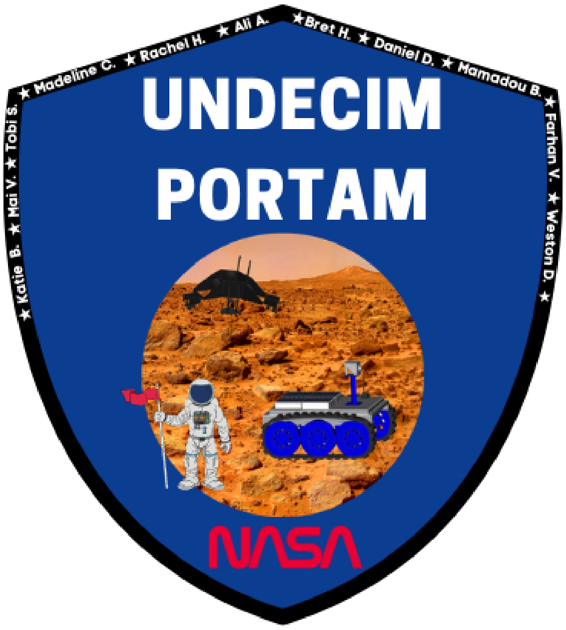


Undecim Portam Mission
2020-2023 Preliminary Design Review

NASA Lucy Student Pipeline Accelerator and
Competency Enabler Academy

Team 10 - Ce-L'EAST-ial

Contents

1 Introduction and Summary

1.1 Team Introduction

Ali Arnaout attends Montgomery College in Maryland where he studies mechanical engineering. His strengths include Problem Solving, Critical Thinking, Time management , Communication, CAD and MATLAB. He loves working in teams, and believes it allows for more ideas and creativity to generate which is very beneficial for projects. He is very dependable and always the cherry one! Ali will be serving as an administrative member and engineer on the team.

Mamadou Bah attends Baltimore City College in Maryland where he studies electrical engineering. His strengths include Math, C programming, CAD, Matlab, Circuit boards and his exceptional work ethic. He loves speaking different languages and has a lot of engineering courses under his belt, so he brings a lot of technical engineering expertise to the team. Mamadou will be serving as an engineer on the team.

Katie Bishop attends Georgia Tech in Atlanta where she is a rising third year studying electrical engineering. Her strengths come from her passion for space as well as past experiences interning with Boeing last summer and with Virgin Galactic this summer. She also has had experience writing a PDR for her school's Undergraduate Student Launch Initiative. Her technical strengths include her experience with PDR, systems engineering, airworthiness/FAA certification, signal processing as well as time management and organization. Katie will be serving as the Project Manager on the team.

Madeline Clyburn attends Berry College in Georgia where she is a rising Senior majoring in physics with a minor in math. Her strengths include Python as well as time management, good work ethic, schedule-making and helping keep others accountable. She also has had past experience doing a research internship at Jefferson National Lab that she brings to the table. Madeline will be serving as the Lead Administrator as well as a scientist on the team.

Weston DeCambra attends Grand Canyon University in Arizona where he is a rising senior studying biochemistry and molecular biology. His strengths include biological and chemical conceptualization, critical thinking, and many laboratory skills. He has also has extensive experience in a research and design program at his school which transfers well to this project. Weston will be serving as the Lead Scientist on the team.

Daniel Diab attends Arizona State University where he is a rising senior studying Astrophysics. His strengths include his experience with PDR, Astronomy, Programming in Python and MATLAB. He also has plenty of research laboratory experience where he has acquired skills in critical thinking, machining, and ESD control. He is passionate about space exploration and enjoys working as a team member as well as independently. Daniel will be serving as a scientist on the team.

Rachel Harvey attends the University of Maryland in Maryland where she studies aerospace engineering. She is technically strong in CAD, engineering concepts, and technical writing. She has past internship experience in the industry at Aurora and is currently interning there for a second time. She also has a lot of experience in design reviews and writing proposals. Rachel will be serving as the Lead Engineer on the team.

Bret Hendricks attends Georgia Tech in Atlanta where he studies mathematics. He is technically strong in mathematical computations and solving abstract problems. He is extremely enthusiastic about learning new things and working on real world problems on the team. He enjoys working on problems till he understands it. Bret will be serving as a scientist on the team.

Oluwatobiloba Sanni attends Maryland, College Park in Maryland where he studies mechanical engineering. He is technically strong in MATLAB, C++, and LibreCAD. He has experience working on many collaborative engineering projects. Tobi will be serving as an engineer on the team.

Farhan Virani attends Georgia Tech in Atlanta where he studies electrical engineering. He is technically strong in programming, CAD modeling, and microcontrollers. He loves working towards his goals and has an open mindset in that he is always willing to learn new things. Farhan will be serving as an administrative member and engineer.

Mai Vo attends Georgia Tech in Atlanta where she is a rising third year studying computer science. Her strengths come from her technical skills in C++, Java, Python, website design, and knowledge in electronics with regards to PCB creation and software development. Her skills have come from internship experiences with The Aerospace Corporation and Lockheed Martin for the summer as well as research with the Space Systems Design Laboratory. Through the Yellow Jacket Space Program at Georgia Tech, she has gained experience with systems engineering. Mai will be serving as the Deputy Project Manager on the team.

1.2 Mission Overview

1.2.1 Mission Statement

The mission goal for Undecim Portam is to search for oxygen wells in Northeast Syrtis as well as for chemical components required for life. This goal is in hopes to better understand the history and geography of Mars as well as to find evidence for seasonal oxygen and methane atmosphere swells through conducting subsurface analysis and high-resolution photos. Subsurface oxygen deposits are a likely candidate for the observed seasonal increase in concentration due to the drastic increases and ruling-out of atmospheric involvement. Additionally, liquid water, ice, novel brines, and geologic features of Mars' subsurface can be investigated. Identification of such would give further incentive to explore the planet's geologic makeup and climate relation. Sedimentary rock can give insight to the history of Mars and geologic characteristics it possesses. Though none of these are indicative of life, they all are required for such. Substantial amounts of obtainable oxygen, water, or methane could be used for future manned missions to Mars in both the realm of fuel and respiration or resource usage for personnel. Subsurface data, surface images, and chemical composition data will be gathered to determine the presence of oxygen wells. If the existence of oxygen wells on Mars were to be discovered, techniques to access that oxygen would change future Mars missions. Future missions could utilize these oxygen deposits to resupply missions which would help cut costs, save weight, and preserve other precious materials and resources; thus allowing room for more space and resources to send additional science experiments to Mars. The discovery of oxygen would allow humanity to better understand Mars by enabling all of mankind to further explore Mars due to a potentially drastically lowered barrier to the means of attainable manned voyage and other relevant scientific discoveries.

1.2.2 Mission Requirements

The mission will be transported as a secondary payload onboard a spacecraft that will be in orbit around Mars and land at the site in Northeast Syrtis. There were two options given for mission choices and they each had different constraints, but the team chose to move forward with the large payload concept and therefore will be adhering to those constraints. The large concept payload with size constraints of 180 kg for its mass and volume of 61cm x 71cm x 96cm. The allotted total budget is $100 million dollars or less. Additionally, the size constraints must include the heat shield to protect the payload during entry and descent through Mars' thin atmosphere. The heat shield will not be counted against the mass limit, however, or budget. A maximum of 72 kg for the heat shield mass and other items used in the EDL (e.g. parachute, thrusters, fuel, etc.) was allotted.

1.2.3 Mission Success Criteria

The mission success criteria include: protect the scientific payload from the extreme environment of the Mars surface for the mission duration, enable the instruments to execute their tasks to collect scientific data, and transmit all the data from the surface back to earth complete for analysis and study.

Though the mission has multiple objectives, the primary concern is that of oxygen deposit identification in the subsurface of Mars. After successful rover and communications system touchdown in Northeast Syrtis, the rover must deploy, successfully startup, and run its various instruments. It then must travel on a preset yet adaptable route. Subsurface imagery must be taken intermittently, roughly every 4 inches, throughout the terrestrial transit by the rover [17]. The on-board systems will work to identify possible anomalies and subsurface makeup involving subsurface gaseous, liquid, or solid deposits and classify the material accordingly. Navigation will be determined on-the-fly through artificial intelligence utilizing data from the navigation cameras [47]. All data including subsurface makeup of void depth, volume, state of matter, and material contents as well as surface images must be relayed to Earth by means of a rover-to-surface comms system via low frequency radar. It is only with all these objectives' completion that the mission can be deemed successful.

1.2.4 Concept of Operations (Graphic)

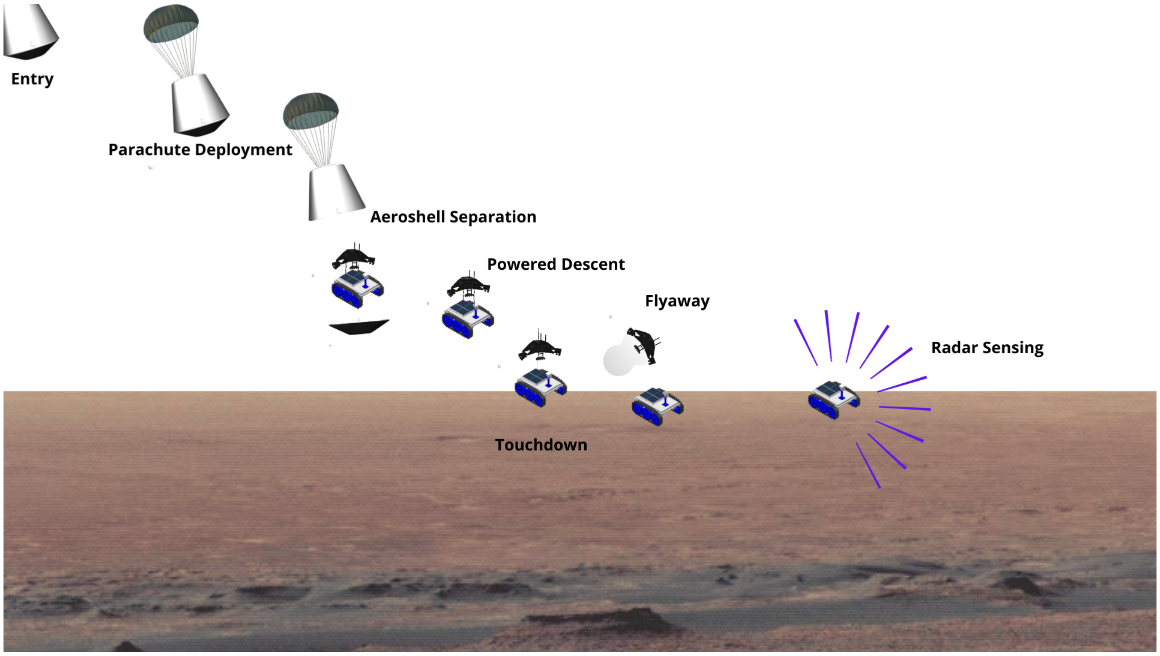


Figure 1: Displayed above is an overview of how the payload will operate and land from orbital deployment in the Mars atmosphere to landing at the surface to mission fulfillment and completion.

Undecim Portam will enter the Martian atmosphere above Northeast Syrtis as seen in Figure 1. The designed aeroshell and heat shield will protect the probe from damage from extreme temperature. A parachute will deploy for necessary deceleration, followed by the separation of the aeroshell and heat shield from the probe. A designed skycrane will lower the lander to the predetermined location on Northeast Syrtis, and then the skycrane will fly away so as to protect the lander. The lander will move approximately 100 meters forward while conducting radar sensing with a modified RIMFAX sensor in order to collect information about the landscape and possible underground oxygen wells.

1.2.5 Major Milestones Schedule

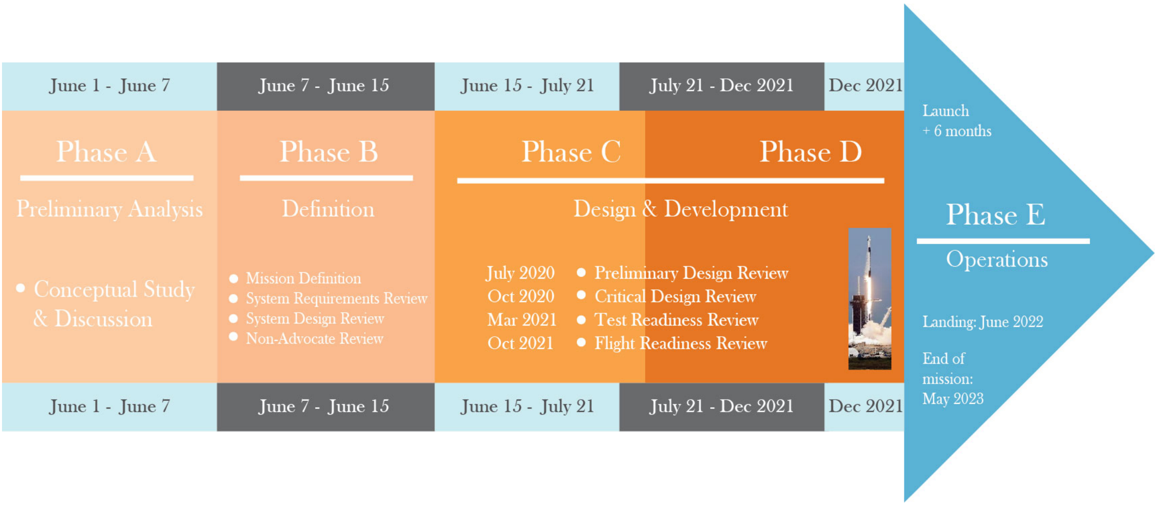


Figure 2: The Undecim Portam mission milestones from Phase A through Phase E.

1.3 Descent and Lander Summary

Upon Undecim Portam reaching the Martian atmosphere above the surface of the Northeast Syrtis landing area, the orbiter and probe will separate, thus beginning the entry process. The system will have an entry angle of 14.8 degrees and a velocity of 860 m/s. After initial atmospheric entry, the probe will stabilize with the assistance of an inertial measurement unit. Once contacting the upper atmosphere, the heat shield will begin to experience high temperatures of 3200 degrees Fahrenheit. Atmospheric friction will decrease the probe's velocity, although a powered deceleration is still required for a safe landing. Once Undecim Portam slows down to a predetermined speed to prevent excessive heat buildup, the parachute on the backshell will be deployed, releasing it from the probe. The parachute will decrease the velocity from 1000 m/s to 100 m/s. After this decrease in velocity, the backshell will separate and the system will enter power descent mode. Undecim Portam will then safely descend through the atmosphere on its way to Northeast Syrtis. During the descent, Undecim Portam will capture detailed atmospheric analysis and panoramic imaging. The system will descend for 2km, all while assessing the landing conditions with radar technology. At 20 meters from the surface the skycrane touchdown system will be initiated. Four of its eight throttle-controllable rocket engines will begin firing and lowering Undecim Portam on a bridle. The lander descends while maintaining a constant vertical velocity of 3 m/s. The rover is connected to the descent stage by three nylon tethers and by an umbilical providing a power and communication connection. The bridle will extend to full length, about 25 feet (7.5 meters) as the descent stage continues reducing in altitude. When touchdown is detected by the altimeter, the bridle is cut at the rover end. Finally, the descent stage will detach and accelerate in the opposite direction to stay clear of the landing site.

The aeroshell and heat shield have a volume of .302m^3, and the lander has a volume of .092 m^3. The lander has a mass of 27.2 kg including the scientific payload, chassis, propulsion system, and communication system.

Figure 3: Displayed above is the isometric view of the mission aeroshell and heat shield assembly (first iteration).

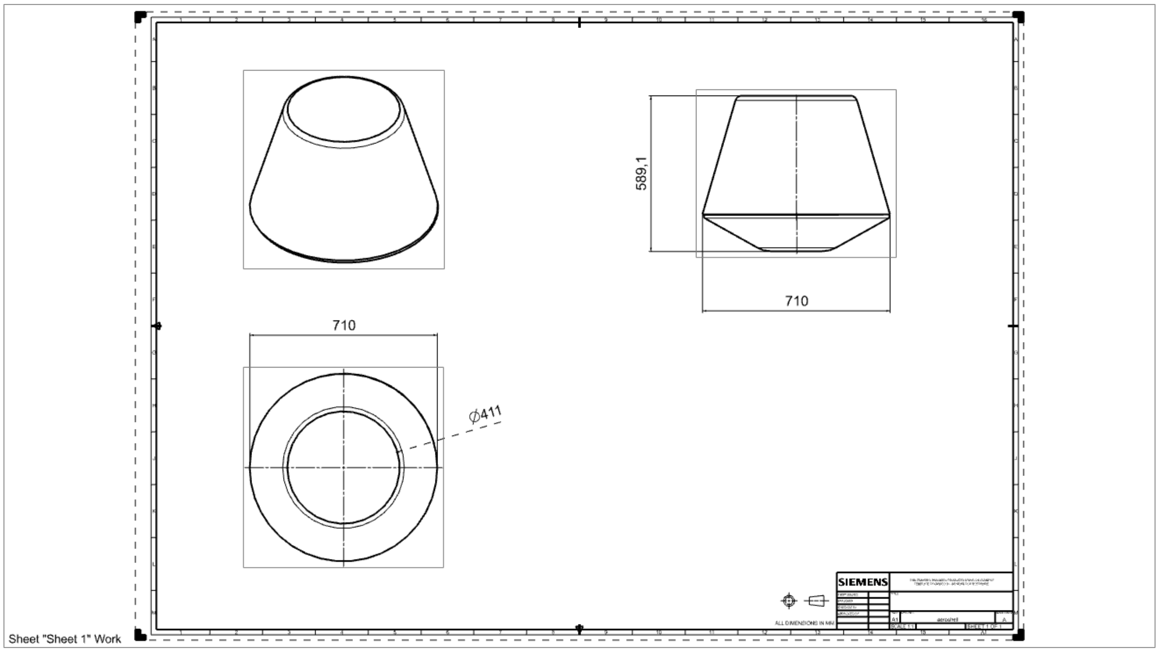


Figure 4: Displayed above is the isometric, top and right side views of the mission aeroshell and heat shield assembly. Dimensions show are in millimeters.

