a hyperfocal distance of 1.0 meters. Given that the maximum height of the robotic arm will be approximately 1.9 m from the ground, it will be more than capable of providing distinct images of rocks beneath it.

Additionally with a field of view of 45 x 45 degrees and 67 degrees diagonally, uploaded images display a wide view of the surrounding surface. Its detector is a frame-transfer device with a 12.3 mm x 12.3 mm imaging region containing 1024 x 1024 pixels. Considering that the NAVCAM is very conservative in power consumption, it can continuously operate through a Martian sol; however, it is restricted by power constraints of the CheMin and overheating issues from the RAT. The NAVCAM will only operate during midday hours. The NAVCAM will be able to gather data of its immediate environmental surroundings by capturing high quality images to be downloaded to the uplink with a compression rate of 3.0 bits per pixel.

5. Safety

5.1. Personnel Safety

5.1.1. Safety Officer

The Safety Officer is Erika Szaldobagyi and her responsibilities are to make sure the mission is safe and everything is in working order. On the team, the Safety Officer is responsible for assessing and consolidating the personnel and environmental risk analysis and collaborating with the Lead Scientist and Lead Engineer to understand technical risk (design) and environmental hazards. Her role is to help during all phases of the project and keep everyone safe at any point of the mission. Hazards can come up at any time, so having the Safety Officer will prepare for any possible disaster and be available to address concern during the progress of the mission.

For the past few weeks, she has been helping the Science and Engineering teams with research on how to approach these ideas with safety in mind. Later after taking into account all the safety risks the team made the final decisions on the project, which helped progress the mission. During any project, plans will change, so being prepared to deal with unexpected problems is important.

5.1.2. List of Personnel Hazards

In any mission, there are personnel hazards, but planning ahead is crucial to prevent them from causing danger to the personnel and the mission. For this mission, the team is working remotely when it comes to planning and organizing the mission. Personnel will be forced to follow safety guidelines during the process, particularly during the concept's manufacturing.

The Safety Officer needs to keep in mind people on sick leave due to COVID-19 situations and other health issues.

If workers are exposed to hazardous chemicals and machines, personnel health will be affected. Machine work hazard situations include, but not limited to: accidental cuts, burns from chemicals or fire, and radioactive machines and equipment.

Figure 5.1: Personal Protective Equipment Examples.

A safety officer must ensure that individuals have proper Personal Protective Equipment (PPE) in order to reduce damage to equipment and themselves [56]. Figure 5.1 shows the way people will dress when working in the clean rooms, which is important to keep their vital organs safe while building the lander.

Figure 5.2: Globally Harmonized System of Classification [57].

Implementation of safety cycles and charts will help to educate employees on how to properly keep themselves safe while working in dangerous areas. Globally Harmonized System of Classification and Labelling of Chemicals (GHS) Hazard signs located outside/inside of the door of a room that contains specific types of potential hazards that can be found in Figure 5.2 to protect personnel and the mission’s lander [57]. Informing personnel on how to properly take care of themselves in dangerous situations is important, so employees will be trained in workplace safety classes. First aid kits and basic safety kits will be in the team's lab and machine shop for any staff member to use if needed. Medic areas in the facility and wash locations for chemical exposure are important too, which our team will have access to them.

5.1.3. Hazard Mitigation

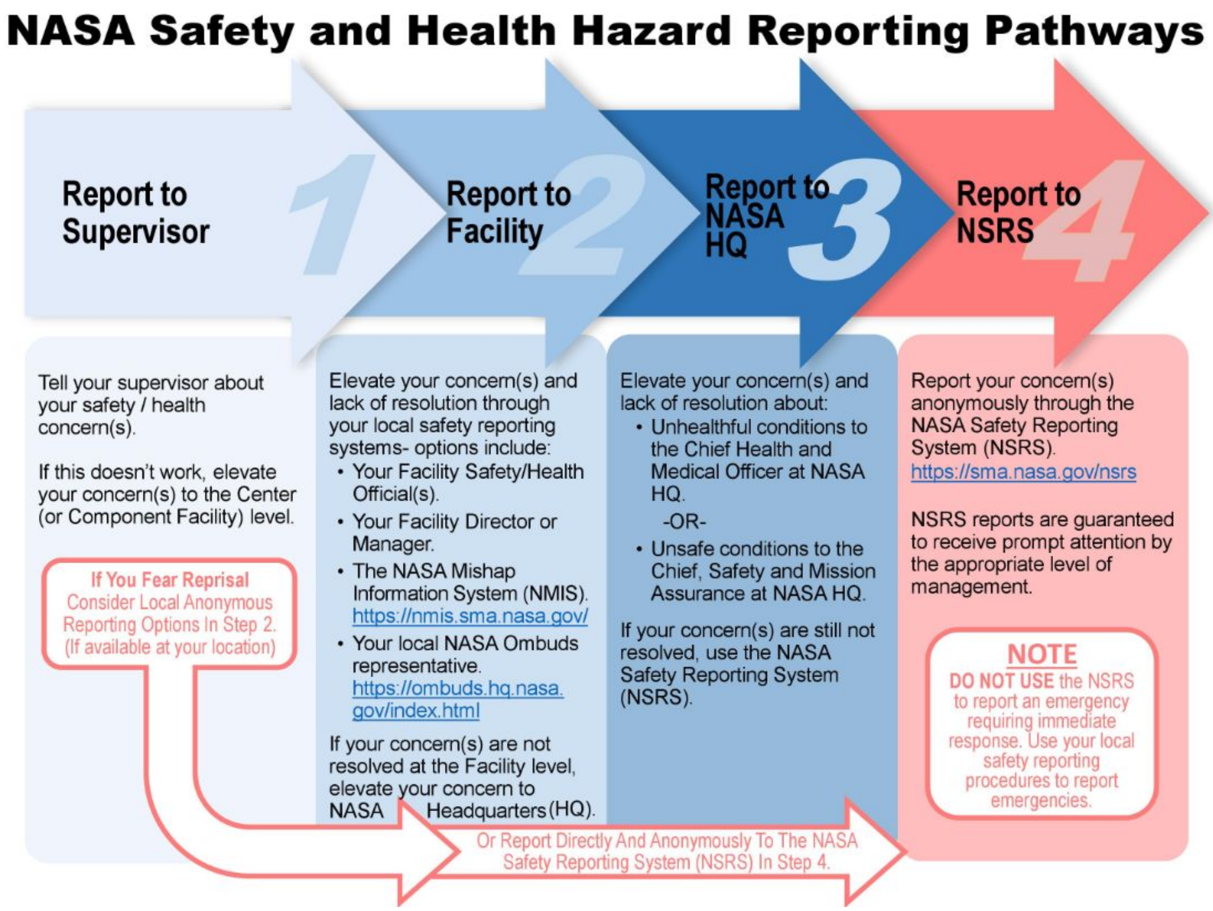


Figure 5.3: NASA Safety Pathway [58].