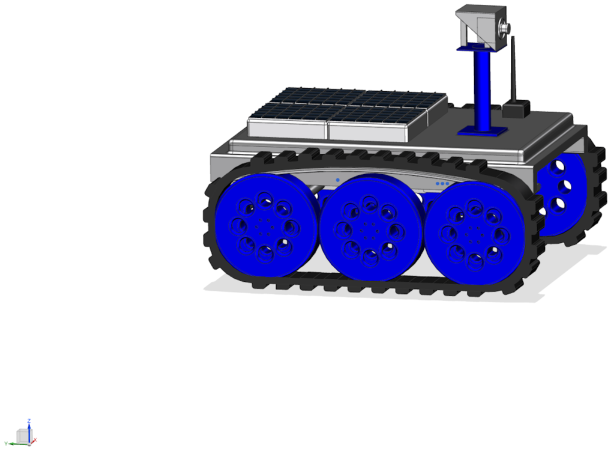


Figure 5: The image above is an isometric view of the mission rover - chassis, payload, and drive train (iteration 1).

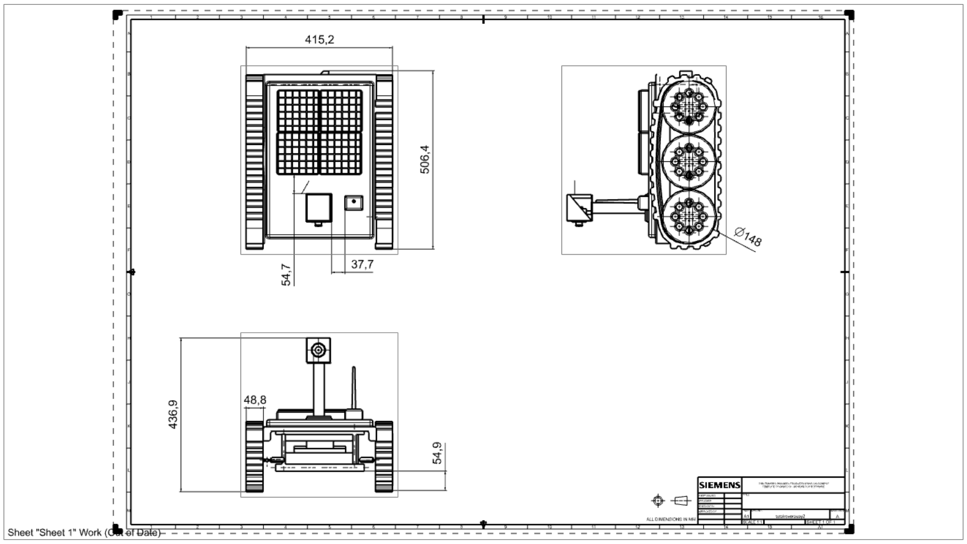


Figure 6: Displayed above is the isometric, right, and top views of the mission rover assembly (first iteration). Dimensions shown are in millimeters.

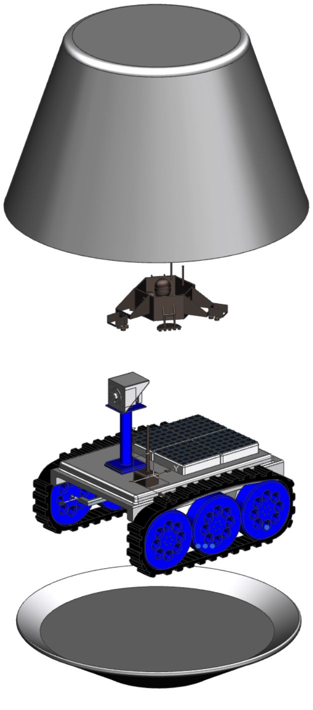


Figure 7: Isometric view of exploded Undecim Portam system assembly.

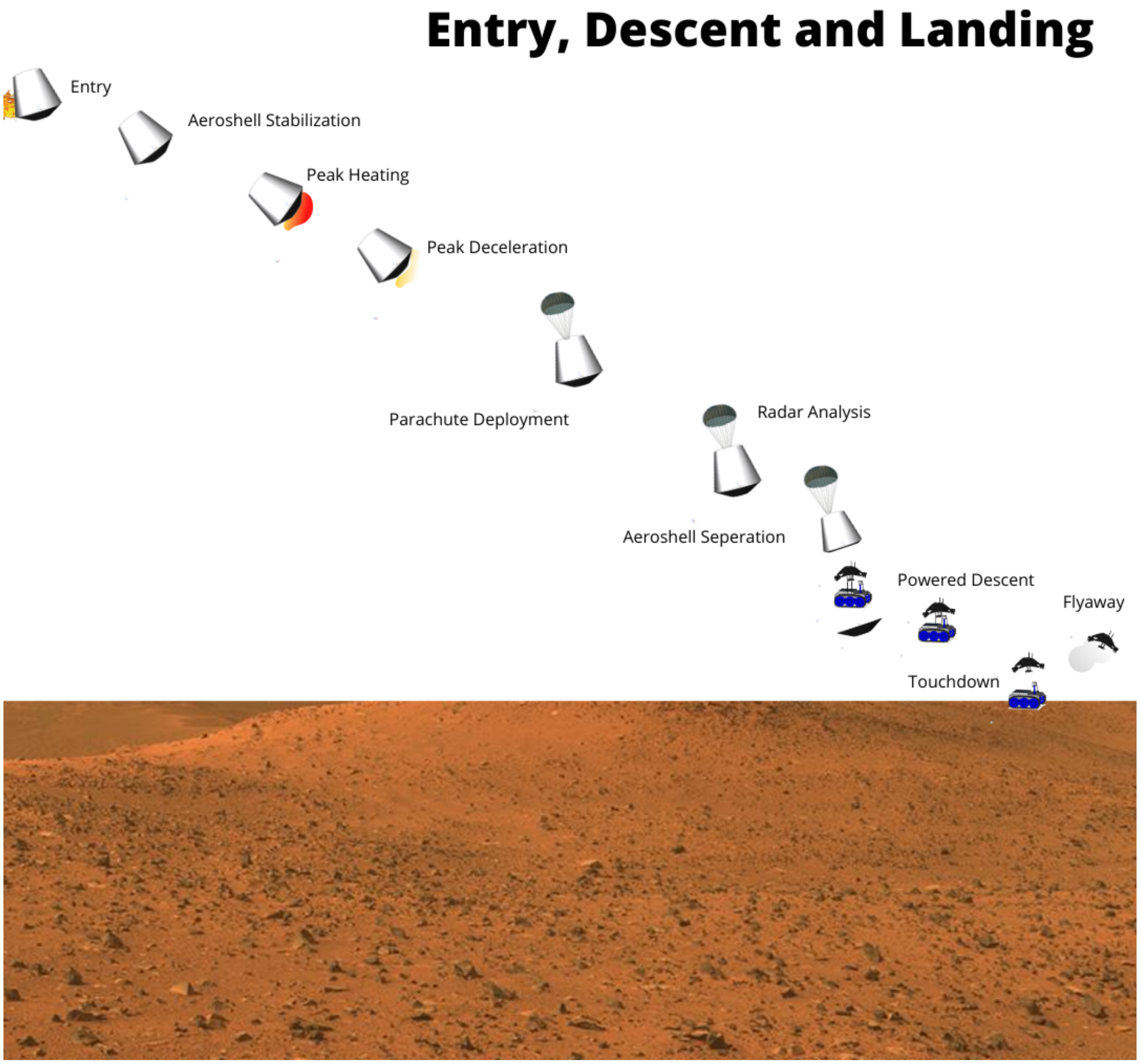


Figure 8: Displayed above is the entry, descent, and lander summary graphic. The aeroshell and heatshield assembly will enter the Martian atmosphere, proceed to deploy its parachute, release the designed Skycrane, and then complete a safe, powered descent of the mission lander.

1.4 Payload and Science Summary

The rover will tote the Radar Imager for Mars' Subsurface Experiment (RIMFAX) as well as a radio transmitter and receiver in order for the rover to export and import data to and from the comms system. A navigation camera (Navcam) will also make up the payload. Navcam will be mounted on a raised stand and gimbal in the center of the rover chassis and, using the dual camera system, AI, and the onboard computer, will safely traverse the terrain with and without remote controller input [47]. 360 degree images of Mars will be used to image the path and surface of Mars [31]. The RIMFAX system will work by generating radio waves to penetrate the surface within a 150 to 1300 megahertz frequency [20]. The radio waves reflected back to the system receiver can be interpreted by the onboard computer and will help determine factors such as depth, materials, state of matter, and structure. The instrument will be tuned to a resolution of approximately 8 inches in order to achieve the ideal resolution to penetration depth ratio [43]. RIMFAX will be mounted on the underside of the rover with designed mounting brackets. The data from the instruments will be exported through the radio transmitter to the comms system which will amplify the signal and relay the data to Earth.

2 Evolution of Project

2.1 Evolution of Descent and Lander

The descent and lander system has evolved significantly throughout the design of the Undecim Portam mission. With the variations in scientific instrumentation and the size changes within each system, a new design iteration was required. The volume (0.61 m × 0.71 m × 0.96 m) and 180 kg mass constraints were considered with each iteration.

Figure 9: First iteration Isometric CAD of the aeroshell assembly.

The initial design of the aeroshell assembly centered on maximizing the entry vehicle's volume. Due to the early nature of the mission, the engineering team wanted to ensure there was space for the largest possible rover, parachute, and skycrane. The lower portion of the aeroshell, the heat shield, was 0.5 m tall - an unreasonable height for the designed rover. Upon the release of the heat shield, the lander would not be protected from the Martian environment during descent.

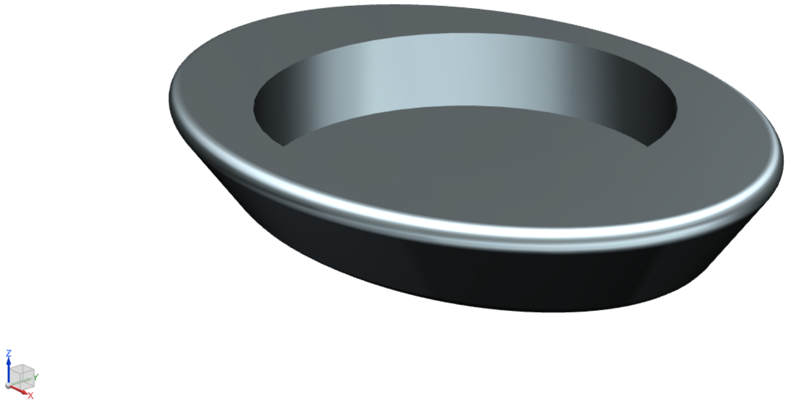


Figure 10: Second iteration Isometric CAD of the heat shield.

The second design iteration of the aeroshell assembly featured a shorter, and more ovular-shaped heat shield. This design was intended to provide a larger protective surface area to encapsulate the lander, parachute, and skycrane. A 600 mm diameter space was extruded within the heat shield for the lander to sit in. As the rover design matured, this heat shield design did not provide adequate space for the RIAMAR rover and its instruments.

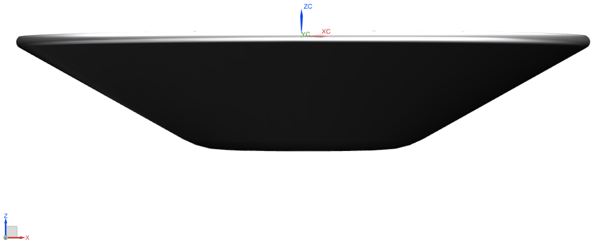


Figure 11: Final iteration side-view of the Undecim Portam heat shield.

The final design iteration of the aeroshell includes a .15 m tall heat shield. The final heat shield is analogous to the rounded, cone-like design of the Curiosity rover heat shield.

At a diameter of 0.75 m, it provides enough clearance for the RIAMAR rover to sit securely within the aeroshell.

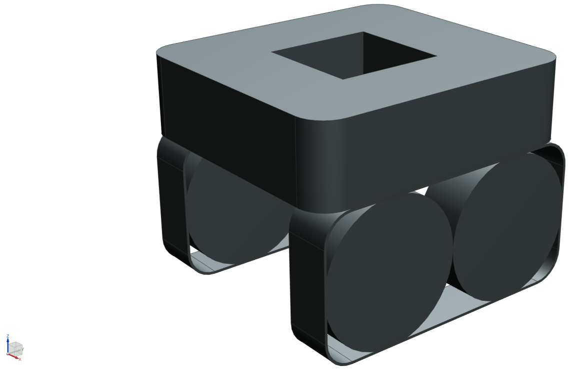


Figure 12: First iteration Isometric CAD of the RIAMAR rover.

The initial design for the RIAMAR rover was focused on utilizing a drill to search for Oxygen wells beneath the Martian surface. The first design only has two wheels within the propulsion system - remarking on the simplicity of this initial iteration.

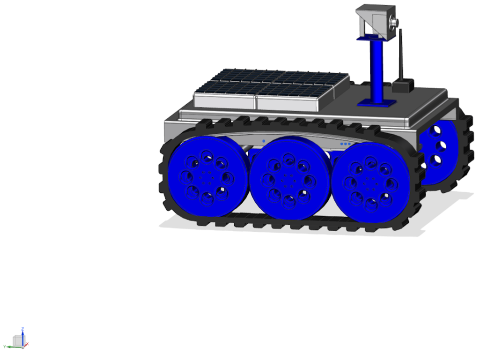


Figure 13: Final iteration Isometric CAD of the RIAMAR rover.

The final RIAMAR rover design has a slimmer chassis and three wheels in the propulsion system. The chassis is of smaller height, but is wider than the first iteration to fit the payload, communication system and solar panels. The continuous track in the final iteration is wide, with pronounced tracks (48 mm) for the Martian soil.

2.2 Evolution of Payload

The science instrument payload changed multiple times throughout Team Ce-L'EAST-ial's preliminary design. At first, the payload included four scientific instruments for navigation and data collection: the Alpha Particle X-Ray Spectrometer (APXS), a Navcam, RIMFAX, and a simple camera to take photos. The APXS was to be used to identify exactly which chemical compounds are present on the Martian surface and would be used not only to more accurately identify the chemical makeup of identified subsurface features, but also to identify materials indicative of life, be it past or present. The RIMFAX instrument was to be used to scan the ground underneath to search for any signs of gaseous or solid wells, water, ice, or brine. The two cameras were going to be used for the rover's navigation and to take photos of the Martian surface to send back to Earth for closer inspection. Multiple drills were also considered to drill to the wells to confirm what is inside of the wells found by the RIMFAX, those of which included the auto-gopher ultrasonic drill.

However, after hearing from the engineering team and realizing that having a drill would be unrealistic due to its size and weight, the payload was decided to only include the four scientific instruments, thus relying on the RIMFAX to search for wells and having the APXS identify them. As the team continued to perform more research, more issues arose concerning the payload. Due to budget constraints to stay under the allotted $100 million dollars, the science team decided to cut out the APXS and the simple camera from the payload to allow the mission-specific instrument to stay on the mission: RIMFAX. Therefore the current payload only includes the RIMFAX to search for signs of gaseous wells, water, ice, brine and the Navcam to navigate the terrain and take photos for further investigation on Earth.

2.3 Evolution of Mission Experiment Implementation Plan

Throughout the planning process and preliminary design, the Undecim Portam mission has changed multiple times due to scientific and budgeting factors. The original mission objective was to search for oxygen wells and other gaseous wells along with searching for water, ice, and brine, thus allowing us to reduce the amount of oxygen and water that we'd need to bring to Mars in future manned missions to Mars. Undecim Portam's original mission included four instruments: the Alpha Particle X-Ray Spectrometer (APXS), a Navcam, RIMFAX, and a simple camera to take photos. Drills were also considered to ensure the content of the wells found. However, it was found unrealistic to have a drill on the rover due to size and weight constraints. As a result, it was decided that the payload would include only the four instruments, using the APXS to identify the contents. The drill would have made the mission much more accurate, but otherwise the loss of the drill did not change the objective of the mission.

However, upon calculating the budget and factoring in margins for a three-year plan from start to finish, the team realized that science instruments would need to be cut out in order for the budget to stay under the allotted \$100 million dollars, since the four instruments totaled a cost of \$70 million. It was decided that the Undecim Portam mission would only use the Navcam and RIMFAX, thus changing its mission objective slightly. The RIMFAX can determine if there are gaseous wells underneath the surface of Mars, but without the APXS, it would not be possible to determine exactly which gases those wells would contain. Thus the mission objective changed to primarily look for water, ice, and brine with supporting evidence that there would be oxygen wells underneath the surface of Mars.

3 Descent and Lander Design

3.1 Selection, Design, and Verification

3.1.1 System Overview

The system comprises four stages - entry, descent, landing, and scientific operation. The entry vehicle, our aeroshell, comprises the backshell and heat shield assembly. Made of durable, aluminum honeycomb structures [37], the aeroshell protects the lander from extreme heating and provides an aerodynamic deceleration for descent. A polyester-nylon parachute and aluminum Skycrane will conduct a controlled descent of the lander. Once safely on the Martian surface, the Skycrane will execute a "flyaway" maneuver and land safely 500 m away from the landing site, and the rover, RIAMAR, will begin to traverse the designated path within Northeast Syrtis. While moving at approximately 0.2 mph, the RIAMAR rover will use the RIMFAX sensor to fulfill the mission's scientific goals.

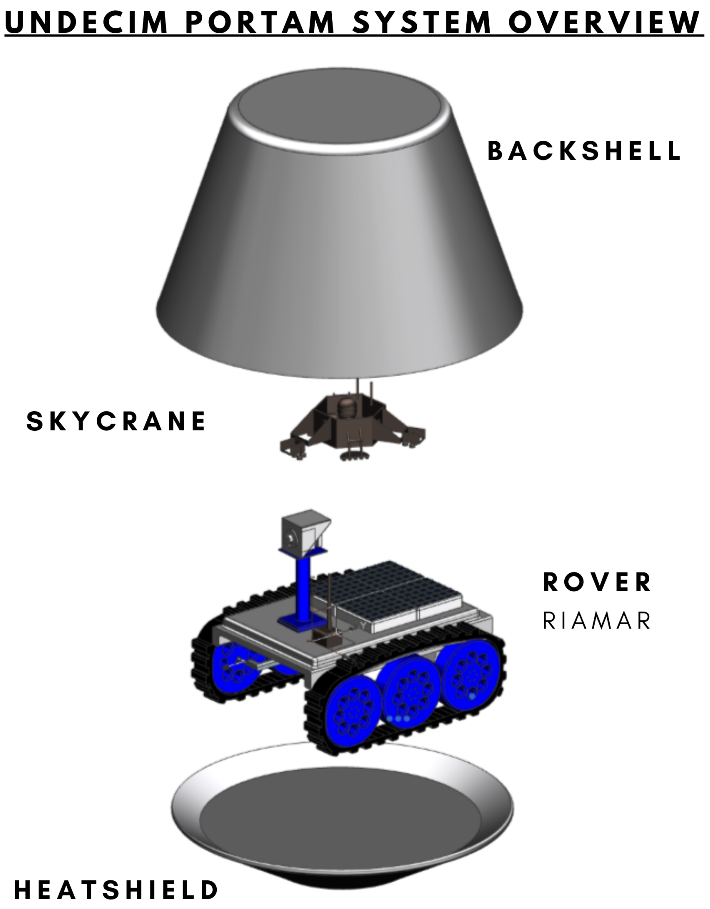


Figure 14: Undecim Portam Mission system overview with a CAD rendering of the backshell, Skycrane, Undecim Portam rover, and heatshield.

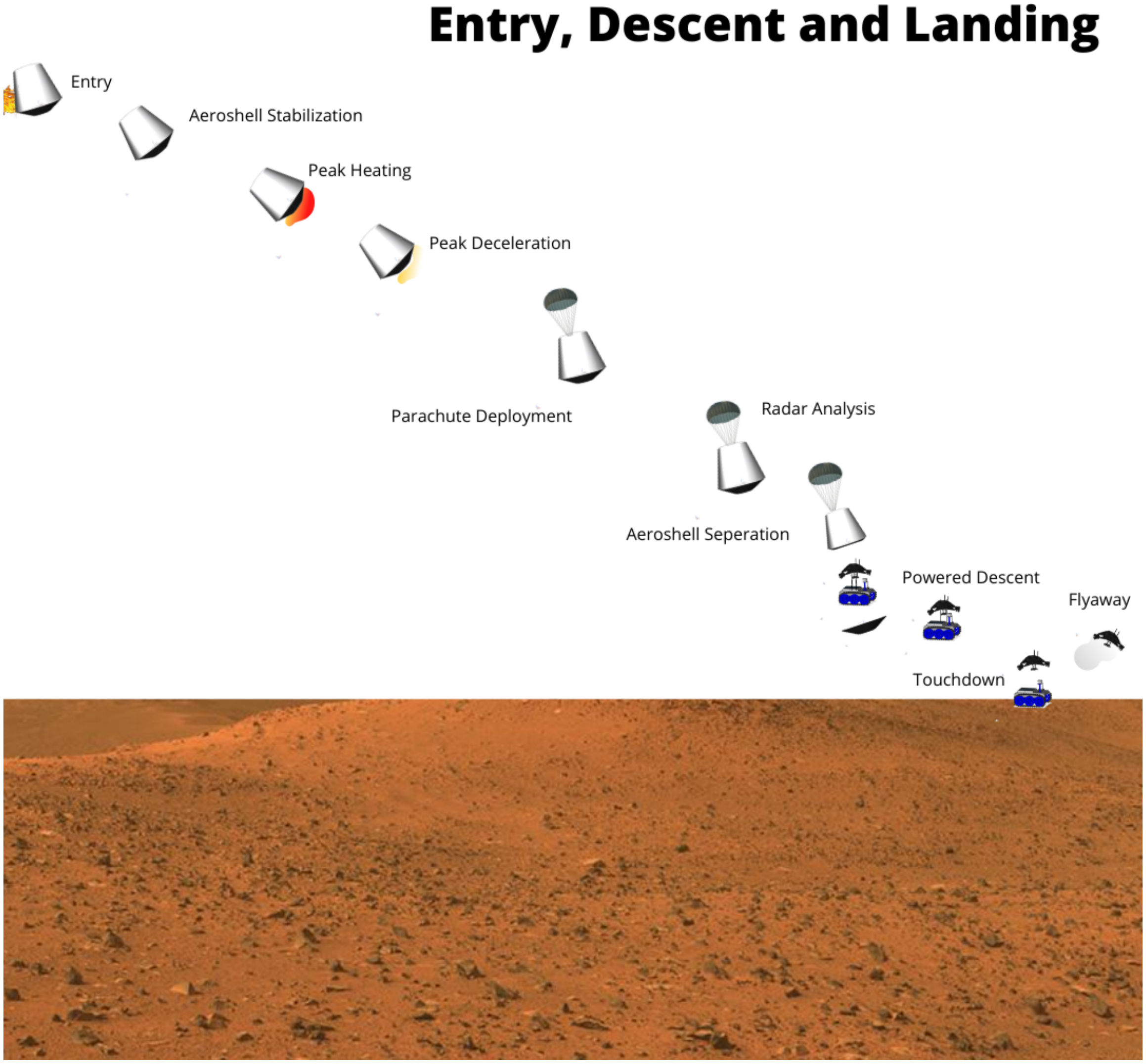


Figure 15: Undecim Portam Entry, Descent, and Landing overview.

3.1.2 Subsystem Overview

Aeroshell

The aeroshell assembly includes the heat shield and backshell. The heat shield has a diameter of 0.71m, a width of 0.71 and a height of 0.150 m. The backshell has a diameter of 0.61m, a width of 0.71m and a height of 0.438 m. The total height of the aeroshell assembly is 0.588m. The backshell will contain the folded parachute and Skycrane, while the Undecim Portam rover will sit within the heatshield. Both the heat shield and backshell structure will be made of durable aluminum A356 alloy. The outer, protective layer of both components will be made of layered composites created with additive manufacturing. The layered composites increase in density until the final, exterior layer of phenolic resin-infused composite tiles. The top layer consists of AS4 carbon fiber and is designed to burn away in a controlled fashion to carry heat away from the aeroshell. The lowest layer, closest to the aluminum body, is the least dense and is an amalgamation of low-density phenolic yarn and AS4 carbon fiber [15].

Figure 16: Isometric CAD rendering of the aeroshell assembly configuration.

Parachute

Undecim Portam will utilize a single 25 ft diameter parachute. The parachute is made of a nylon and polyester blend and attaches to the backshell with a 15 ft long Kevlar triple bridle. To fit within the backshell assembly, the parachute is pressure packed into a 200mm by 200mm by 50mm unit. The parachute has a wide, Zylon band around its perimeter to minimize back and forth movement. Zylon is advanced fiber material that has been utilized on both the Curiosity and Pathfinder missions [37]. After the system has reached a velocity of 1000 m/s, which is determined by flight software, the parachute will deploy and decrease the velocity to 100 m/s in a matter of minutes.

Skycrane

The Skycrane descent system will be initiated 20m from the Martian surface. Using a 10ft long Kevlar tether, this small rocket-powered vehicle will lower RIAMAR to the Martian surface wheels-down. After safely delivering RIAMAR to the landing site, Skycrane will conduct a "flyaway" to the crash site 500 m away. The dimensions of Skycrane is 0.3 m by 0.15 m by 0.1 m. Despite the small size of the aluminum Skycrane, six powerful retrorockets will provide enough thrust for RIAMAR's powered descent to the Martian surface [9].

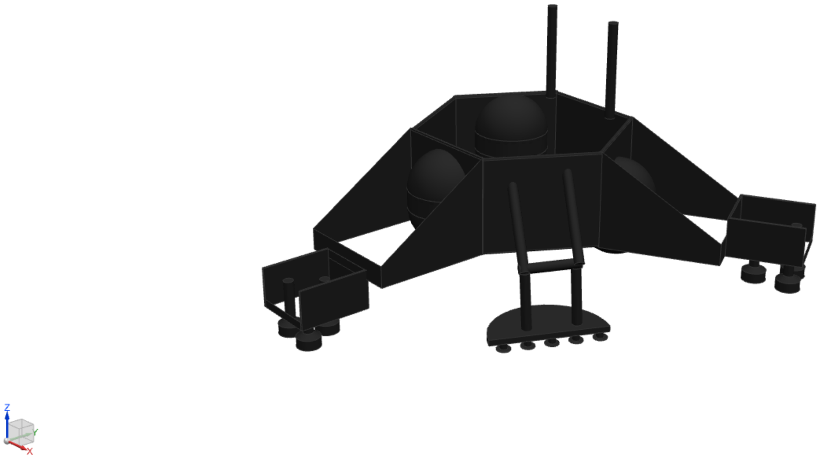


Figure 17: Isometric view of Skycrane CAD model.

Propulsion System

The drivetrain is designed to have three wheels on each side. Each aluminum wheel has a diameter of 160 mm, and a mass of 9.94 kg. The drive train belt is an aluminum reinforced belt with a 48mm thick rubber tread. The three wheels are connected to the drivetrain.The overall design was based on an automotive Rear Wheel Drive System. The design supports extra stability and handling and improved weight distribution along the chassis allowing for smooth motion and durability under extreme conditions. On each axle there is a rotational cage allowing the rover to steer accordingly which resembles the same functionality as a tank. The secondary drive component is in place to change the speed of either track to allow a full 360 degree rotation; this system works similarly to a Variable Frequency Drive (VFD). For example, one track moves forward and the other track is able to move in the reverse direction concurrently at inter-changeable speeds for rotation to occur.

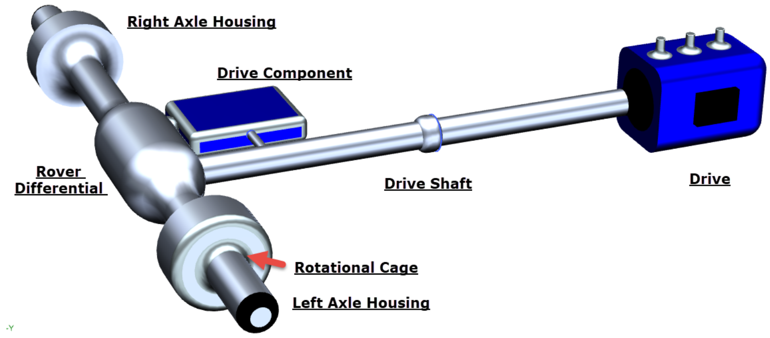


Figure 18: Labeled drawing of the drive train configuration.

Three Maxon brushless DC motors will be utilized on Undecim Portam. Two motors will be delegated to the propulsion assembly: the Maxon ECX Torque motors with hall sensors. These motors have a nominal voltage of 24 V, require 40 W of electricity, a no-load speed of 10300 rpm, a stall torque of 684 mNm and a thermal resistance of 13.4K/W. The operational temperature for the ECX Torque motors is -40 to 100 degrees Celsius, requiring each motor housing to have substantial, 5mm thick carbon-nanofiber insulation [42] for the Martian environment. The propulsion motors have a diameter of 22 mm, and will be outfitted with larger gearheads to fit adequately to the rover wheels and track system.

One smaller Maxon motor, the 13 mm ECX Speed, will allow the Navcam to rotate on its stand for maximum visibility. The ECX Speed motor has an 18 V nominal voltage, requires 12 W of power, has a no-load speed of 44700 rpm, and a stall torque of 28 mNm. The motor's thermal resistance is 29.5 K/W. Just as with the ECX Torque motors, the ECX speed motor operates between -20 and 100 degrees Celsius. It will require insulation within the motor housing and Navcam stand in order to function properly in the Martian environment.

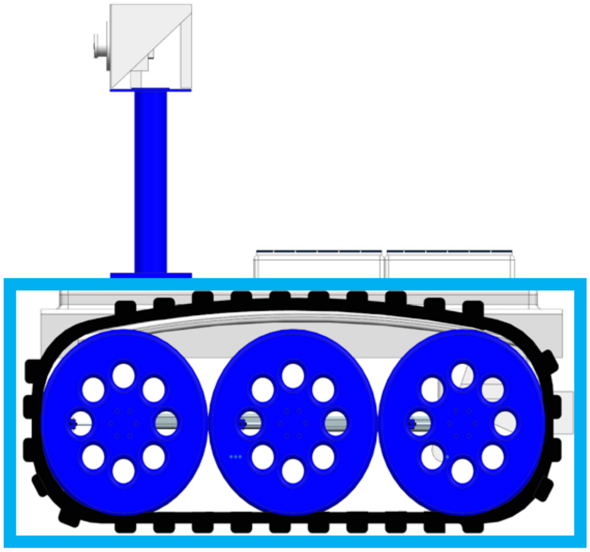


Figure 19: Side view of RIAMAR chassis (propulsion subsystem in blue box).

Onboard Computer

Undecim Portam will have a single board computer, the BAE Rad-hard RAD 750 Processor. This processor, manufactured by BAE Systems, has a core clock of 110 to 200 MhZ. It can withstand temperatures from -55 to 125 degrees Celsius. The BAE RAD 750 requires 5 watts of power. The processor is radiation-hardened and has been utilized on various spacecraft including the Lunar Reconnaissance Orbiter, the Juno spacecraft, and the Curiosity Rover [3].

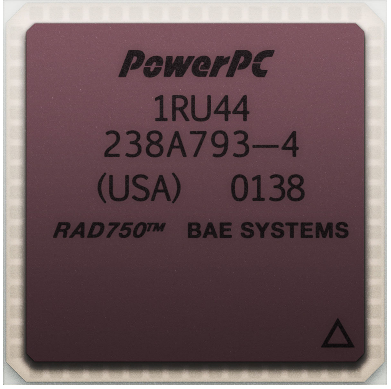


Figure 20: BAE Systems Radiation-Hardened RAD 750 Processor Chip.

Comms System

The communications transducer will be dropped as a separate package from the RIAMAR rover. A wide-band, high-gain X-Band OMNI antenna from Alaris Antenna will be placed on the rover chassis and can transmit at frequencies between 8100-8600 MHz. The OMNI antenna only requires 5W of power for efficient usage. The antenna stands at 120 mm tall, with a small diameter of only 22 mm. It is flight-ready and designed for usage in extreme space environments. The antenna can withstand winds up to 100 km/hr and is water and dust resistant to standard IP 65 [1].

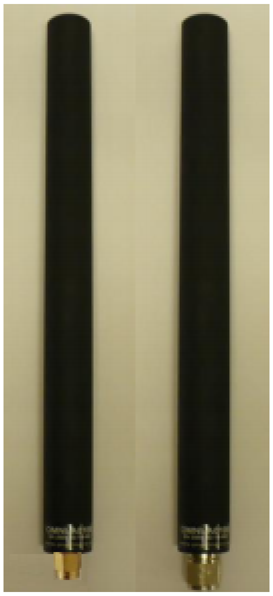


Figure 21: Two side view images of the Alaris X-Band OMNI antenna (120mm height).

Chassis

The chassis has overall dimensions of 480 mm by 399.2 mm by 60 mm, without included instrumentation. The chassis design was chosen to be sleek, lightweight, and provide ample space for the necessary instrumentation and sensors. The underside of the chassis is wider than the top platform by (insert dimension). This design choice provides space for the motors, lithium ion batteries, and RIMFAX to be attached. The left and right side of the chassis have curved supports to provide structure for the robot's rubber tracks to slide across. The rover chassis is cut from A356 Aluminum. The material's ultimate tensile strength is

235 MPa and its yield tensile strength is 165 MPa. Its shear modulus is 27.2 GPa, and its approximate shear strength is 143 MPa.

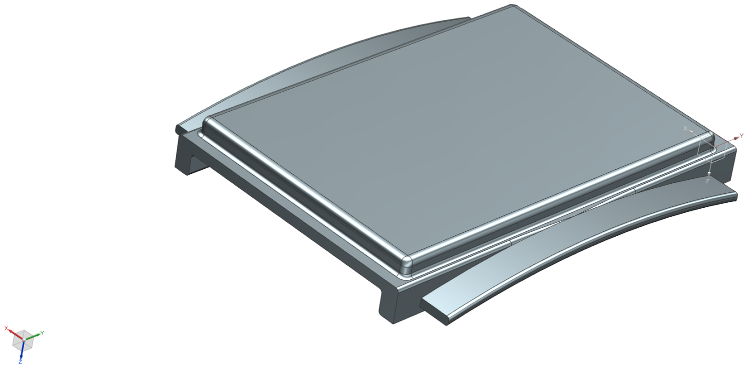


Figure 22: Isometric 3D rendering of rover chassis structure.

Battery

Two batteries will be contracted out to SAFT based on their Lithium-Ion battery standard design for Low Earth Orbit [41]. The batteries will each have a nominal voltage of 24 V and a wattage of 64 Wh. The recommended operating temperature for SAFT Lithium-Ion batteries is -40 degrees Celsius, as they are currently designed for Low Earth Orbit. For our mission's purposes, the batteries will require significant insulation and temperature testing to validate operation in -80 degrees Celsius and Martian atmospheric pressure [41].

Solar Panels

The solar array size is a design variable iteratively determined to satisfy the rover power requirement. To minimize array area and mass the Triple Junction Gallium Arsenides GaInP2/ GaAs/Ge photovoltaic is chosen. These cells are widely used as they are the most efficient, and have demonstrated excellent performance under cold, blue deficient illumination operating conditions on the surface of Mars. The Triple Junction Gallium Arsenides are arranged on the Orbital ATK UltraFlex arrays made by the Northrop Grumman Innovation Systems. RIAMAR has two solar panels of 52 cm diameter and is designed to produce up to 1.1kwhr on sol 1. The cost is approximately \$1.6 million.

Airborne dust is well known to pose serious challenges to exploration on mars, the Solar arrays on RIAMAR are not exempt from this problem. Dust accumulation on the solar arrays can reduce power generation up to eighty percent [52]. While cleaning events such as dust devils help clear up the dust on solar panels this is not enough to mitigate the problem. Several solutions have been proposed to solve this problem, the Linear Piezoelectric Actuator is chosen for the mission.