The following steps in Figure 5.3 will be followed to mitigate all types of hazards [58]. Material Safety Data Sheets (MSDS) will be available for anyone working in hazardous areas. The hazard mitigation process works if people follow the rules given to them before they start working on the site. Being prepared will be done by following previous steps given in the Safety Manual from NASA. Our team will prepare for any possible disaster [59]. Also, the Safety Officer will establish International Organization for Standardization (ISO) certification in safety standards for the mission. Safety training and safety tests will be required for anyone working in labs and machine shops.

The Safety Officer will verify testing is done thoroughly, double check their abilities, and have workshops with step by step instructions to ensure parts operate smoothly. There are many ways to improve the safety for a successful mission, so it is up to the crew to prepare. The charts and examples above just show some of the most unique ways to deal with risks on NASA missions.

5.2. Lander/Payload Safety

5.2.1. Environmental Hazards

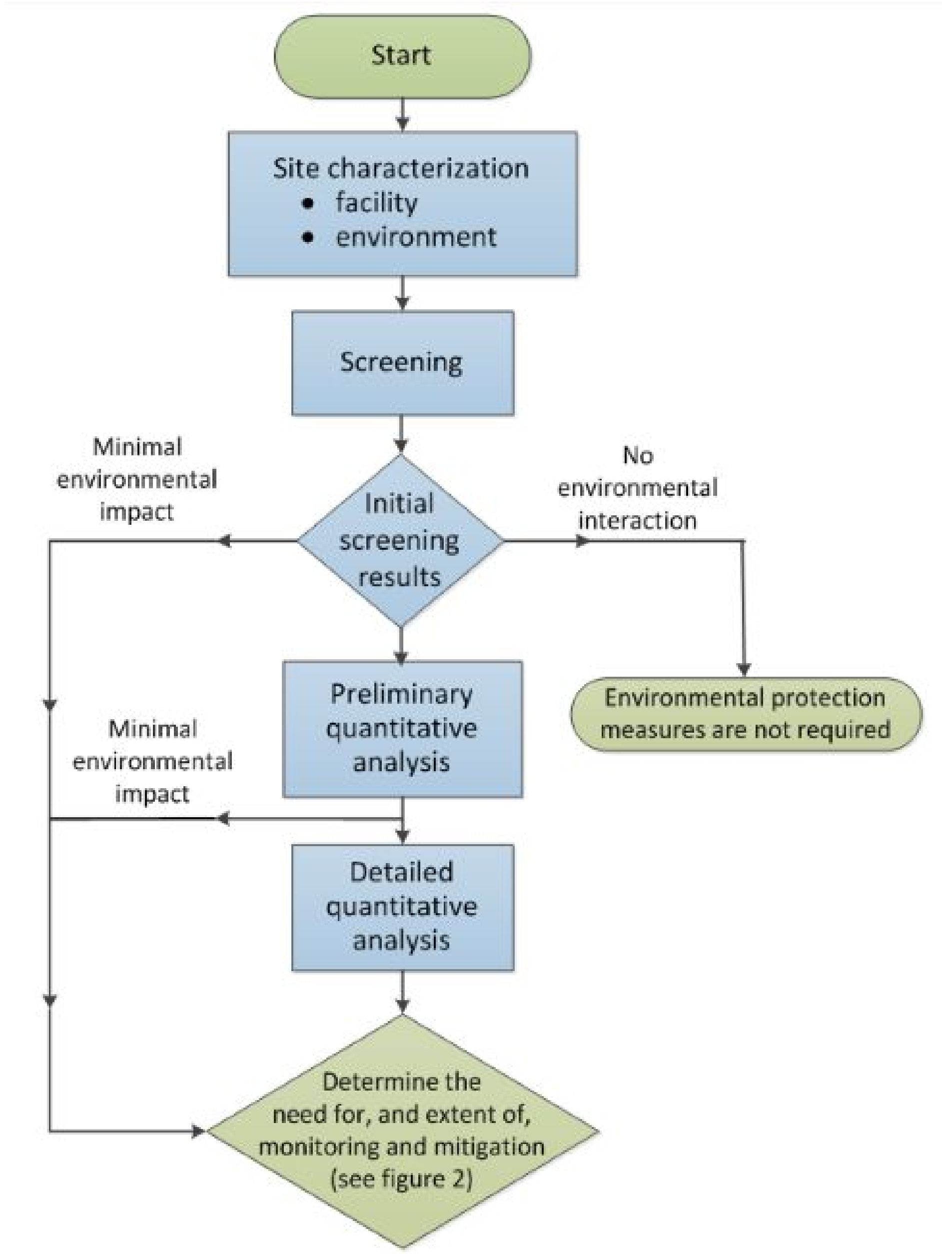


Figure 5.4: Environmental Hazard FlowChart

Environmental hazards are important for all departments to be prepared for before any journey, so having anything leave Earth and head to Mars will require several environmental perspectives. In Figure 5.4, one can see the process of how to mitigate environmental hazards [60]. Environmental Management Systems (EMS) is a department of NASA that looks into environmental safety on Earth and Risk Management. Making sure materials are able to withstand extreme high and low temperatures is important for a successful mission in space, so safety measures will be made to keep this mission working as planned. Actions done to address these hazards are addressed in Section 4.1.4; there are steps to a safe environment when the lander is on Mars.

A possible way to protect the lander would be to make a special coating that is electrically charged, so that it could shield the lander from particulates that could possibly damage the machinery. It would also help in collecting data. The team found a coating that protects the lander's exterior with a layer of hydrophobic material in combination with anti-corrosive and anti-dust spray, in order to reduce mechanical faults that could happen from the harsh dust and rock storms on Mars. Another goal for the layering is to make the science data gathered more precise and accurate. This process could possibly extend the mission. For example, if there was a dust storm on Mars, the dust can potentially cover the solar panels that are on the lander, leading to reduction in electrical energy used to power the lander. Protecting the lander is critical to the success of this mission.

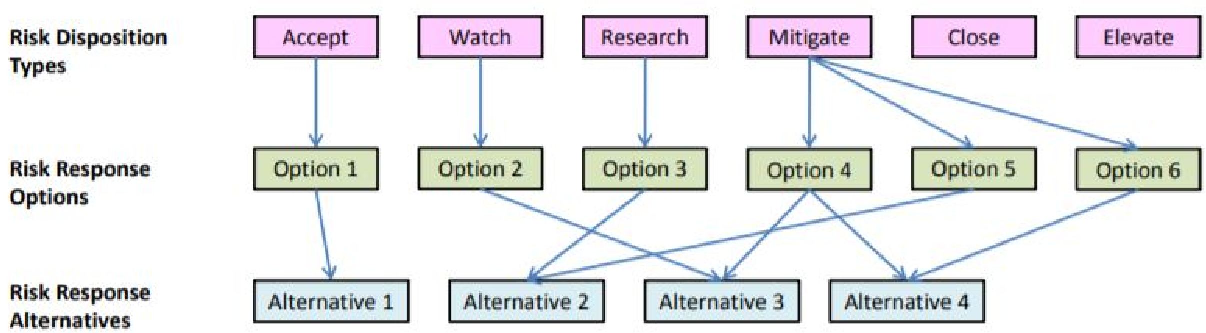


Figure 5.5: Relationship between Risk Response Options and Risk Response Alternatives [60].

Figure 5.5 shows the relationship between risk response options and risk response alternatives in an organized diagram, which will be handy during the mission [60].

5.2.2. Hazard Mitigation

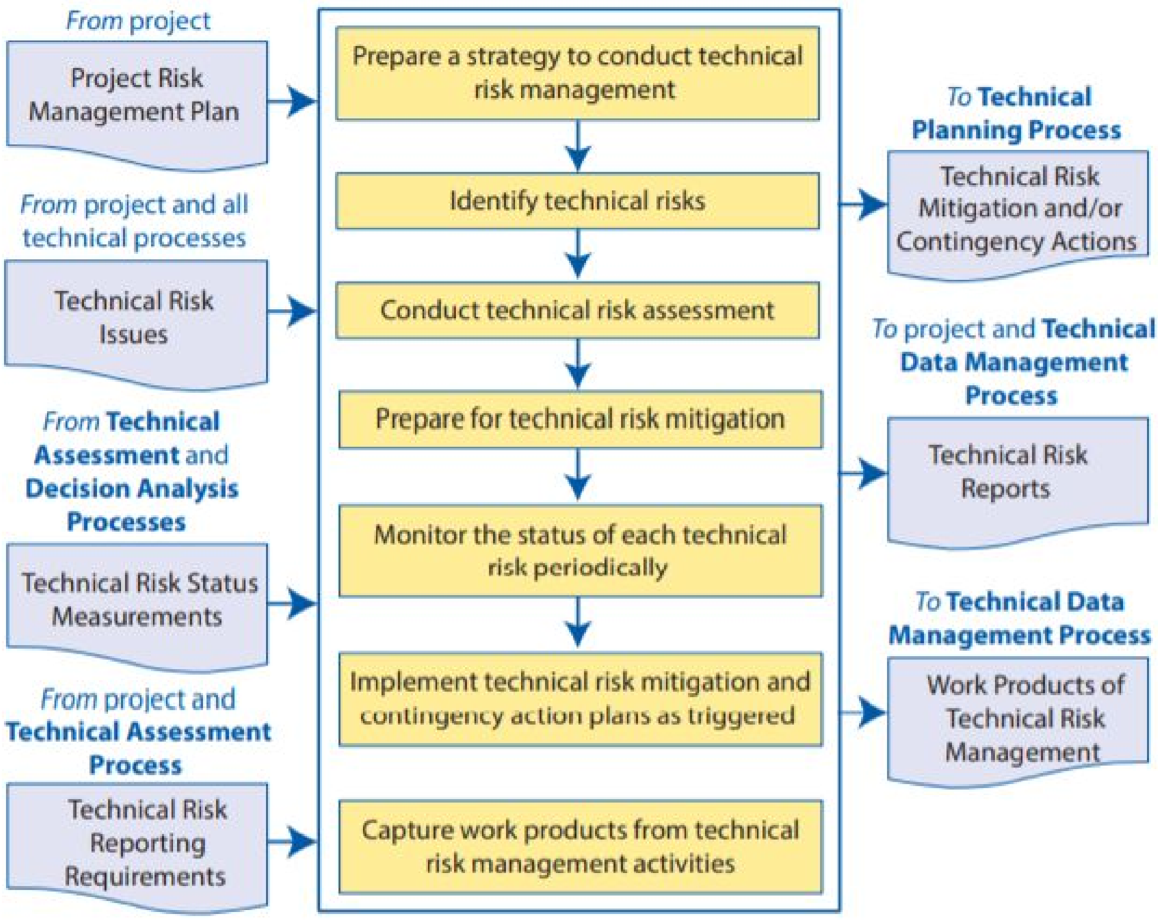


Figure 5.6: Hazard Mitigation Flowchart.

When it comes to hazard mitigation, as seen in Figure 5.6, there are many strategies to plan the best mission possible [60]. Some of the ways to test the parts of the lander are through a wind tunnel, sound resistance room, vibration platforms, and many other methods of checking the capabilities on Earth as if it was in space. The team will see how the lander reacts in space whilst being on Earth in order to ensure that the mission will operate and perform properly, and that any problems that arise can be fixed before space flight. Additional info on safety tips can be found in NASA's Risk Management Handbook [60].