The Linear Piezoelectric Actuator, the actuator linearly moving on a guide is employed to drive a wiper fixed on the actuator. At a proper pressure force between the wiper and solar panel, the actuator can drive the wiper to effectively wipe a dust layer away from the solar panel's surface [24]. The merits of using the piezoelectric actuator in a solar panel cleaning system are that the cleaning system has a lightweight and compact Structure and the problem is that it is not as efficient as the other cleaning solutions [24].

3.1.3 Dimensioned CAD Drawing of Entire Assembly

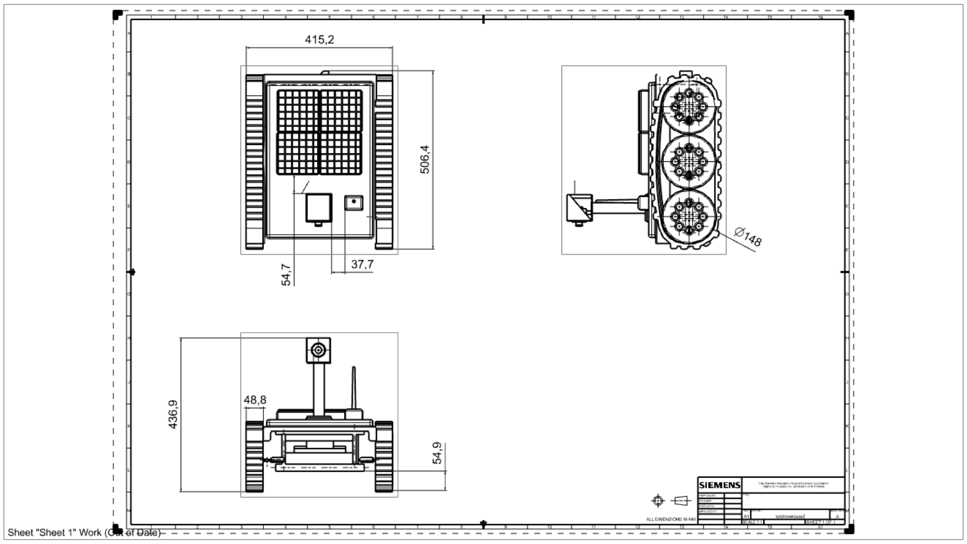


Figure 23: Dimensioned RIAMAR rover CAD (dimensions shown in millimeters).

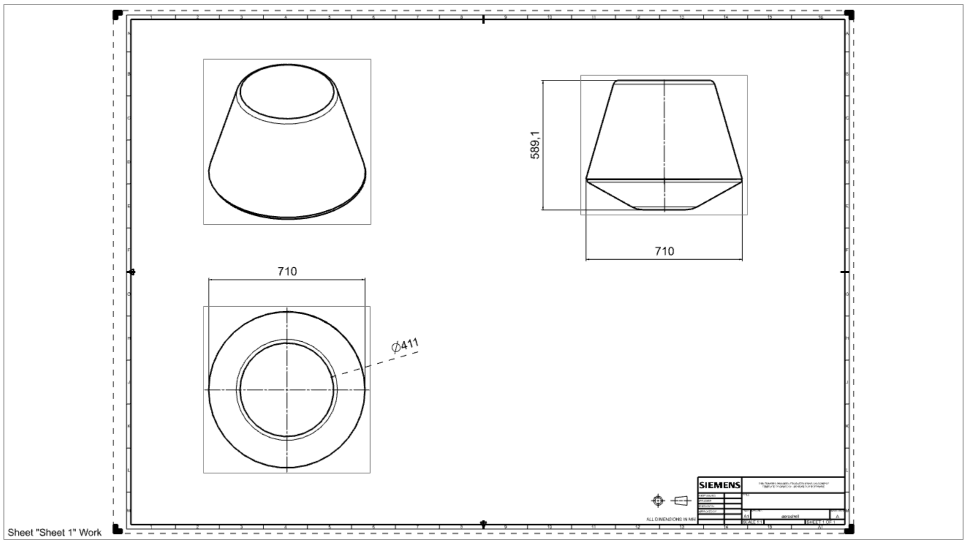
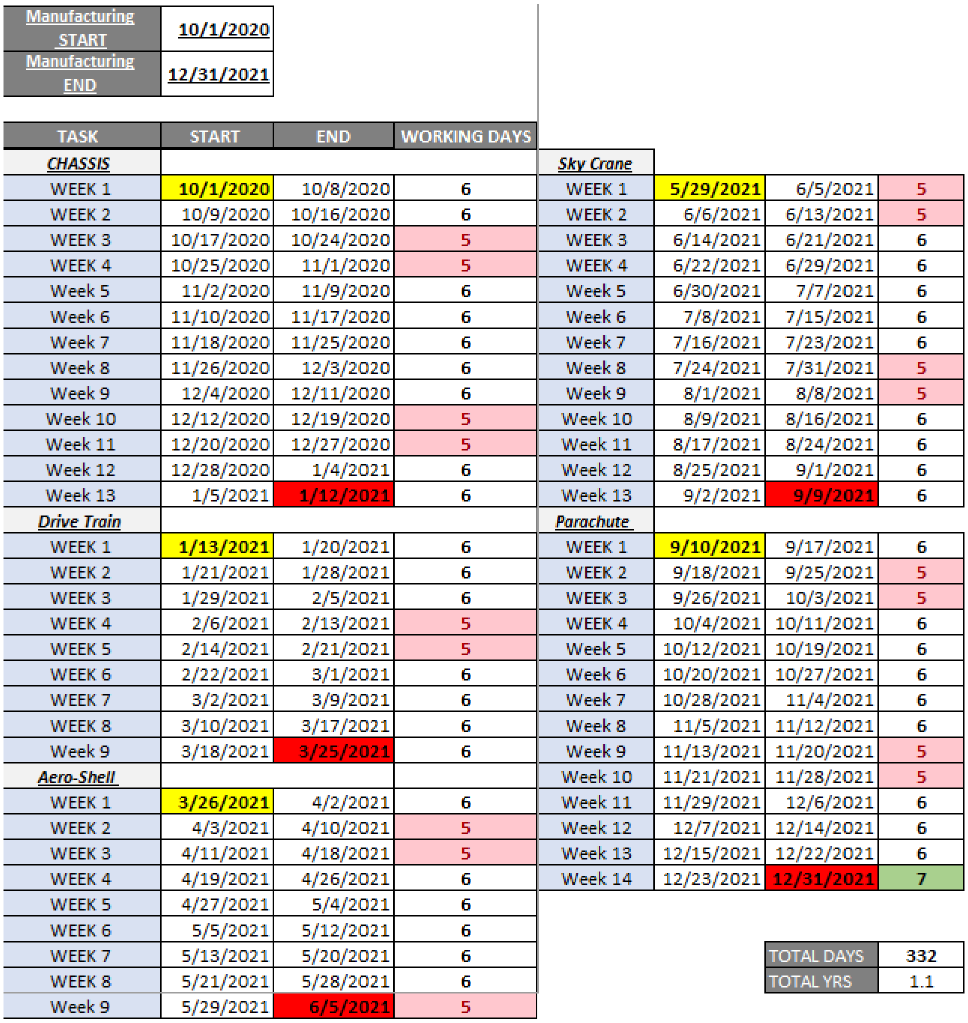


Figure 24: Dimensioned aeroshell assembly CAD (dimensions in millimeters).

3.1.4 Manufacturing and Testing Plans

Our team's manufacturing and testing plan is planned for one year and two months, the primary goal is to manufacture one part every one-two months and test for seven months in this time frame. There are currently five engineering personnel, each engineering personnel is based at a salary cap of $80,000,00 with a fringe benefit of 0.28%. Engineering personnel scope of work will be to manufacture the rover's chassis, drivetrain, heat shield, sky crane and lastly the parachute in this duration. Motors and batteries will be manufactured and subcontracted through a second party concurrently [32][41]. Each part on-board is fabricated with certain materials to ensure the overall structure is able to withstand entry, descent, and landing stage. For example, both the chassis and heat shield are made up of aluminum. Aluminum is a very good conductor of heat which absorbs heat efficiently and rapidly. A small scale prototype will be rapidly manufactured by Northrop Grumman. The prototype will allow for preliminary testing to be conducted while a full-scale Undecim Portam is being manufactured in-house.



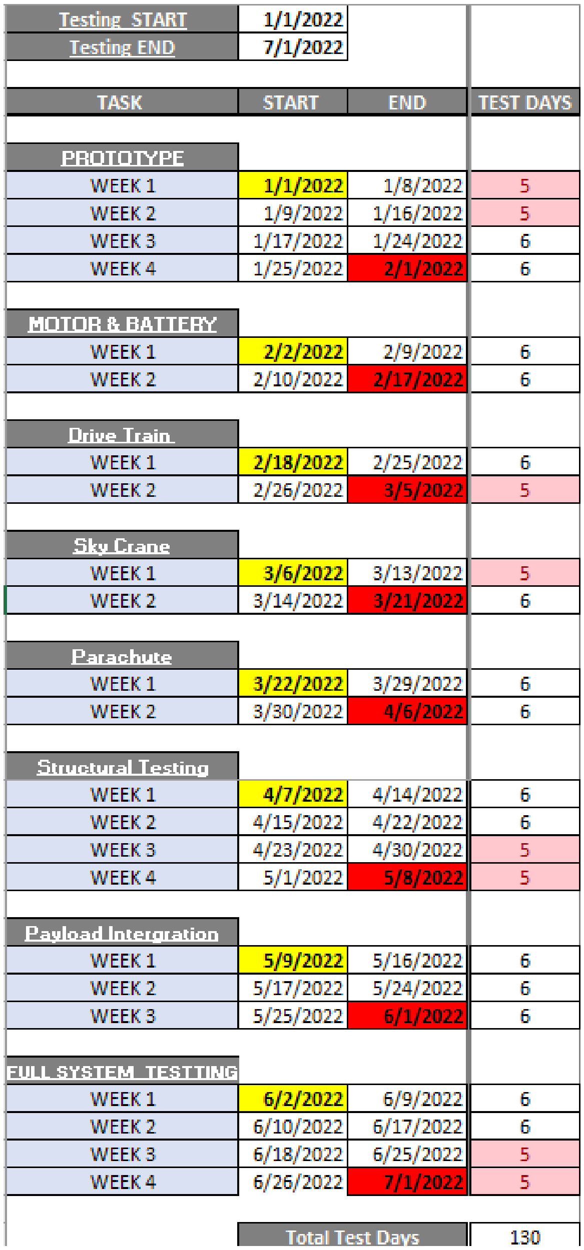
Manufacturing START	10/1/2020
Manufacturing END	12/31/2021

TASK	START	END	WORKING DAYS
CHASSIS			
WEEK 1	10/1/2020	10/8/2020	6
WEEK 2	10/9/2020	10/16/2020	6
WEEK 3	10/17/2020	10/24/2020	5
WEEK 4	10/25/2020	11/1/2020	5
Week 5	11/2/2020	11/9/2020	6
Week 6	11/10/2020	11/17/2020	6
Week 7	11/18/2020	11/25/2020	6
Week 8	11/26/2020	12/3/2020	6
Week 9	12/4/2020	12/11/2020	6
Week 10	12/12/2020	12/19/2020	5
Week 11	12/20/2020	12/27/2020	5
Week 12	12/28/2020	1/4/2021	6
Week 13	1/5/2021	1/12/2021	6
Drive Train			
WEEK 1	1/13/2021	1/20/2021	6
WEEK 2	1/21/2021	1/28/2021	6
WEEK 3	1/29/2021	2/5/2021	6
WEEK 4	2/6/2021	2/13/2021	5
WEEK 5	2/14/2021	2/21/2021	5
WEEK 6	2/22/2021	3/1/2021	6
WEEK 7	3/2/2021	3/9/2021	6
WEEK 8	3/10/2021	3/17/2021	6
Week 9	3/18/2021	3/25/2021	6
Aero-Shell			
WEEK 1	3/26/2021	4/2/2021	6
WEEK 2	4/3/2021	4/10/2021	5
WEEK 3	4/11/2021	4/18/2021	5
WEEK 4	4/19/2021	4/26/2021	6
WEEK 5	4/27/2021	5/4/2021	6
WEEK 6	5/5/2021	5/12/2021	6
WEEK 7	5/13/2021	5/20/2021	6
WEEK 8	5/21/2021	5/28/2021	6
Week 9	5/29/2021	6/5/2021	5

Sky Crane			
WEEK 1	5/29/2021	6/5/2021	5
WEEK 2	6/6/2021	6/13/2021	5
WEEK 3	6/14/2021	6/21/2021	6
WEEK 4	6/22/2021	6/29/2021	6
Week 5	6/30/2021	7/7/2021	6
Week 6	7/8/2021	7/15/2021	6
Week 7	7/16/2021	7/23/2021	6
Week 8	7/24/2021	7/31/2021	5
Week 9	8/1/2021	8/8/2021	5
Week 10	8/9/2021	8/16/2021	6
Week 11	8/17/2021	8/24/2021	6
Week 12	8/25/2021	9/1/2021	6
Week 13	9/2/2021	9/9/2021	6
Parachute			
WEEK 1	9/10/2021	9/17/2021	6
WEEK 2	9/18/2021	9/25/2021	5
WEEK 3	9/26/2021	10/3/2021	5
WEEK 4	10/4/2021	10/11/2021	6
Week 5	10/12/2021	10/19/2021	6
Week 6	10/20/2021	10/27/2021	6
Week 7	10/28/2021	11/4/2021	6
Week 8	11/5/2021	11/12/2021	6
Week 9	11/13/2021	11/20/2021	5
Week 10	11/21/2021	11/28/2021	5
Week 11	11/29/2021	12/6/2021	6
Week 12	12/7/2021	12/14/2021	6
Week 13	12/15/2021	12/22/2021	6
Week 14	12/23/2021	12/31/2021	7

TOTAL DAYS	332
TOTAL YRS	1.1

Figure 25: The Undecim Portam manufacturing schedule.



Testing START	1/1/2022		
Testing END	7/1/2022		
TASK	START	END	TEST DAYS
PROTOTYPE			
WEEK 1	1/1/2022	1/8/2022	5
WEEK 2	1/9/2022	1/16/2022	5
WEEK 3	1/17/2022	1/24/2022	6
WEEK 4	1/25/2022	2/1/2022	6
MOTOR & BATTERY			
WEEK 1	2/2/2022	2/9/2022	6
WEEK 2	2/10/2022	2/17/2022	6
Drive Train			
WEEK 1	2/18/2022	2/25/2022	6
WEEK 2	2/26/2022	3/5/2022	5
Sky Crane			
WEEK 1	3/6/2022	3/13/2022	5
WEEK 2	3/14/2022	3/21/2022	6
Parachute			
WEEK 1	3/22/2022	3/29/2022	6
WEEK 2	3/30/2022	4/6/2022	6
Structural Testing			
WEEK 1	4/7/2022	4/14/2022	6
WEEK 2	4/15/2022	4/22/2022	6
WEEK 3	4/23/2022	4/30/2022	5
WEEK 4	5/1/2022	5/8/2022	5
Payload Intergration			
WEEK 1	5/9/2022	5/16/2022	6
WEEK 2	5/17/2022	5/24/2022	6
WEEK 3	5/25/2022	6/1/2022	6
FULL SYSTEM TESTTING			
WEEK 1	6/2/2022	6/9/2022	6
WEEK 2	6/10/2022	6/17/2022	6
WEEK 3	6/18/2022	6/25/2022	5
WEEK 4	6/26/2022	7/1/2022	5
	Total Test Days		130

Figure 26: The Undecim Portam testing schedule.

3.1.5 Validation and Verification Plans

Validation and verification will run concurrently with manufacturing plans. Simulations will provide baseline system predictions while initial manufacturing is being undertaken. A small scale prototype will be used to ensure the rover can operate autonomously and respond to all commands. Once the proof-of-concept has been built and tested to meet the mission criteria, each full-scale rover subsystem will be tested in an analogous Martian environment to ensure the system's durability. The system's verification plan will be to implement software that "alerts" Mission Control of extraneous conditions. The motors will be utilizing an embedded encoder to determine the distance RIAMAR travels within a set amount of time. The communications system will send a "ping" back to Mission Control every three hours to ensure data is transmitting accurately.

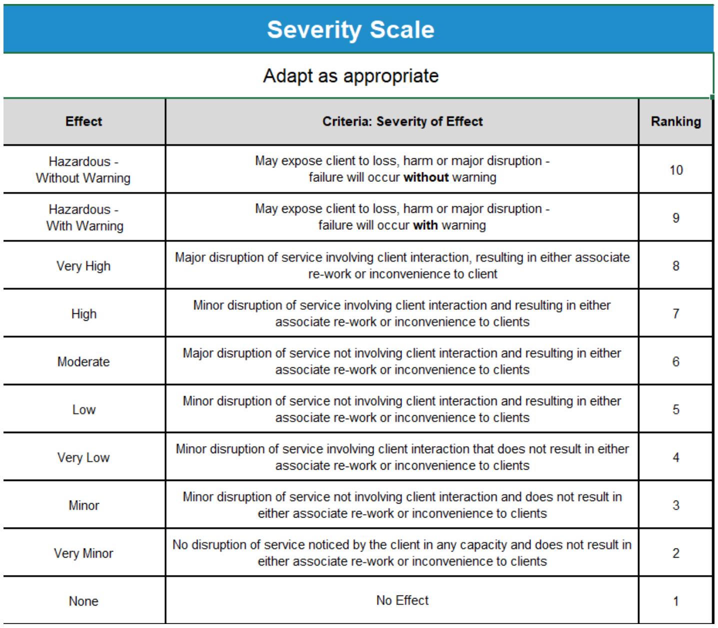
Type	Preliminary testing will be conducted on a proof-of-concept prototype. Once successful, full-scale system testing will begin.
Primary Testing Location	Lab Environment: An analogous Martian environment will be created with comparable temperature, pressure, and terrain within the laboratory.
Secondary Testing Location	Death Valley, Eastern CA: The rocky, rugged terrain is comparable to that of the Martian environment. Testing of the rover propulsion system and mobility capabilities would be conducted at this location.
Analysis	Mathematical modeling techniques will be used to simulate the success of entry, descent, and landing. Analytical techniques will be used to predict the performance and reliability of the communication system, batteries, and motors. FMEA, vibrational testing, and failure load tests will be conducted on each system component.