Testing on a microscopic level is critical to keep information and data as accurate as possible. The payload must be able to send in information properly, so that it can communicate properly back to Earth or its small communication station on Mars. A simulation of Mars, like the one found at JPL can help prepare the lander for possible obstacles on Mars' surface. Several trial runs to collect samples on the artificial surface will prepare the lander for its journey to Mars and ensure the CheMin and Robotic Arm functions properly. Due to these factors, building of the lander takes place at JPL. This mission has many factors for good performance, so Figure 5.7 shows steps to ensure the best results [60].

Performance Measures for Planetary Spacecraft	**Performance Measures for Launch Vehicles**
• End-of-mission (EOM) dry mass • Injected mass (includes EOM dry mass, baseline consumables and upper stage adaptor mass) • Consumables at EOM • Power demand (relative to supply) • Onboard data processing memory demand • Onboard data processing throughput time • Onboard data bus capacity • Total pointing error	• Total vehicle mass at launch • Payload mass (at nominal altitude or orbit) • Payload volume • Injection accuracy • Launch reliability • In-flight reliability • For reusable vehicles, percent of value recovered • For expendable vehicles, unit production cost at the n^{th} unit

Figure 5.7: Performance Measures Examples for Planetary Spacecraft and Launch Vehicles.

6. Activity Plan

6.1. Budget

# People on Science Team:	2		
# People on Engineering Team:	8		
# People on Administrative Team:	1		
# People as Safety Officer	1		
NASA L'SPACE Mission Concept Academy Budget SU 2020 - DAEMONES			
Year	**Yr 1 Total**	**Yr 2 Total**	**Cumulative Total**
PERSONNEL			
Science Team	$ 160,000.00	$ 160,000.00	**$ 320,000.00**
Engineering Team	$ 640,000.00	$ 640,000.00	**$ 1,280,000.00**
Administrative Team	$ 80,000.00	$ 80,000.00	**$ 160,000.00**
Safety Officer	$ 40,000.00	$ 40,000.00	**$ 80,000.00**
Total Salaries	$ 920,000.00	$ 920,000.00	**$ 1,840,000.00**
Total ERE	$ 256,772.00	$ 256,772.00	**$ 513,544.00**
TOTAL PERSONNEL	$ 1,176,772.00	$ 1,176,772.00	**$ 2,353,544.00**
TRAVEL			
Total Flights Cost	$ -	$ 2,365.00	**$ 2,365.00**
Total Hotel Cost	$ -	$ 1,787.00	**$ 1,787.00**
Total Transportation Cost	$ -	$ 1500.00	**$ 1,500.00**
Total Per Diem Cost	$ -	$ 3,600.00	**$ 3,600.00**
Total Travel Costs	$ -	$ 9,252.00	**$ 9,252.00**
OTHER DIRECT COSTS			
Total Outsourced Instrument Cost	$ 2,584,695.00	$ -	**$ 2,584,695.00**
Total Materials and Supplies Cost	$ 29,926,442.78	$ -	**$ 29,926,442.78**
Total Equipment Cost	$ 10,000,000.00	$ -	**$ 10,000,000.00**
Emergency Fund	$ 3,000,000.00	$ 3,000,000.00	**$ 6,000,000.00**

Manufacturing Margin	$ 19,963,221.39	$ -	**$ 19,963,221.39**
Total Direct Costs	$ 66,651,131.17	$ 4,186,024.00	**$ 39,926,442.78**
Total MTDC	$ 51,651,131.17	$ 4,186,024.00	**$ 29,926,442.78**
FINAL COST CALCULATIONS			
Total F&A	$ 5,165,113.12	$ 418,602.40	**$ 5,583,715.52**
Total Projected Cost	$ 71,816,244.29	$ 4,604,626.40	**$ 76,420,870.69**
Total Cost Margin	$ 21,544,873.29	$ 1,381,387.92	**$ 22,926,261.21**
Total Project Cost	$ 93,361,117.57	$ 5,986,014.32	**$ 99,347,131.89**
*********** Do not change percentages in the boxes below unless mission concept instructions specify otherwise.**			
F&A %	10%	10%	
Manufacturing Margin	50%	50%	
Total Cost Margin	30%	30%	
ERE - Staff	28%	28%	

Table 6.1: Budget Sheet.

Overall, we managed to complete our mission within the budget with the total Project Cost of $99,347,131.89. Our budget constraint is $100 million for a large lander concept and the team managed to fit that goal.

6.2. Schedule

Phase Schedule

X Æ L-38

Team Number: 38

Project Team Members: Gerardo Baron Diaz, Dana Chin, Jaira Shayne Farala, Apoorva Gunti, Shayan Javid, Ronell Lim, Susana Salazar, Erika Szaldobagyi, Bryant Ta, Erika Trinh, Maya Zeng, Yogita Bali

Project Start: 5/19/2020

Today: 8/1/2020

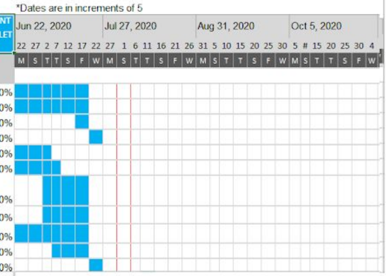
Display Week: 6

Milestones in Orange
Reviews in Blue

* = an automatically calculated cell

TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Phases								
Pre-Phase A Concept Studies								
Review/Identify scope of work	6/16/2020	16	7/19/2020	34	0	34	All Team	0.00%
Identify and involve users and other	6/16/2020	16	7/19/2020	34	0	34	Maya Z	0.00%
Develop and baseline Concept of Operations	7/15/2020	15	7/19/2020	5	0	5	Maya Z	0.00%
Buffer Time	7/19/2020	19	7/26/2020	8	0	8	Maya Z	0.00%
Identify Risk Classification	6/16/2020	16	7/6/2020	21	0	21	Erika S	0.00%
Identify Technical Risks	6/22/2020	22	7/7/2020	16	0	16	Erika S	0.00%
Identify the roles and responsibilities in performing mission objectives	6/28/2020	28	7/21/2020	24	0	24	Hannah and Isabel	0.00%
Develop plans	6/28/2020	28	7/21/2020	24	0	24	Ronell L, Apoorva G, Maya Z	0.00%
Prepare program/project proposals	6/22/20	22	7/21/2020	30	0	30	Ronell L, Apoorva G, Maya Z	0.00%
Buffer Time	7/7/2020	7	7/21/2020	15	0	15	Ronell L, Apoorva G, Maya Z	0.00%
Satisfy Mission Concept Review (MCR)	7/21/2020	21	7/26/2020	6	0	6	Ronell L, Apoorva G, Maya Z	0.00%

*Dates are in increments of 5



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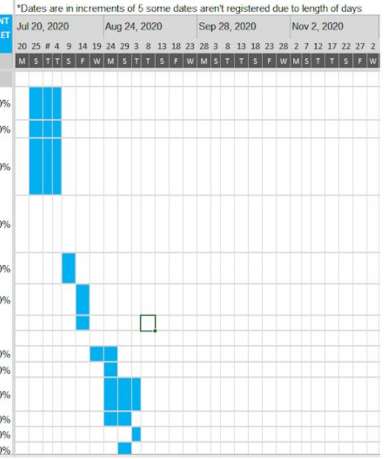
TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Phases								
Phase A Concept and Technology Development								
Review and update documents baselined in Pre-Phase A if needed	7/21/2020	21	8/6/2020	17	0	17	Ronell L, Apoorva G, Maya Z	0.00%
Monitor progress against plan	7/21/2020	21	8/8/2020	19	0	19	Maya Z	0.00%
Develop and baseline top-level requirements and constraints including internal and external interfaces, integrated logistics and maintenance support, and system software functional	7/21/2020	21	8/5/2020	16	16	0	Ronell L, Erika T, Susana S, Gerardo D ,Bryant T, Shayan J	100.00%
Buffer Time	8/5/2020	5	8/8/2020	4	4	0	Ronell L, Erika T, Susana S, Gerardo D ,Bryant T, Shayan J	100.00%
System Design Review (SDR)	8/8/2020	8	8/9/2020	2	0	2	All Teams	0.00%
Allocate system requirements to functions and to next lower level	8/10/2020	10	8/14/2020	5	0	5	Ronell L, Erika T, Susana S, Gerardo D ,Bryant T, Shayan J	0.00%
Validate requirements	8/14/2020	14	8/16/2020	3	0	3	Yogita	
Buffer Time								
Baseline plan	8/16/2020	16	8/25/2020	10	0	10	Ronell L, Apoorva G, Maya Z	0.00%
Develop preliminary verification and validation plan	8/20/2020	20	8/25/2020	6	0	6	Ronell L, Apoorva G, Maya Z	0.00%
Establish human rating plan and perform initial evaluation	8/21/2020	21	9/5/2020	16	0	16	Erika S.	0.00%
Buffer Time	8/23/2020	23	8/31/2020	9	0	9	All Team	0.00%
Mission Concept Review (MCR)	8/31/2020	31	9/7/2020	8	0	8	All Team	0.00%
Develop and baseline mission architecture	8/25/2020	25	9/1/2020	8	0	8	Apoorva G, Ronell L	0.00%

*Dates are in increments of 5 some dates aren't registered due to length of days



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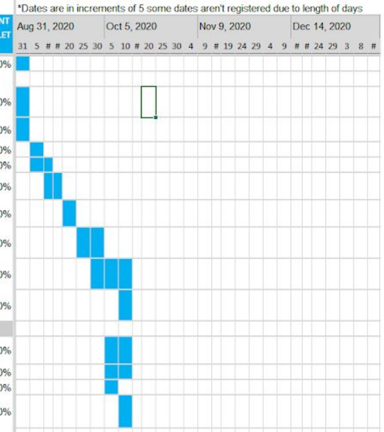
TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Develop and baseline mission architecture	8/25/2020	25	9/1/2020	8	0	8	Apoorva G, Ronell L	0.00%
Buffer Time								
Initiate environmental evaluation/National Environmental Policy Act process	8/25/2020	25	9/1/2020	8	0	8	Erika S.	0.00%
Develop initial orbital debris assessment (NASA-STD-8719.1	8/25/2020	25	9/1/2020	8	0	8	Erika S.	0.00%
Perform technical management	9/1/2020	1	9/5/2020	5	0	5	Hannah and Isabel	0.00%
Identify, analyze and update risk	9/5/20	5	9/10/2020	6	0	6	Erika S.	0.00%
Perform required Phase A technical activities from NPR 7120.5 as applicable	9/10/2020	10	9/17/2020	8	0	8	Ronell L, Apoorva G, Maya Z	0.00%
Buffer Time	9/17/2020	17	9/23/2020	7	0	7	Ronell L, Apoorva G, Maya Z	0.00%
Satisfy Phase A reviews' entrance/success criteria from NPR 7123.1	9/23/2020	23	9/30/2020	8	0	8	Ronell L, Apoorva G, Maya Z	0.00%
Buffer Time	9/30/2020	30	10/10/2020	11	0	11	All Team	0.00%
System Requirements Review (SRR)	10/10/2020	10	10/11/2020	2	0	2	All Team	0.00%
Phase B Preliminary Design and Tech Completion								
Review and update documents baselined in previous phase	10/5/2020	5	10/10/2020	6	0	6	Ronell L, Apoorva G, Maya Z	0.00%
Monitor progress against plan	10/4/2020	4	10/14/2020	11	0	11	Ronell L, Apoorva G, Maya Z	0.00%
Develop the preliminary design	10/4/2020	4	10/8/2020	5	0	5	All Team	0.00%
Develop operations plans based on matured ConOps	10/8/2020	8	10/14/2020	7	0	7	Maya Z	0.00%