Demonstration	Multiple demonstrations will be conducted of the full scale Undecim Portam rover. Final demonstrations of rover mobility, scientific experimentation, and power systems will occur at the Death Valley test site.
Inspection	Visual inspections and load testing will be conducted on all manufactured components. Motors and batteries will endure resistance testing to confirm they meet the design specifications.
Test	The rover will be placed in various situations to assess the system's response to a lack of sunlight, physical barriers and obstacles, motor and battery failure, as well as malfunctioning instrumentation.

Table 1: Detailed test and verification plans.

3.1.6 FMEA and Risk Mitigation

Understanding the critical risks in a project is a significant aspect for mission success. Failure Mode and Effects Analysis (FMEA) is an organized approach to locating potential failures that may exist within the design of a product or process. Process FMEA (PFMEA) discovers failure that impacts product quality, reduced reliability of the process, safety hazards derived from: human factors methods followed while processing, materials used, machines utilized, measurement systems. impact on acceptance environment factors on process performance. Highlighted sections indicated in yellow on each FMEA indicate the most mission ending process in manufacturing. In the "Action taken" column indicates measures taken to prevent the risk from occurring to mitigate the risk. Each FMEA is based on three scales, severity, occurrence and detection. How severe or the effect of the issue on the product, how likely the issue will occur, and how likely you are able to detect the issue.

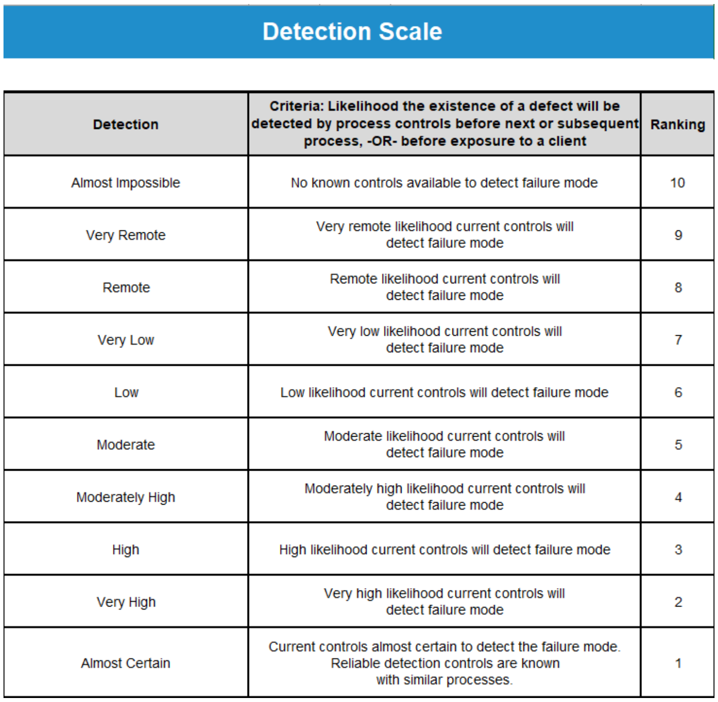


Severity Scale

Adapt as appropriate

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur **without** warning	10
Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur **with** warning	9
Very High	Major disruption of service involving client interaction, resulting in either associate re-work or inconvenience to client	8
High	Minor disruption of service involving client interaction and resulting in either associate re-work or inconvenience to clients	7
Moderate	Major disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	6
Low	Minor disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	5
Very Low	Minor disruption of service involving client interaction that does not result in either associate re-work or inconvenience to clients	4
Minor	Minor disruption of service not involving client interaction and does not result in either associate re-work or inconvenience to clients	3
Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associate re-work or inconvenience to clients	2
None	No Effect	1

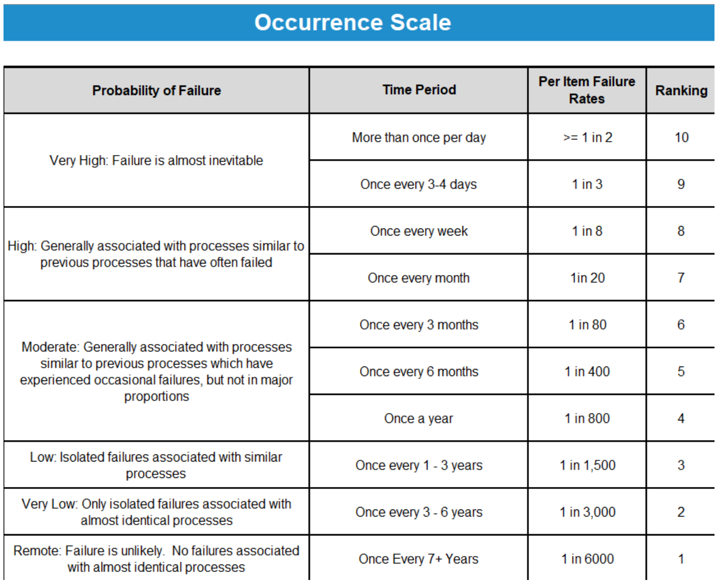
Figure 27: Severity Scale for FMEA.



Detection Scale

Detection	Criteria: Likelihood the existence of a defect will be detected by process controls before next or subsequent process, -OR- before exposure to a client	Ranking
Almost Impossible	No known controls available to detect failure mode	10
Very Remote	Very remote likelihood current controls will detect failure mode	9
Remote	Remote likelihood current controls will detect failure mode	8
Very Low	Very low likelihood current controls will detect failure mode	7
Low	Low likelihood current controls will detect failure mode	6
Moderate	Moderate likelihood current controls will detect failure mode	5
Moderately High	Moderately high likelihood current controls will detect failure mode	4
High	High likelihood current controls will detect failure mode	3
Very High	Very high likelihood current controls will detect failure mode	2
Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1

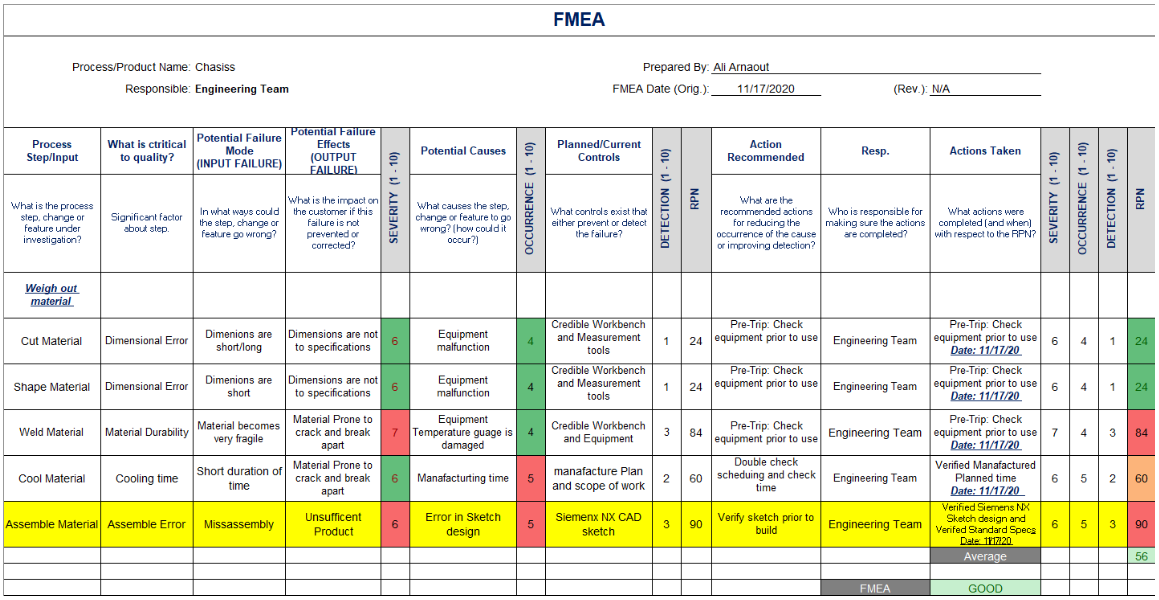
Figure 28: Detection Scale for FMEA.



Occurrence Scale

Probability of Failure	Time Period	Per Item Failure Rates	Ranking
Very High: Failure is almost inevitable	More than once per day	>= 1 in 2	10
	Once every 3-4 days	1 in 3	9
High: Generally associated with processes similar to previous processes that have often failed	Once every week	1 in 8	8
	Once every month	1in 20	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	Once every 3 months	1 in 80	6
	Once every 6 months	1 in 400	5
	Once a year	1 in 800	4
Low: Isolated failures associated with similar processes	Once every 1 - 3 years	1 in 1,500	3
Very Low: Only isolated failures associated with almost identical processes	Once every 3 - 6 years	1 in 3,000	2
Remote: Failure is unlikely. No failures associated with almost identical processes	Once Every 7+ Years	1 in 6000	1

Figure 29: Occurrence Scale for FMEA.



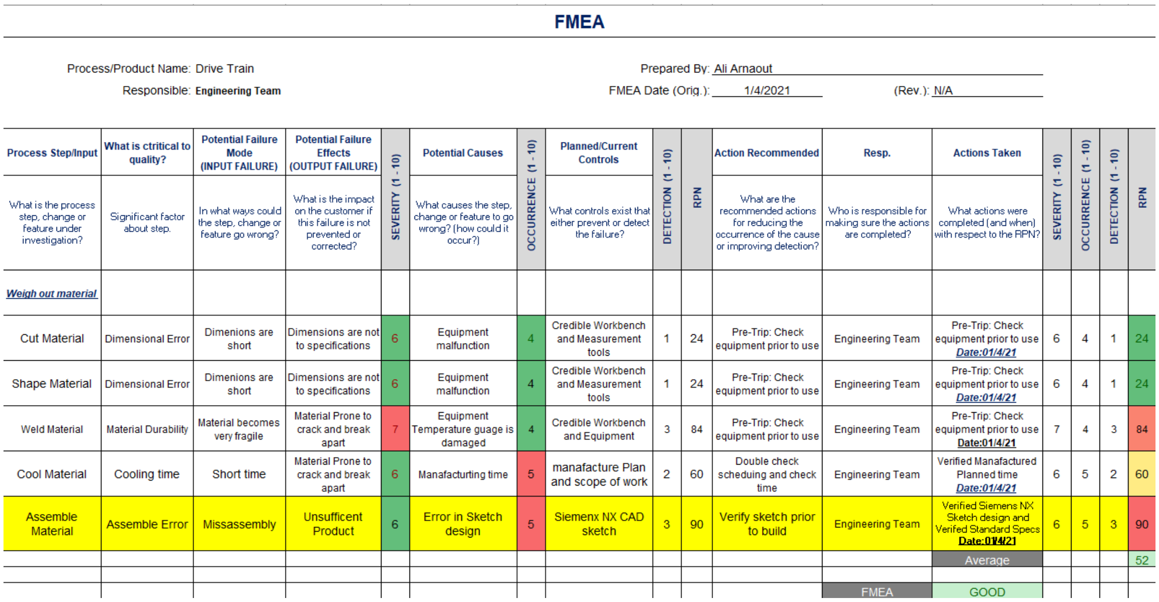
FMEA

Process/Product Name: Chasiss
Responsible: **Engineering Team**

Prepared By: Ali Arnaout
FMEA Date (Orig.): 11/17/2020 (Rev.): N/A

Process Step/Input	What is ctritical to quality?	Potential Failure Mode (INPUT FAILURE)	Potential Failure Effects (OUTPUT FAILURE)	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Planned/Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	Significant factor about step.	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Weigh out material																
Cut Material	Dimensional Error	Dimenions are short/long	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 11/17/20***	6	4	1	24
Shape Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 11/17/20***	6	4	1	24
Weld Material	Material Durability	Material becomes very fragile	Material Prone to crack and break apart	7	Equipment Temperature guage is damaged	4	Credible Workbench and Equipment	3	84	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 11/17/20***	7	4	3	84
Cool Material	Cooling time	Short duration of time	Material Prone to crack and break apart	6	Manafacturting time	5	manafacture Plan and scope of work	2	60	Double check scheduing and check time	Engineering Team	Verified Manafactured Planned time ***Date: 11/17/20***	6	5	2	60
Assemble Material	Assemble Error	Missassembly	Unsufficent Product	6	Error in Sketch design	5	Siemenx NX CAD sketch	3	90	Verify sketch prior to build	Engineering Team	Verified Siemens NX Sketch design and Verifed Standard Specs Date: 11/17/20	6	5	3	90
												Average				56
											FMEA	GOOD				

Figure 30: FMEA Risk Mitigations for the chassis.

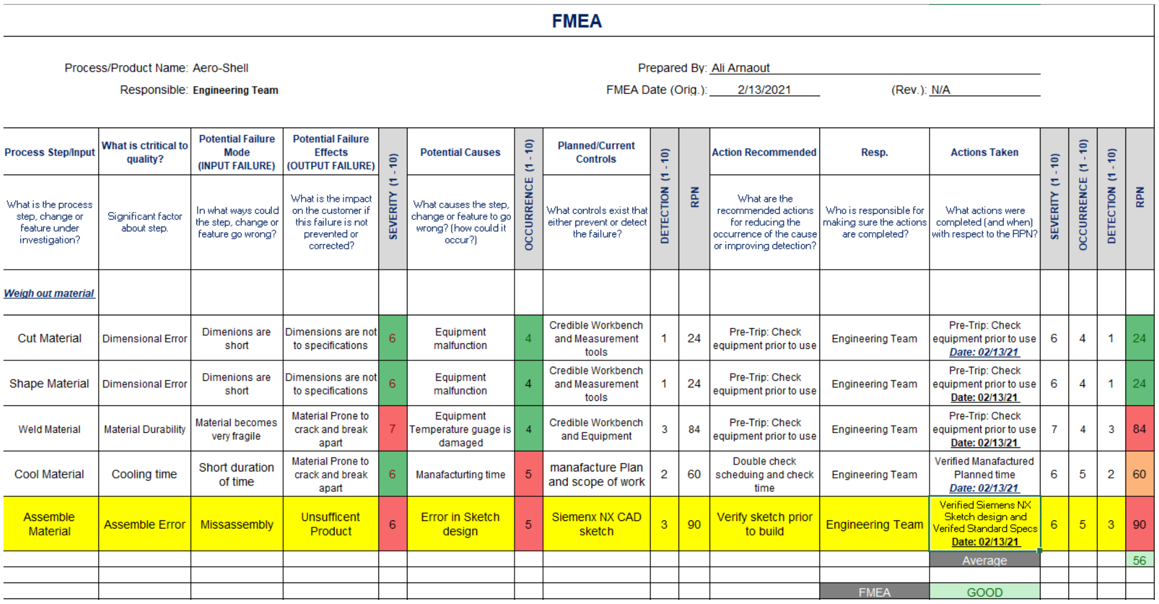


FMEA

Process/Product Name: Drive Train
Responsible: **Engineering Team**
Prepared By: Ali Arnaout
FMEA Date (Orig.): 1/4/2021
(Rev.): N/A

Process Step/Input	What is ctritical to quality?	Potential Failure Mode (INPUT FAILURE)	Potential Failure Effects (OUTPUT FAILURE)	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Planned/Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	Significant factor about step.	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Weigh out material																
Cut Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date:01/4/21***	6	4	1	24
Shape Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date:01/4/21***	6	4	1	24
Weld Material	Material Durability	Material becomes very fragile	Material Prone to crack and break apart	7	Equipment Temperature guage is damaged	4	Credible Workbench and Equipment	3	84	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use **Date:01/4/21**	7	4	3	84
Cool Material	Cooling time	Short time	Material Prone to crack and break apart	6	Manafacturing time	5	manafacture Plan and scope of work	2	60	Double check scheduling and check time	Engineering Team	Verified Manafactured Planned time ***Date:01/4/21***	6	5	2	60
Assemble Material	Assemble Error	Missassembly	Unsufficent Product	6	Error in Sketch design	5	Siemenx NX CAD sketch	3	90	Verify sketch prior to build	Engineering Team	Verified Siemens NX Sketch design and Verifed Standard Specs **Date:01/4/21**	6	5	3	90
												Average				52
											FMEA	GOOD				

Figure 31: FMEA Risk Mitigations for the drive train.