*Dates are in increments of 5 some dates aren't registered due to length of days



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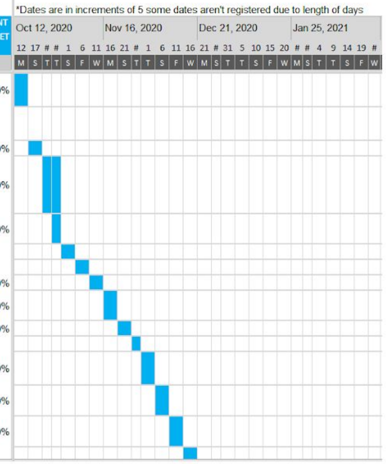
TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Phases								
Develop operations plans based on matured ConOps	10/8/2020	8	10/14/2020	7	0	7	Maya Z	0.00%
Buffer Time								
Report technology development results	10/14/2020	14	10/21/2020	8	0	8	Engineering Team	0.00%
Update cost range estimate and schedule data (Note that after PDR changes are incorporated and costed, at KDP C this will turn into the Agency Baseline Commitmee	10/21/2020	21	10/31/2020	11	0	11	Maya Z	0.00%
Improve fidelity of models and prototypes used in evaluation	10/23/2020	23	10/28/2020	6	0	6	Engineering Team	0.00%
Buffer Time	10/28/2020	28	11/2/2020				All Team	
System Definition Review (SDR)	11/2/2020	2	11/7/2020					
Identify and update risks	11/7/2020	7	11/12/2020	6	0	6	Erika S.	0.00%
Develop appropriate level safety data package and security plan	11/12/2020	12	11/17/2020	6	0	6	Erika S.	0.00%
Develop preliminary plans	11/17/2020	17	11/22/2020	6	0	6	Ronell L, Apoorva G, Maya Z	0.00%
Buffer Time	11/22/2020		11/27/2020					
Perform required Phase B technical activities from NPR 7120.5 as applicable	11/27/2020	27	12/2/2020	6	0	6	Ronell L, Apoorva G, Maya Z	0.00%
Satisfy Phase B reviews' entrance/success criteria from NPR 7123.1	12/2/2020	2	12/7/2020	6	0	6	Ronell L, Apoorva G, Maya Z, Hannah and Isabel	0.00%
Buffer Time	12/7/2020	7	12/12/2020	6	0	6	Ronell L, Apoorva G, Maya Z, Hannah and Isabel	0.00%
Buffer Time								



Reviews in Blue

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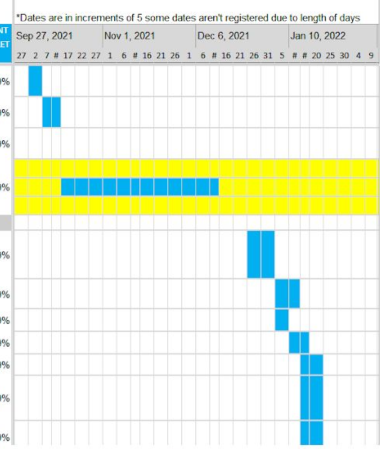
TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Test Readiness Review (TRR)	10/1/2021	1	10/2/2021	2	0	2	All Team	0.00%
Buffer Time	10/3/2021	3	10/13/2021	11	0	11	All Team	0.00%
Operational Readiness Review (ORR)	10/13/2021	13	10/14/2021	2	0	2	All Team	0.00%
LAUNCH	10/15/2021	15	12/14/2021	61	0	61	All Team	0.00%
Phase E Operations and Sustainment								
Conduct launch vehicle performance assessment. Commission and activate science instruments	12/24/2021	24	1/3/2022	11	0	11	Science Team	0.00%
Buffer Time	1/3/2022	3	1/13/2022	11	0	11	Science Team	0.00%
Conduct the intended prime mission(s)	1/3/2022	3	1/8/2022	6	0	6	Science Team	0.00%
Buffer Time	1/8/2022	8	1/18/2022	11	0	11	Science Team	0.00%
Provide sustaining support as planned	1/13/2022	13	1/23/2022	11	0	11	Ronell L, Apoorva G, Maya Z	0.00%
Prepare for deactivation, disassembly, decommissioning as planned (subject to mission extension)	1/13/2022	13	1/23/2022	11	0	11	Maya Z	0.00%
Perform verification and validation on assemblies according to the V&V Plan and	1/13/2022	13	1/23/2022	11	0	11	Erika S	0.00%



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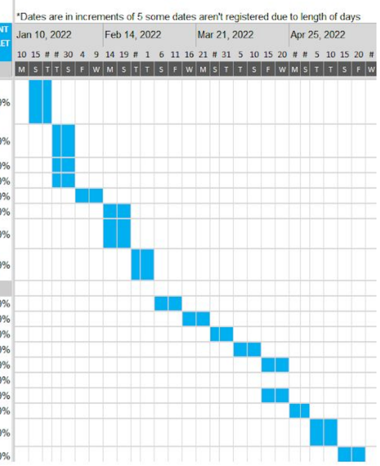
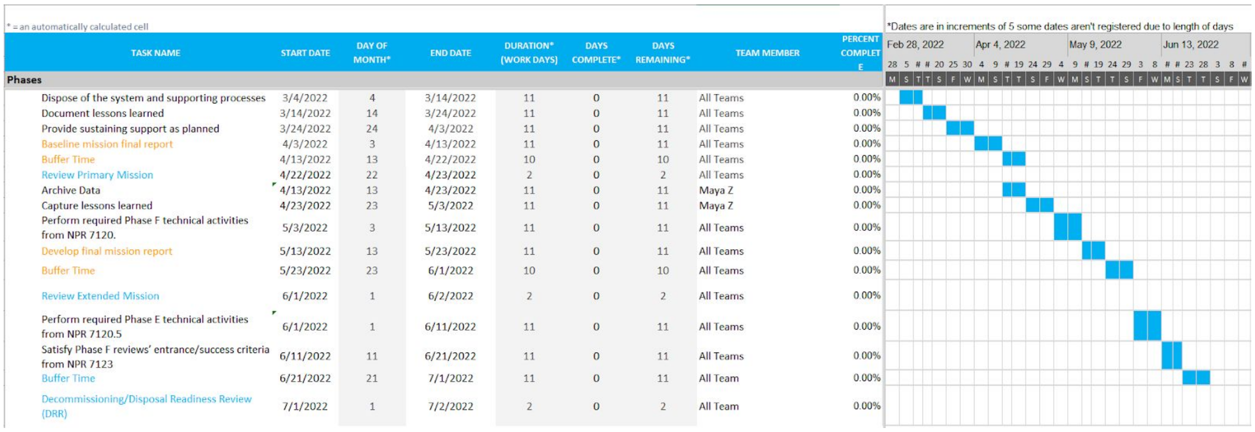
TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Phases								
Perform verification and validation on assemblies according to the V&V Plan and procedures	1/13/2022	13	1/23/2022	11	0	11	Erika S	0.00%
Buffer Time	1/23/2022	23	2/2/2022	11	0	11	All Team	0.00%
Capture lessons learned	1/23/2022	23	2/2/2022	11	0	11	Maya	0.00%
Complete post-flight evaluation reports	1/23/2022	23	2/2/2022	11	0	11	Engineering Team	0.00%
Develop final mission report	2/2/2022	2	2/12/2022	11	0	11	Ronell L, Apoorva G, Maya Z, Hannah and Isabel	0.00%
Buffer Time	2/12/2022	12	2/22/2022	11	0	11	All Team	0.00%
Perform required Phase E technical activities from NPR 7120.5	2/12/2022	12	2/22/2022	11	0	11	Ronell L, Apoorva G, Maya Z, Hannah and Isabel	0.00%
Satisfy Phase E reviews' entrance/success criteria from NPR 7123.1	2/22/2022	22	3/4/2022	11	0	11	Ronell L, Apoorva G, Maya Z, Hannah and Isabel	0.00%
Phase F Closeout								
Dispose of the system and supporting processes	3/4/2022	4	3/14/2022	11	0	11	All Teams	0.00%
Document lessons learned	3/14/2022	14	3/24/2022	11	0	11	All Teams	0.00%
Provide sustaining support as planned	3/24/2022	24	4/3/2022	11	0	11	All Teams	0.00%
Baseline mission final report	4/3/2022	3	4/13/2022	11	0	11	All Teams	0.00%
Buffer Time	4/13/2022	13	4/22/2022	10	0	10	All Teams	0.00%
Review Primary Mission	4/22/2022	22	4/23/2022	2	0	2	All Teams	0.00%
Archive Data	4/13/2022	13	4/23/2022	11	0	11	Maya Z	0.00%
Capture lessons learned	4/23/2022	23	5/3/2022	11	0	11	Maya Z	0.00%
Perform required Phase F technical activities from NPR 7120.	5/3/2022	3	5/13/2022	11	0	11	All Teams	0.00%
Develop final mission report	5/13/2022	13	5/23/2022	11	0	11	All Teams	0.00%





* = an automatically calculated cell

*Dates are in increments of 5 some dates aren't registered due to length of days

TASK NAME	START DATE	DAY OF MONTH*	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	TEAM MEMBER	PERCENT COMPLETE
Phases								
Dispose of the system and supporting processes	3/4/2022	4	3/14/2022	11	0	11	All Teams	0.00%
Document lessons learned	3/14/2022	14	3/24/2022	11	0	11	All Teams	0.00%
Provide sustaining support as planned	3/24/2022	24	4/3/2022	11	0	11	All Teams	0.00%
Baseline mission final report	4/3/2022	3	4/13/2022	11	0	11	All Teams	0.00%
Buffer Time	4/13/2022	13	4/22/2022	10	0	10	All Teams	0.00%
Review Primary Mission	4/22/2022	22	4/23/2022	2	0	2	All Teams	0.00%
Archive Data	4/13/2022	13	4/23/2022	11	0	11	Maya Z	0.00%
Capture lessons learned	4/23/2022	23	5/3/2022	11	0	11	Maya Z	0.00%
Perform required Phase F technical activities from NPR 7120.	5/3/2022	3	5/13/2022	11	0	11	All Teams	0.00%
Develop final mission report	5/13/2022	13	5/23/2022	11	0	11	All Teams	0.00%
Buffer Time	5/23/2022	23	6/1/2022	10	0	10	All Teams	0.00%
Review Extended Mission	6/1/2022	1	6/2/2022	2	0	2	All Teams	0.00%
Perform required Phase E technical activities from NPR 7120.5	6/1/2022	1	6/11/2022	11	0	11	All Teams	0.00%
Satisfy Phase F reviews' entrance/success criteria from NPR 7123	6/11/2022	11	6/21/2022	11	0	11	All Teams	0.00%
Buffer Time	6/21/2022	21	7/1/2022	11	0	11	All Team	0.00%
Decommissioning/Disposal Readiness Review (DRR)	7/1/2022	1	7/2/2022	2	0	2	All Team	0.00%

Figure 6.1: Project Phase Schedule Gantt Chart.

6.3. Outreach Summary

Due to the current situation with COVID-19, the team has established to reach out to students and K-12 students remotely. Depending on the situation, the team wants to target the outreach plan towards K-12 students that are from disadvantaged schools. The team plans to use Zoom as a platform to meet with the students during lessons due to its popularity and ease of use. In order to establish a presence and awareness of the program, the team will reach out through teachers or social media platforms, such as Instagram, Facebook, and LinkedIn, given their low cost yet high view rate to posts. During these sessions, the team is planning to implement science experiments that are relevant to NASA science and mission objectives. If an individual is unable to attend these sessions, the team is planning to upload these sessions to Youtube in order to spread awareness of NASA's activities while fostering excitement towards space exploration and science.

In the promotion of NASA's mission to Mars, the team is going to implement the readily available resources provided by NASA in relation to Mars research and education. Arizona State University has a website intended for that purpose and the team would like to implement the lesson plans and activities, such as Maker Mars. Maker Mars introduces systems engineering to students by using the "Engineering Design Cycle to develop a prototype to solve a problem" [61]. The Engineering Design Cycle is pertinent to the current NASA missions since it provides insight to the real-world constraints that NASA may encounter that can affect the completion of a mission. For a more hands-on activity, the team may also introduce the Soda Straw Rockets to let students "plan and conduct an investigation into the effects of forces on the distance and path traveled of a soda straw rocket using empirical evidence to explain the impact of a net force on an object" [62]. The students can create something with their own hands while learning the principles of engineering.

6.4. Program Management Approach

A team that works together cohesively thrives. When teammates help each other overcome challenges, problems are solved efficiently. Organization workflow provides an extra layer of reinforcement to team mission, which reduces errors. All teammates worked together and had the opportunity to share and contribute to a project of high caliber. The only way to collaborate on a project is to coordinate with the team on a project according to their line of work, strength and expertise, which guided the teams towards their achievements. Communication is key and channels must be open to get information out to the right people as fast as possible.