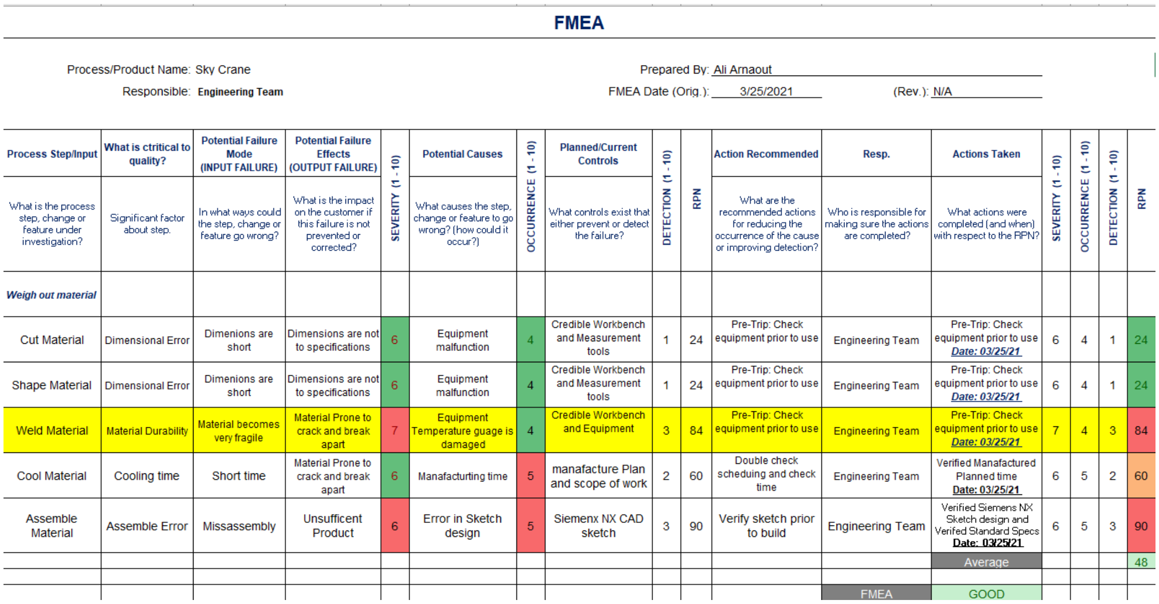


FMEA

Process/Product Name: Aero-Shell
Responsible: **Engineering Team**
Prepared By: Ali Arnaout
FMEA Date (Orig.): 2/13/2021
(Rev.): N/A

Process Step/Input	What is ctritical to quality?	Potential Failure Mode (INPUT FAILURE)	Potential Failure Effects (OUTPUT FAILURE)	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Planned/Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	Significant factor about step.	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Weigh out material																
Cut Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 02/13/21***	6	4	1	24
Shape Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use **Date: 02/13/21**	6	4	1	24
Weld Material	Material Durability	Material becomes very fragile	Material Prone to crack and break apart	7	Equipment Temperature guage is damaged	4	Credible Workbench and Equipment	3	84	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use **Date: 02/13/21**	7	4	3	84
Cool Material	Cooling time	Short duration of time	Material Prone to crack and break apart	6	Manafacturing time	5	manafacture Plan and scope of work	2	60	Double check scheduling and check time	Engineering Team	Verified Manafactured Planned time ***Date: 02/13/21***	6	5	2	60
Assemble Material	Assemble Error	Missassembly	Unsufficent Product	6	Error in Sketch design	5	Siemenx NX CAD sketch	3	90	Verify sketch prior to build	Engineering Team	Verified Siemens NX Sketch design and Verifed Standard Specs **Date: 02/13/21**	6	5	3	90
												Average				56
											FMEA	GOOD				

Figure 32: FMEA Risk Mitigations for the aero-shell.



FMEA

Process/Product Name: Sky Crane

Responsible: **Engineering Team**

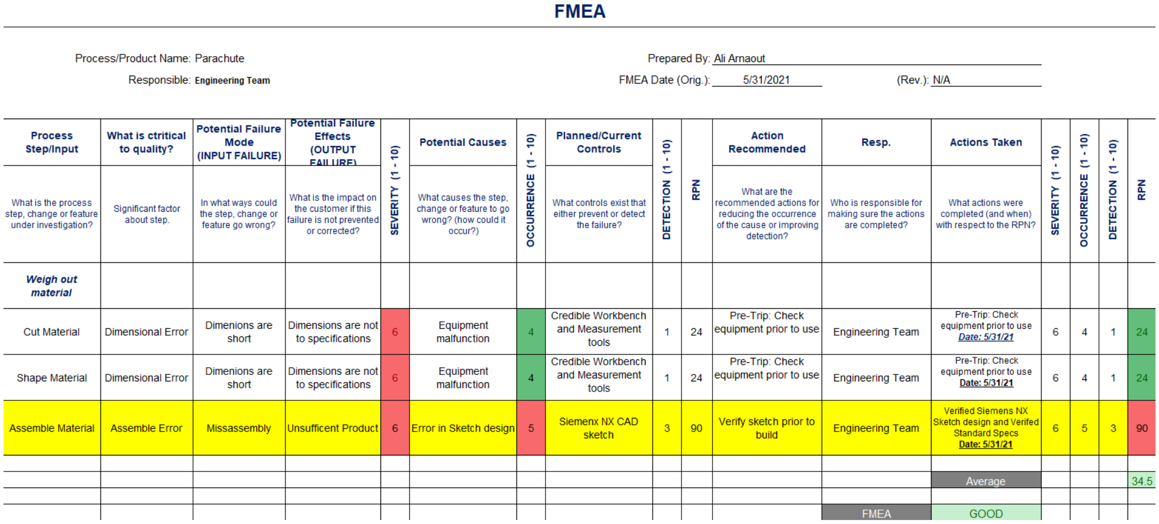
Prepared By: Ali Arnaout

FMEA Date (Orig.): 3/25/2021

(Rev.): N/A

Process Step/Input	What is ctritical to quality?	Potential Failure Mode (INPUT FAILURE)	Potential Failure Effects (OUTPUT FAILURE)	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Planned/Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	Significant factor about step.	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Weigh out material																
Cut Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 03/25/21***	6	4	1	24
Shape Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 03/25/21***	6	4	1	24
Weld Material	Material Durability	Material becomes very fragile	Material Prone to crack and break apart	7	Equipment Temperature guage is damaged	4	Credible Workbench and Equipment	3	84	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 03/25/21***	7	4	3	84
Cool Material	Cooling time	Short time	Material Prone to crack and break apart	6	Manafacturing time	5	manafacture Plan and scope of work	2	60	Double check scheduling and check time	Engineering Team	Verified Manafactured Planned time **Date: 03/25/21**	6	5	2	60
Assemble Material	Assemble Error	Missassembly	Unsufficent Product	6	Error in Sketch design	5	Siemenx NX CAD sketch	3	90	Verify sketch prior to build	Engineering Team	Verified Siemens NX Sketch design and Verifed Standard Specs **Date: 03/25/21**	6	5	3	90
												Average				48
											FMEA	GOOD				

Figure 33: FMEA Risk Mitigations for the sky crane.



FMEA

Process/Product Name: Parachute

Responsible: **Engineering Team**

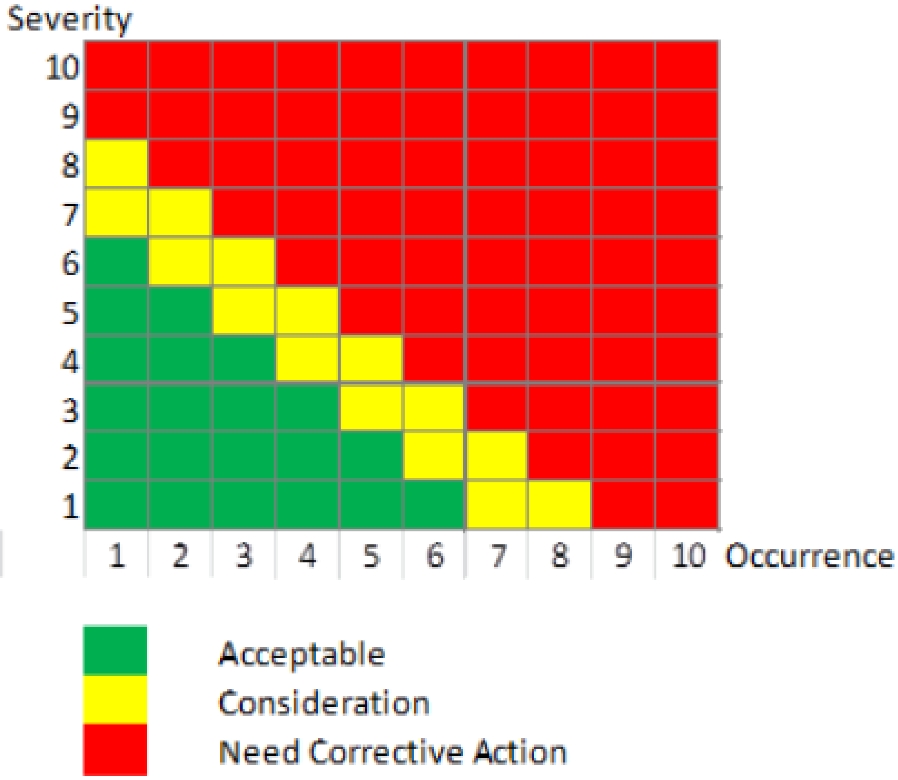
Prepared By: Ali Arnaout

FMEA Date (Orig.): 5/31/2021

(Rev.): N/A

Process Step/Input	What is ctritical to quality?	Potential Failure Mode (INPUT FAILURE)	Potential Failure Effects (OUTPUT FAILURE)	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Planned/Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	Significant factor about step.	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Weigh out material																
Cut Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use ***Date: 5/31/21***	6	4	1	24
Shape Material	Dimensional Error	Dimenions are short	Dimensions are not to specifications	6	Equipment malfunction	4	Credible Workbench and Measurement tools	1	24	Pre-Trip: Check equipment prior to use	Engineering Team	Pre-Trip: Check equipment prior to use **Date: 5/31/21**	6	4	1	24
Assemble Material	Assemble Error	Missassembly	Unsufficent Product	6	Error in Sketch design	5	Siemenx NX CAD sketch	3	90	Verify sketch prior to build	Engineering Team	Verified Siemens NX Sketch design and Verifed Standard Specs **Date: 5/31/21**	6	5	3	90
												Average				34.5
											FMEA	GOOD				

Figure 34: FMEA Risk Mitigations for the parachute.



Severity											
10	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
9	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
8	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
7	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
6	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
5	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	
4	🟩	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	
3	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	
2	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟥	🟥	
1	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟥	
	1	2	3	4	5	6	7	8	9	10	Occurrence

🟩 Acceptable
🟨 Consideration
🟥 Need Corrective Action

Figure 35: Risk Matrix for the Descent and Lander design.

3.1.7 Performance Characteristics and Predictions

Undecim Portam's designed entry, descent, and lander systems is predicted to be successful in the Martian environment. In order to reach the mission success criteria, each system has been designed to effectively operate in the Martian environment, provide for the most efficient data collection, and ultimately transmit data from the Martian surface back to Earth for analysis.

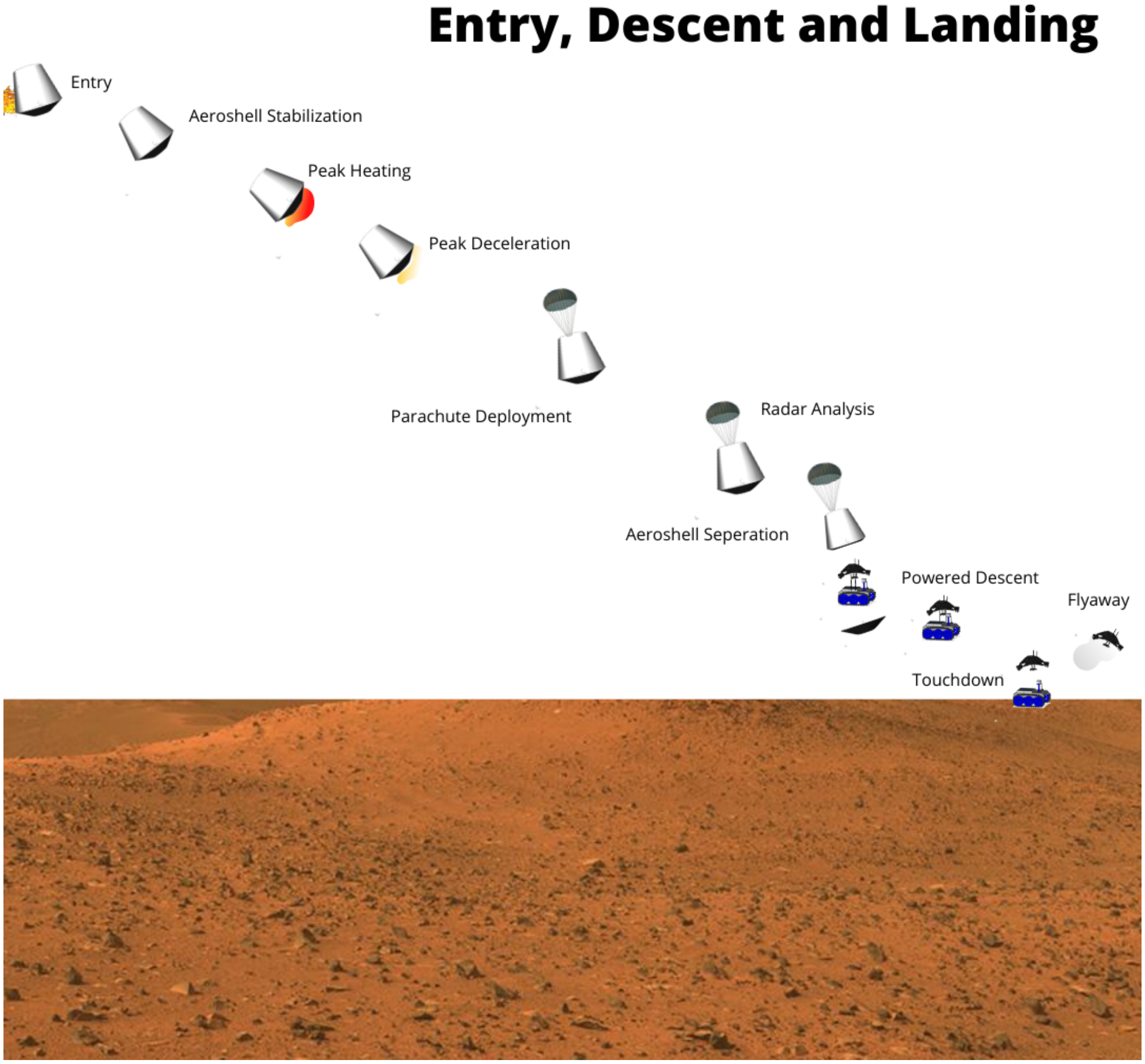


Figure 36: Entry, descent, and landing graphic for the Undecim Portam mission.

With a launch in December of 2021, the Undecim Portam mission will arrive during the Martian summer. The system may encounter increased dust storms and higher temperatures due to the season of arrival [14]. In order to mitigate these risks and ensure the success of the mission, added layers of composite tiles have been added to the aeroshell assembly to protect from heat damage. The solar panels on-board RIAMAR have been outfitted with durable linear piezoelectric actuators that will mitigate the accumulation of dust. The multi-stage entry and descent of the lander has taken into account the extreme temperatures with the entry vehicle, while any physical obstacles on the Martian surface may be avoided by use of the Skycrane powered descent system. The Skycrane touchdown mitigates the effects of Martian winds interfering with the safe landing of the RIAMAR rover and its valuable payload. Unlike with airbags or another cushioning system, the Skycrane system will slowly lower RIAMAR to the surface and may direct the land to another position if the chosen landing site is not viable due to obstacles or wind conditions.

The Undecim Portam mission systems have been efficiently designed to successfully meet the mission criteria. Each system has been developed to effectively operate within the Martian environment. Utilizing flight-ready hardware and testing the system in an analogous Martian landscape will only further reinforce the mission's successful performance.

3.1.8 Confidence and Maturity of Design

The Undecim Portam systems have evolved in design to meet the mission criteria. The entry and descent systems utilize cutting edge 3D composite materials to protect the payload from the extreme temperatures endured upon entering the Martian atmosphere. The Skycrane and parachute system have been made lightweight and durable to fit within the design constraints, but will provide a calculated, safe descent for the lander. Various simulations will ensure the entry and descent systems enter at the correct trajectory and can deliver the payload to the Martian surface successfully.

The RIAMAR rover has undergone design revision as well. The chassis has been made slimmer and lighter, all while accommodating the rover's essential components. By utilizing flight ready hardware (radiation-hardened batteries, processor, communication system and instrumentation), the RIAMAR rover is well-equipped to succeed after landing on Northeast Syrtis. Structural, stress, temperature, vibrational testing, and simulations will verify the durability of individual system components. Final testing conducted on the RIAMAR rover in an analogous Martian environment will solidify the system's accuracy and allow for further assessment of potential detriments.

3.2 Recovery/Redundancy System

Undecim Portam sets out to search and explore the Northeast Syrtis for oxygen wells in order to learn more about Mars and its history. Additionally, the mission hopes to pave a path for future manned missions to come to Mars. Undecim Portam will spend the entirety of its lifetime trying to fulfill its mission on the Mars surface.

Power management is a vital sub-system on the vehicle. Utilizing solar panels and lithium-ion batteries, each of the instruments and systems have a back-up power source. While the solar panels have a high energy production, excess energy will be stored within the lithium-ion batteries. Once the solar panels are unable to produce a significant amount of wattage, the lithium-ion batteries will become the primary power source. This design choice will enable the vehicle to complete the mission goals even if one of the power sources becomes depleted or one power source has stopped working.

While the instruments on the vehicle cannot be replaced or fixed in the event that they stop working during the mission, many measures have been put in order to prevent the instruments from being damaged. With the frequent occurrence of dust storms on Mars, there is a high chance that dust may accumulate on the entirety of the vehicle. This accumulation of dust will not affect the Navcam as it is constantly moving. Dust accumulation will be minimal on RIMFAX as the instrument is in the underbelly of the vehicle, but it will greatly affect the solar panels that sit atop the chassis. This accumulation of dust may prevent the sunlight from reaching the photovoltaic cells on the solar panels. In order to mitigate the accumulation of dust particles on the solar panel, Undecim Portam is equipped with linear piezoelectric actuators on the surface of the solar panels. This is a lightweight and compact cleaning system for the surface of the solar panels. With a proper pressure force between this wiper and solar panel, the actuator drives the wiper to effectively wipe the dust layer off of the surface. The linear piezoelectric actuators will wipe the surface of the solar panels every few hours and after dust storms to prevent the accumulation of dust and maximize the energy production.

Vital to the movement of the vehicle, many precautionary measures have been set in place to protect the drivetrain and motors of the vehicle. Special coverings for these components have been designed to protect them from unwanted materials such as dust particles, as well as insulate them from the frigid Martian temperatures. Additionally, the design of the drivetrain and the different placement and use of motors will greatly increase the longevity of the vehicle. With an unforeseen failure of a motor, the onboard software has the ability to give power to another motor in order to cover the workload that the other motor did.

3.3 Payload Integration

The RIAMAR rover utilizes RIMFAX and Navcam to complete the Undecim Portam mission goals. RIMFAX is carefully placed on the underside of the RIAMAR chassis, behind the solar panel configuration. The instrument is mounted with a designed aluminum bracket assembly to ensure the sensor can effectively scan the Martian terrain. There is 100mm of clearance from the RIMFAX bracket assembly to the propulsion drivetrain.

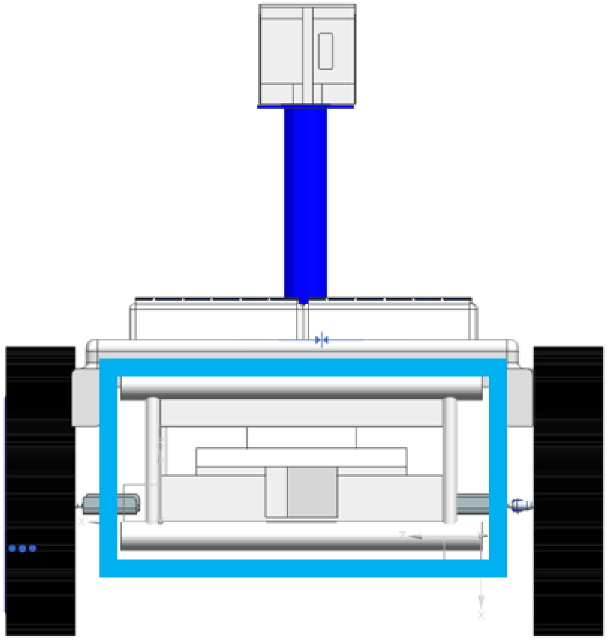


Figure 37: RIMFAX and bracket (boxed in blue), placed on the underside of the RIAMAR chassis.

Navcam is positioned at the front center of the rover chassis for expansive visibility, and stationed on a 150 mm tall rotating stand 65mm from the solar panel assembly.

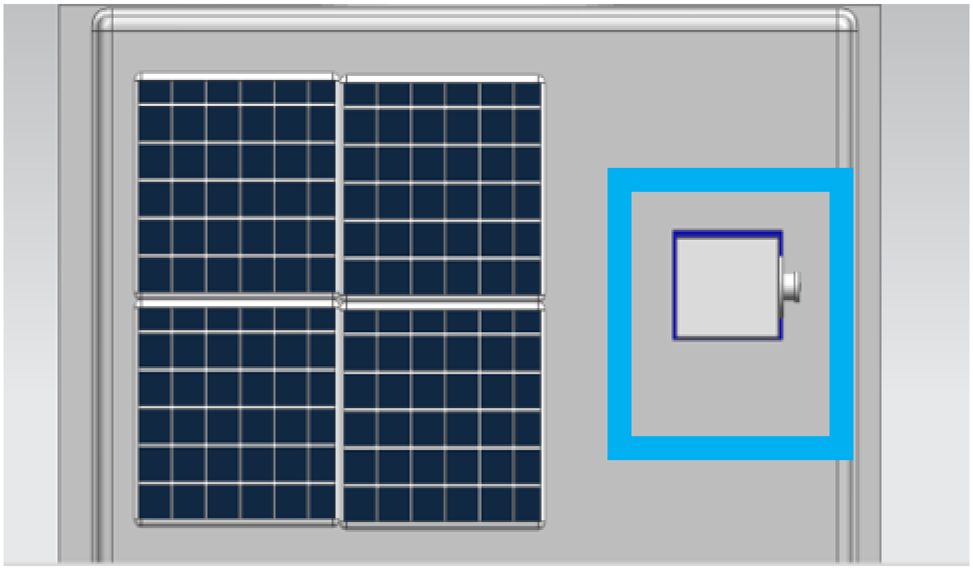


Figure 38: Top-view of Navcam (boxed in blue) and the solar panels positioned on the RIAMAR chassis.

4 Payload Design and Science Experiments

4.1 Selection, Design, and Verification

4.1.1 System Overview - N^2 Chart

The systems of the rover, and rover itself, work in unison and are dependent upon electrical power, primarily provided by the solar cells. The rover drivetrain consists of two Maxon brushless DC motors which require an operating wattage of 40 with a 13.4 Kelvin per watt thermal resistance allowance [32]. These motors receive inputs from the computer to regulate torque and rpm independently while simultaneously delivering velocity and resistance data back to the computer. The onboard computer, the BAE RAD 750 Processor, has a core clock of 110 to 200 MHz. It requires 5 watts to operate while retaining a miniscule thermal deficit [3]. It regulates power distribution of the battery, controls the gimbal and imaging commands of Navcam, commands RIMFAX firing, and relays data from all systems to the radio communications center. The solar cells power everything on RIAMAR and provide 1.1 kilowatts per hour to every component of the rover [6]. The solar panels provide the computer with its functioning information and deliver power to the battery. The lithium ion battery is capable of storing 64 watt hours at 24 volts [41]. This battery distributes power to the rover, computer, Navcam, RIMFAX, and radio comms system. Navcam requires 2.2 watts while the gimbal it is seated with requires 12 watts while moving, with a thermal resistance of 29.5 Kelvin per watt [32]. RIMFAX demands 5 to 10 watts [17]. Finally, the communications system requires 0.075 watts and utilizes a high gain X-band Omni Antenna capable of frequencies between 8100 and 8600 megahertz (MHz) [1]. The data acquisition from Navcam, RIMFAX, and the radio communications system are all sent to the computer. After interpretation and computing, all data can be exported through the radio communications instrument to be picked-up by a local orbiting satellite in order to amplify the signal to send to Earth.

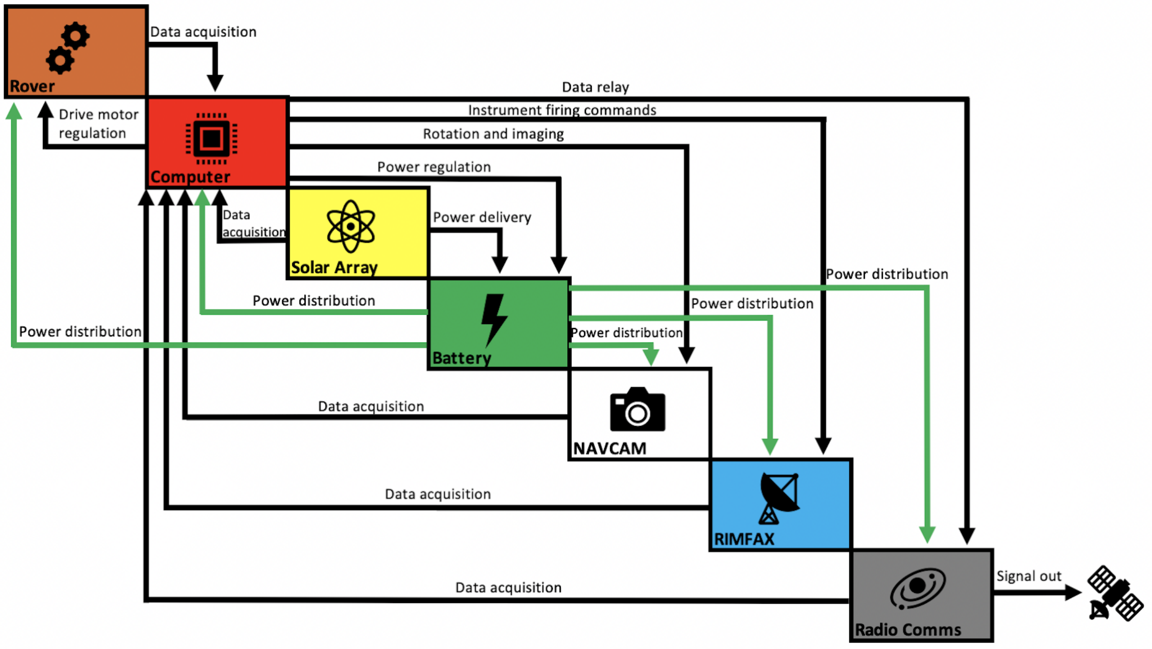


Figure 39: N^2 chart depicting payload relations.

4.1.2 Subsystem Overview

The rover is made up of three different components: data relay, power supply, and data acquisition. The primary instrument in the data relay system is the computer. The computer aids in regulating the battery's power supply, sending commands to the scientific instruments, and relaying data to the radio communication system. The power supply component is composed of the solar array and the battery. The main function of the solar array is to deliver power to the battery while the battery distributes power to the rest of the rover. The data acquisition component is made up of the scientific instruments: Navcam, RIMFAX, and the radio communication system. The scientific payload contains a navigation camera and the main scientific instrument, the RIMFAX radar imager. The navigation camera, or Navcam, will be mounted on a gimbal and will be used to help the rover safely explore our selected landing site of Northeast Syrtis on Mars. The main instrument in this mission will be the RIMFAX which uses radar waves to evaluate the ground under the rover. Its main function is to see the geological features below the surface with a ground-penetrating radar. The design of RIMFAX is very similar to radar systems used on Earth which probe underground rock and ice in the Arctic. RIMFAX will be able to detect ice, water, or brines approximately 10 meters underneath the Martian surface [17]. This will help aid in determining the depth, elements, minerals, and state of matter of the contents below the surface in the Northeast Syrtis region of Mars. After the scientific instruments and the radio communication system gathers the data, it relays the information to the rover's computer. The computer then computes the data and relays it back to the radio communication system where it then sends the computed data to Earth.

Mass	Approximately 250 grams each
Image Size	1024 × 1024 pixels
Image Resolution	0.82 milliradians per pixel
Focal Length	in focus from 20 inches (0.5 meters) to infinity

Table 2: Technical Specifications for the Navigation Cameras [7].

Mass	3 kilograms
Power	5–10 Watts
Volume	196 × 120 × 66 millimeters
Data Return	5–10 kilobytes per sounding location
Frequency Range	150–1200 MegaHertz
Vertical Resolution	15–30 centimeters thick

Table 3: Technical Specifications for the Radar Imager for Mars' Subsurface Experiment [17].

4.1.3 Precision of Instrumentation, Repeatability of Measurement, and recovery system

The Navcam uses a f/12, 14.67 mm f-theta fisheye lens to create a 45 degree x 45 degree field of view (equivalently, a 67 degree diagonal field of view), with the pixel scale at the center of the field of view being 0.82 mrad/pixel. It also uses a 1024 x 1024 pixel detector and uses three filters to create a red bandpass filter centered at 650 nm, with a bandwidth (full width at half maximum) of approximately 140 nm, creating an effective spectral range of 600-800 nm as pictured in Figure 41 [25]. The Navcam has a hyperfocal distance of 1.0 meters with a depth of field ranging from 0.5 meters to infinity. Based on previous calibrations, the Navcam's average error is 0.558 ± 0.001 pixels ($\approx 0.027°$) in the azimuth direction and 2.099 ± 0.001 pixels ($\approx 0.099°$) in the elevation direction [26].

The RIMFAX utilizes radio waves with frequencies ranging from 150 MHz to 1.2 GHz to scan the subsurface. Because different materials can absorb, reflect, or even scatter the radar energy, the depth of the RIMFAX's measurements can widely vary. For example, the radar pulse can essentially pass straight through pure water ice, allowing the RIMFAX to take measurements at a depth of nearly 3 km. However, the RIMFAX was only able to penetrate roughly 2 m into the Earth's surface [51]. The varying ground conditions on Mars allows RIMFAX to potentially penetrate to depths ranging from 20 - 100 meters, with a minimum of approximately 10 meters. As the ranging error is inversely proportional to frequency, RIMFAX's largest error range should occur at the lowest frequency of 150 MHz, which is calculated to be approximately 3% error. The RIMFAX is capable of vertical resolutions from 15 to 30 centimeters thick. For the Undecim Portam mission, the RIMFAX will be tuned to a vertical resolution of 20 centimeters in order to maximize resolution while minimizing error.

Data from both the Navcam and RIMFAX will be processed and saved by the onboard computer and sent via radio transmitter to the nearby comms system, which will use a low frequency radar to amplify and send the signal back to Earth.

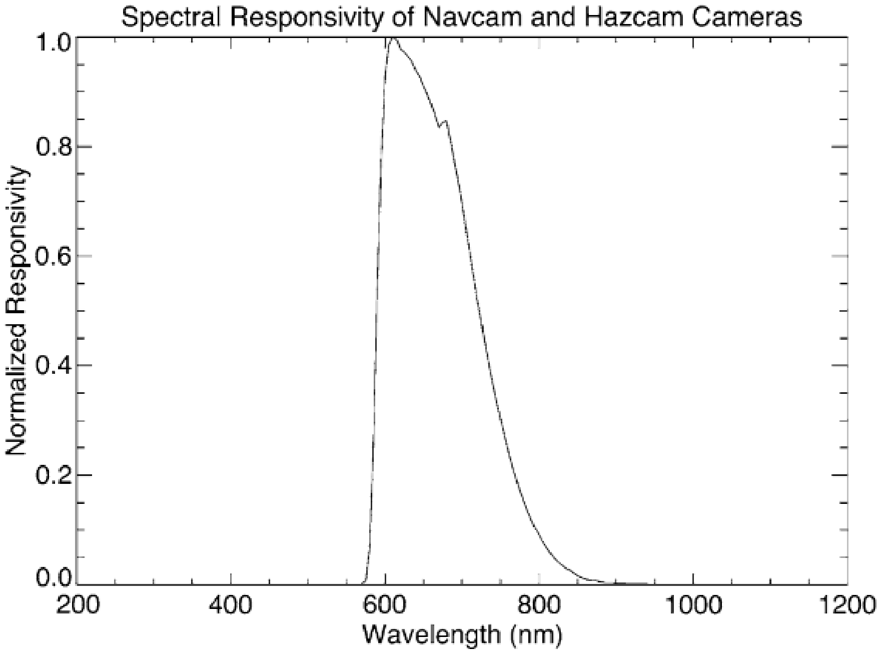


Figure 40: Normalized, representative spectral responsivity for the Navcam [25].

4.1.4 Validation and Verification Plan

The Navcam has a 45 degree x 45 degree field of view, meaning a minimum of 32 pictures must be taken to fully capture a 360° spherical view. The verification plan entails taking 33 pictures. The Navcam will first take a picture (Picture 1) at a vertical incline of 22.5° (with 0° being parallel to the surface of Mars), capturing an image that has a vertical range of 0° to 45°. If while Picture 1, is being taken or at any other phase of this process, a picture is failed to be taken (e.g., the contents of the picture are a black screen, the data is unreadable, etc.) troubleshooting will occur to find the cause of the error before rotating. Assuming Picture 1 is a “success”, Picture 2 will be taken after the Navcam is rotated 45° counter-clockwise (azimuth direction). Picture 3 will be taken after an additional 45° counter-clockwise rotation, and this process continues for Pictures 4 through 8. After Picture 8, the Navcam should rotate an additional 45° such as to return to its original orientation. The Navcam will then increase its vertical incline by 45° such that it will be at an incline of 67.5°. Pictures 9 through 16 will repeat the process of taking pictures at 45° intervals, capturing images with a vertical range of 45° to 90°. After Picture 16 is taken, the top hemisphere of a 360° view should be captured, and the Navcam will again rotate 45° to return to its original azimuth orientation. Pictures 17 through 24 will repeat the 45° counterclockwise rotation at a vertical incline of -22.5°, capturing a range from -45° to 0°, and Pictures 25 through 32 will repeat the rotation at a vertical incline of -67.5°, capturing a range from -90° to -45°, as to capture the bottom hemisphere. After Picture 32 is taken, the Navcam will increase its vertical incline by 67.5° and rotate 45° in the counter-clockwise as to return to the initial position of 0°. Picture 33 will be taken at this orientation.

With Pictures 1 through 32, a 360° rendition of RIAMAR’s field of view can be composed. Picture 33 is to ensure that the gimbal is able to accurately and precisely rotate. As such, Pictures 1 and 33 will be compared. The verification plan is considered successful if a 360° composite is made and the contents of Pictures 1 and 33 can be considered an accurate and exact match. A preliminary 360° composite will also help determine the best direction that RIAMAR will initially travel.

At any given reading of the subsurface, RIMFAX will send two signals at once. The first signal will be to ensure that a signal was sent and properly calibrate the system for signal reflections. An internal log will check and note if the RIMFAX’s system is actually calibrated/updated. If the first signal indicates that the current calibrations are appropriate for the reading, the internal log will still note an “update”. The second signal will actually measure the reflections. If the first signal does not properly calibrate the RIMFAX, the data from the second signal will be disregarded as it cannot be considered accurate. As such, RIMFAX can be verified by simply performing a preliminary reading immediately after being deployed. If at any given point the first signal fails to calibrate the system (which can be indicated by the internal log), or the second signal fails to return any measurements of reflections, it can be inferred that RIMFAX is not functioning properly [18].

4.1.5 FMEA and Risk Mitigation

It was important to also recognize and analyze all potential areas of risk, failure, and error for the payload and scientific experiments of the Undecim Portam mission. To do this, a risk mitigation chart was created to include a top-level summary of the risks and mitigations. There were four areas of risk that needed to be studied:

1. Technical - the area of the mission associated with achieving the scientific objectives
2. Schedule - whether or not the mission is on track to reach the launch date
3. Cost - whether or not the mission is staying below budget
4. Safety - whether or not the payload has had any destruction.

Each risk area had an associated consequence from very low to very high as seen in Table 4.

Level	**Very Low (1)**	**Low (2)**	**Medium (3)**	**High (4)**	**Very High (5)**
Technical	Minimal or no impact	Moderate Reduction with same scientific approach	Moderate Reduction with alternate approaches available	Major Reduction with alternate approaches available	Major Reduction with no alternative approaches available
Schedule	Minimal or no impact	Minor setbacks, able to meet major deadlines	Major setbacks pushing deadlines back < 1 month	Major setbacks pushing deadlines back > 1 month	Cannot achieve major mission objectives
Cost	Minimal or no impact	Total Budget increase of < 2 %	Total Budget increase of > 2 %	Total Budget increase of > 5 %	Total Budget increase of > 10 %
Safety	Minimal or no impact	May cause minor treatment to payload and equipment	May cause minor damage to payload and equipment	May cause major damage to payload and equipment	May cause destruction of payload and equipment

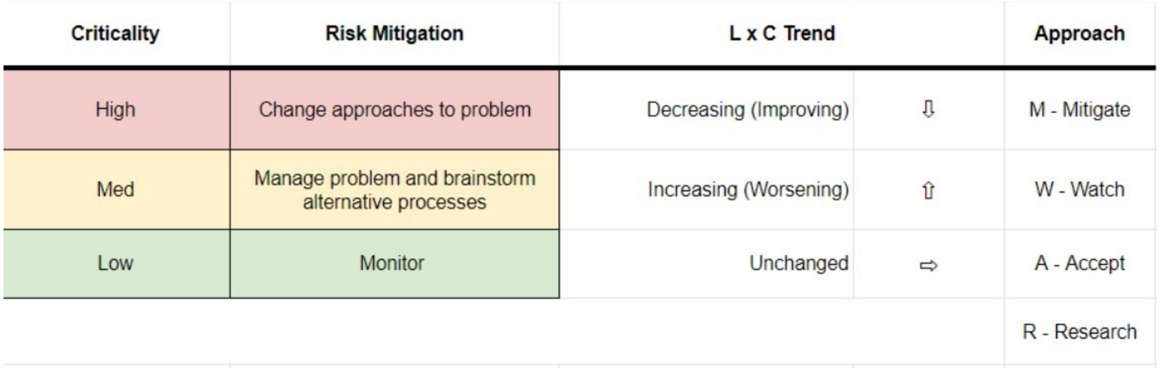
Table 4: Consequences: Given the event occurs, what is the magnitude of the impact to the Undecim Portam Mission?