Originally, team structure was decided based on an individual's interest towards a particular role. Reason being was that the team with their preferred roles would work more effectively. However, the roles had to be changed midway and coordinator intervention was necessary to continue making progress

In the end, the team had mentors established as Project Manager (PM) and Deputy Project Manager (DPM), and created a new organization chart to reflect the changes that were happening in the team. New roles were established, described, and assigned by the PM and DPM.

To get the team back on track, the PM and DPM established a traceability matrix for the PDR and a new shared drive to keep everything in one place. The team also established to actively use Trello tools, finalizing the use of Discord as the main point of communication between team members. Teams were formed to facilitate communication between the newly created teams and the general group meeting format had been addressed to be more inclusive of the concerns and comments of the team members.

Mission Assurance consists of Yogita Bali, and her responsibilities are to receive updates on mission requirements. She received constraints for mass, volume, cost, and power from the Lead Engineer; she also received updates on science requirements and progress in science payload from the Lead Scientist. Yogita later compiled a list with all written information for purposes of documentation.

The following are the operation guidelines for Team 38. The team followed road-maps created by the team PM and DPM.

1 - Team Project Organization formed and Org chart created. Discord is the communication tool used by the team.

2 - Master Gantt chart created to keep the process and progress for the team.

3 - Traceability matrix created for team task assignments, followed by internal review and then external review by mentors.

4 - Queries and clarification sessions with mentors.

5 - Trello tasks created as per the Traceability Matrix and used for task assignments and progress.
6 - Schedule calendar - Team meets virtually on a weekly basis via Zoom.

All-team meetings: Sundays

Sub-team meetings:

Engineering Team: Saturdays

Science Team: Saturdays

Science-Engineering Teams: Sundays

Tiger Teams: during the week

7 - Team progress status shared on All team meetings for requirements coverage and constraints and future steps to be taken by the team.
8 - Shared Google drive created for the relevant documents to be added to cover requirements for the PDR.
9 - Project requirements document added on L'space Mission Team 38 on a weekly basis which covers the Science team, Engineering team, Safety Officer, and Administration updates. Links for team progress status were added to this document which covers science, engineering, budget, schedules, documentations, payloads specifications, costs, mass volume, designs.
10 - All team sign-off is listed with requirements in progress or successfully met.
11 - Team constraints and deliverables related queries to PM and mentors.
12 - Clarification translated to team leads for the constraints as discussed with PM and mentors.
13 - Feedback by PM and mentors need to be updated for final submission.
14 - Continuous interaction with team leads and reaching out for clarification on dependencies as needed.

In the end, it is the responsibility of Mission Assurance to ensure that requirements are being met successfully.

7. Conclusion

The goal of DAEMONES is to study the presence and characteristics of water and potential microbial activity on Columbia Hills to further the discovery of possible habitation of an Earth-like planet. Data from this mission can also uncover Earth's potential history and beginnings of life. This is achieved by using the RAT to collect rock samples, with the assistance of the NAVCAM, to be analyzed by the CheMin on the lander. The payload will land on Mars using an EDL consisting of a backshell, Nano-ADEPT heat shield, parachutes, four rockets, and airbags.

L'Space Team38 Mission Requirements Final Report 2020				
Team	**Constraints**	**Budget Allocation**	**Budget At Completion**	**Success**
Engineering, Science Team	Mass	180 Kg	117.11 kg	Pass
	Mass EDL	72 Kg	55.36 kg	Pass
	Power	196.02	189.82 Watts	Pass
	Cost	$100 Million	Total cost: 32,511,137 Manufactured: 29,926,442 Outsourced: 2,584,695	Pass
	Volume	61cm x 71cm x 96 cm (24in x 28in x 38in)	24 inch x 24 inch x 38 inch	Pass
Administration	Mission Cost	$100 Million	$ 99,346,953.14	Pass

Table 7.1. Mission Requirements Fulfillment.

All the mission documents and requirements were reviewed and successfully met by Team 38. The team shows the ability to successfully complete objectives and mission requirements. A summary table of the mission requirements are shown in Table 7.1.

The mass constraint of 180 kg with an additional EDL allotment of 72 kg was met by a mass of 117.11 kg and with 55.36 kg for the EDL.

The volume constraint of 24 inch by 28 inch by 38 inch (60.96 cm by 71.12 cm by 96.52 cm) was met with the concept’s volume of 24 inch by 24 inch by 38 inch (60.96 cm by 60.96 cm by 96.52 cm).

The budget constraint of $100 million was met with a $99,347,131.89 mission budget proposal.

The team is now working towards completing the Critical Design Review (CDR). The team is conducting research to further reduce the size of the CheMin and have already heard that the next generation of this instrument will be smaller [63]. With a reduced size of the instrument, the team can possibly incorporate more science instruments such as the Dynamic Albedo of Neutrons (DAN) which can help further the search for signs of water. If implementation of another instrument is possible, an added science objective could be considered.

Mars' soil composition contains perchlorates, which are dangerous to human health. If the team decides to explore this concept further, solutions can be developed to mitigate environmental hazards on Mars' surface. Further exploration of potential perchlorate-reducing bacteria or mitigation of environmental hazards on Mars' surface can also benefit Earth as there are superfund sites within the United States with high levels of perchlorate contamination.

The team is also considering exploring the particle content within Mars' atmosphere to gain a better sense of the material composition that is within the planet's surface. The reason why the team would like to explore this is to see what particles would stick on the suits of future astronauts that would be considered toxic to inhale or digest. This would be a novel investigation to analyze challenges to overcome for Mars habitation.

Some other considerations for exploring particle content within Mars' atmosphere is to identify the effect of UV rays depending on changes in the atmosphere, such as when dust storms occur. It can also aid in understanding ways to decrease levels of carbon dioxide for human habitability on Mars, which can help gain more knowledge to reduce the progression of climate change.

In the future, the team would strongly consider implementing a mobile design for the mission if size can be reduced further to integrate mobility, as was originally intended. Added mobility would increase the diversity of samples collected, increasing the chances of discovering water and microbial life. Diversity of samples is important as it can provide more accuracy for the data collected. As more samples are collected around Columbia Hills, they will better reflect the value of the site as a whole. With the data collection method in place so far, although it provides precision and accuracy, it will only be restricted to a fraction of the site, rather than all of Columbia Hills.

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