Similarly, each associated area had an associated probability or likelihood of the risk happening as seen in Table 5.

Level	**Mission Performance and Risk Probability (Technical)**	**Project Implementation Risk Probability (Schedule and Cost)**	**Safety Risk Probability**
Very High (5)	$P > 50\%$	$P > 75\%$	$P > 10^{-1}$
High (4)	$25\% < P \leq 50\%$	$50\% < P \leq 75\%$	$10^{-2} < P \leq 10^{-1}$
Medium (3)	$10\% < P \leq 25\%$	$25\% < P \leq 50\%$	$10^{-3} < P \leq 10^{-2}$
Low (2)	$2\% < P \leq 10\%$	$10\% < P \leq 25\%$	$10^{-5} < P \leq 10^{-3}$
Very Low (1)	$0.1\% < P \leq 2\%$	$2\% < P \leq 10\%$	$10^{-6} < P \leq 10^{-5}$

Table 5: Likelihood: What is the probability that the situation will happen?

Each potential risk to the payload and scientific instruments of the Undecim Portam Mission was given a ranking on criticality based on likelihood and consequences, also known as the L x C trend, and the approach the team is taking to mitigate the risk (the legend can be found in Figure 41). An "Accept" approach is when a certain level of the risk is accepted when it is within the tolerance of the program. "Mitigate" entails actions that will address the problem and create solutions to decrease consequences. "Watch" includes observation of the issue and the creation of plans if the situation escalates. Finally, the "Research" approach is a detailed effort to better understand the risk and brainstorm ideas on how to reduce uncertainties.



Criticality	**Risk Mitigation**	**L x C Trend**		**Approach**
High	Change approaches to problem	Decreasing (Improving)	⇩	M - Mitigate
Med	Manage problem and brainstorm alternative processes	Increasing (Worsening)	⇧	W - Watch
Low	Monitor	Unchanged	⇨	A - Accept
				R - Research

Figure 41: Legend for the Risk Management Table and Risk Matrix.

The science team found the six most pressing potential risks for the payload and scientific instruments on reaching the martian atmosphere, which can be found in Table 6 with an accompanying risk matrix found in Figure 42. Due to the fact that the Undecim Portam mission is a secondary payload and will not be spending an extended time collecting data, it is important to note that all risks are not of high level criticality. Nevertheless, careful monitoring will be in place to watch all potential risks.

Rank	**Trend**	**Approach**	**Risk Title**	**Likelihood**	**Consequence**
1	⟹	M	Rover gets stuck and unable to travel trajectory	3	4
2	⟹	M	Instrument or equipment failure	2	4
3	⟹	M	Data loss or scrambled	2	4
4	⟹	R	Inability to discover oxygen wells and fulfill mission objectives	4	3
5	⟹	M	Power loss to rover	3	3
6	⟹	A	Poor characterization of planetary atmospheric environment	2	2

Table 6: Risk Management: Potential Risks and the steps the team are making to mitigate them.

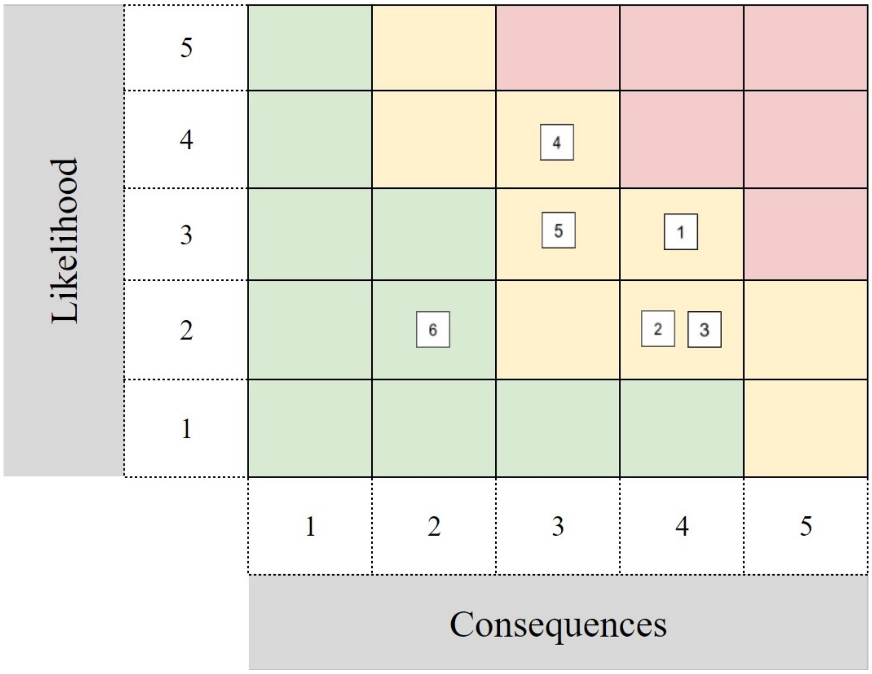
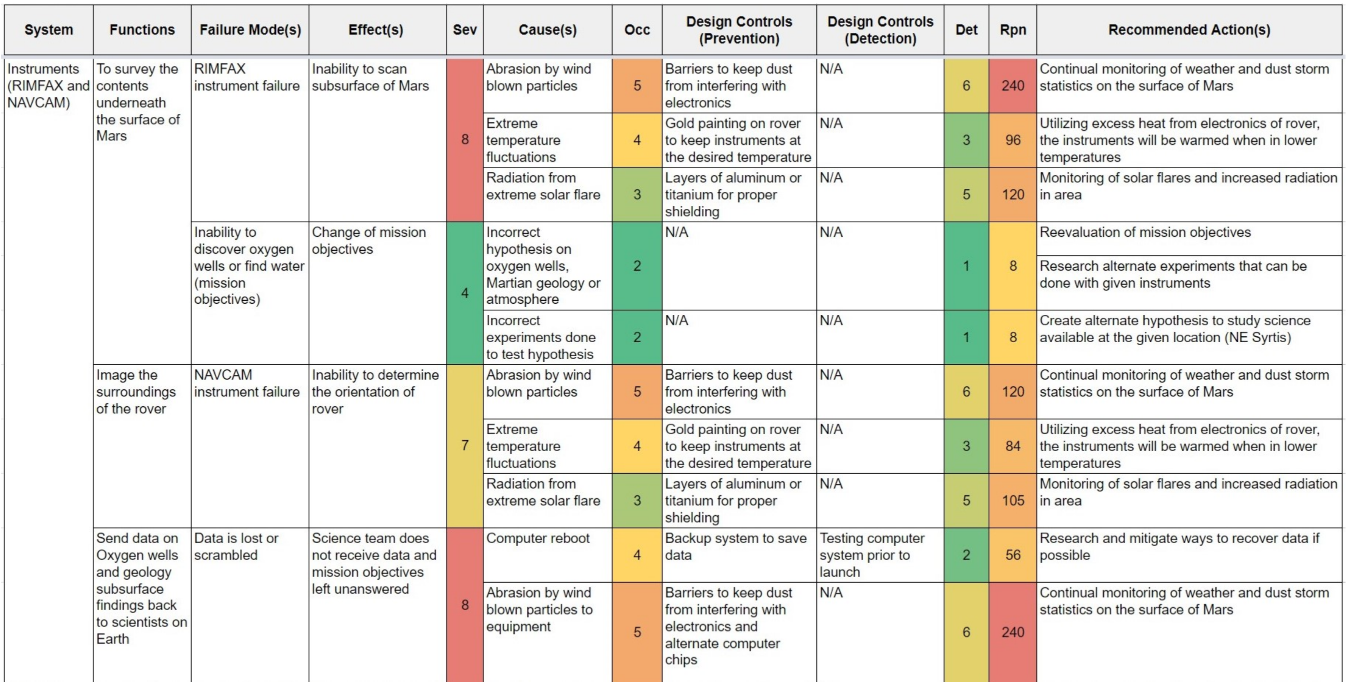


Figure 42: Risk Matrix with associated risks found in Risk Management Table.

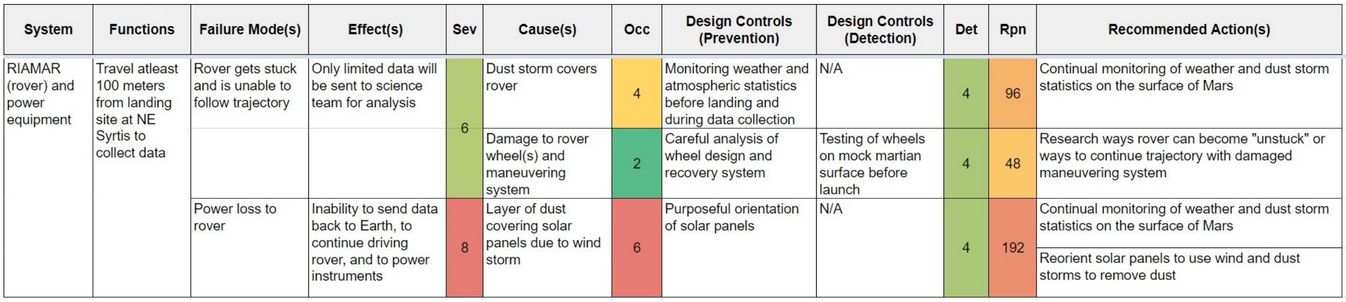
Next, a Failure Mode and Effects Analysis (FMEA) was created to list and provide an in-depth description of potential failures that may exist within the design and implementation of the payload and scientific experiments. For each system with potential risk the function, failure mode(s), effect(s), severity, cause(s), occurrence, prevention designs, detection designs, detection number, risk priority number (RPN), and recommended action(s) the team will take were listed (as seen in Figures 43 and 44).

The severity number is based on a scale from 1-10, where a 1 is when there is no discernible effect to the rover; a 10 is where there is a failure to meet safety requirements. The occurrence number is the likelihood of the system failing to meet the standard from a 1, where failure is eliminated through preventative control, to a 10, where the likelihood of failure is high due to new and untested technology. Similarly, the detection number is based on the likelihood of detection before or during launch on a scale from 1-10. Finally, the RPN is the multiplication of the severity, occurrence, and detection number in order to rank the risks based on priority.



System	Functions	Failure Mode(s)	Effect(s)	Sev	Cause(s)	Occ	Design Controls (Prevention)	Design Controls (Detection)	Det	Rpn	Recommended Action(s)
Instruments (RIMFAX and NAVCAM)	To survey the contents underneath the surface of Mars	RIMFAX instrument failure	Inability to scan subsurface of Mars	8	Abrasion by wind blown particles	5	Barriers to keep dust from interfering with electronics	N/A	6	240	Continual monitoring of weather and dust storm statistics on the surface of Mars
					Extreme temperature fluctuations	4	Gold painting on rover to keep instruments at the desired temperature	N/A	3	96	Utilizing excess heat from electronics of rover, the instruments will be warmed when in lower temperatures
					Radiation from extreme solar flare	3	Layers of aluminum or titanium for proper shielding	N/A	5	120	Monitoring of solar flares and increased radiation in area
		Inability to discover oxygen wells or find water (mission objectives)	Change of mission objectives	4	Incorrect hypothesis on oxygen wells, Martian geology or atmosphere	2	N/A	N/A	1	8	Reevaluation of mission objectives Research alternate experiments that can be done with given instruments
					Incorrect experiments done to test hypothesis	2	N/A	N/A	1	8	Create alternate hypothesis to study science available at the given location (NE Syrtis)
	Image the surroundings of the rover	NAVCAM instrument failure	Inability to determine the orientation of rover	7	Abrasion by wind blown particles	5	Barriers to keep dust from interfering with electronics	N/A	6	120	Continual monitoring of weather and dust storm statistics on the surface of Mars
					Extreme temperature fluctuations	4	Gold painting on rover to keep instruments at the desired temperature	N/A	3	84	Utilizing excess heat from electronics of rover, the instruments will be warmed when in lower temperatures
					Radiation from extreme solar flare	3	Layers of aluminum or titanium for proper shielding	N/A	5	105	Monitoring of solar flares and increased radiation in area
	Send data on Oxygen wells and geology subsurface findings back to scientists on Earth	Data is lost or scrambled	Science team does not receive data and mission objectives left unanswered	8	Computer reboot	4	Backup system to save data	Testing computer system prior to launch	2	56	Research and mitigate ways to recover data if possible
					Abrasion by wind blown particles to equipment	5	Barriers to keep dust from interfering with electronics and alternate computer chips	N/A	6	240	Continual monitoring of weather and dust storm statistics on the surface of Mars

Figure 43: FMEA for Undecim Portam payload and scientific instruments.



System	Functions	Failure Mode(s)	Effect(s)	Sev	Cause(s)	Occ	Design Controls (Prevention)	Design Controls (Detection)	Det	Rpn	Recommended Action(s)
RIAMAR (rover) and power equipment	Travel atleast 100 meters from landing site at NE Syrtis to collect data	Rover gets stuck and is unable to follow trajectory	Only limited data will be sent to science team for analysis	6	Dust storm covers rover	4	Monitoring weather and atmospheric statistics before landing and during data collection	N/A	4	96	Continual monitoring of weather and dust storm statistics on the surface of Mars
					Damage to rover wheel(s) and maneuvering system	2	Careful analysis of wheel design and recovery system	Testing of wheels on mock martian surface before launch	4	48	Research ways rover can become "unstuck" or ways to continue trajectory with damaged maneuvering system
		Power loss to rover	Inability to send data back to Earth, to continue driving rover, and to power instruments	8	Layer of dust covering solar panels due to wind storm	6	Purposeful orientation of solar panels	N/A	4	192	Continual monitoring of weather and dust storm statistics on the surface of Mars Reorient solar panels to use wind and dust storms to remove dust

Figure 44: Continued FMEA for Undecim Portam payload and scientific instruments.

Another important thing to note in the FMEA is that design controls prevention and detection are based on pre-launch endeavors. Thus, a majority of the payload and scientific experiment risks will not be detectable until out in the Martian atmosphere. However, it was possible to receive research on past missions that have dealt with similar risks, such as the Mars Pathfinder and the Curiosity rover. Both of these resources gave better insight on probability of successful landing and statistics on computer malfunctions and mitigation.

The underlying risk mitigation steps for the Undecim Portam payload and scientific experiments are meticulous monitoring and control of the listed risks. This includes proactive and innovative prevention steps that will hopefully prevent the risks before they become uncontrollable.

4.1.6 Performance Characteristics

he tolerances of the rover and its payload must be proven as to minimize the possibility of hardware failure at any point during the mission. The failure of any one piece of equipment could jeopardize the entire mission. Every component must be tested and proven to withstand the extreme conditions of the Mars surface as well as the harsh acceleration, deceleration, pressure changes, and vibrations that will occur during the endeavor. Extreme cold terrestrial temperatures, solar energetic particles, cosmic rays, atmospheric composition, low atmospheric pressure, fine dust, high winds, and magnetosphere fluctuations must all be accounted for [2]. The RIAMAR drivetrain has an operating temperature of -40 degrees Celsius to 100 degrees Celsius so insulated housing is required (Maxon, 2020). This housing not only would provide optimal operating temperatures but would also protect from the fine dust particles in the environment. Navcam has proven its durability during its flight on the Mars Science Laboratory Rover as well as the Curiosity Rover [27]. The motors that make up its gimbal have an operating temperature between 20 degrees Celcuis and 100 degrees Celsius so, like the rover drivetrain, insulated housing will be used for the Navcam stand [32].

RIMFAX has been developed for the past 25 years and readied for the Mars 2020 rover. It has proven its capabilities through its extensive testing under multiple constraints. Testing in the Arctic, Antarctic, and in the four field seasons in the ice and permafrost of Svalbard have shown its low temperature performance reliability [12]. The dry, dusty environment was simulated through testing at Lone Mesa and Coral Pink Sand Dunes in Utah where penetration was observed while being able to analyze the subsurface through a medium similar to Mars [40]. Field testing in the Mojave Desert in California was also performed and ensured promising material penetration. Due to these testing procedures, further modifications were made [40]. The computer system is capable of withstanding temperatures from -55 to 125 degrees Celsius. The BAE RAD 750 Processor is designed to withstand extreme environments, radiation, and pressure [3]. The lithium ion battery has operating temperatures that range from 10 to 30 degrees Celsius, can be transported in temperatures from -20 to 40 degrees Celsuis and has a greater than 5 year 25,000 charge cycle life [41]. Because of the high operating temperatures, the battery will be insulated. The solar panels are a scaled-down version of the panels flown on multiple missions including the InSight mission provided by ATK.

A piezoelectric actuated wiper will be equipped to clean the panels to allow for optimal function. Electrodynamic dust shields will be used as well to protect the components from the fine dust particles found on the Martian surface [6]. The communications system antenna, designed for space flight, has been radiation tested [1]. The data from manufacturers prove the component functionality under harsh conditions, but further testing after all slight modifications to all components must be done to assure their operating functionality as a unit.

4.2 Science Value

4.2.1 Science Payload Objectives

Although the mission has multiple scientific objectives, the main priority is the detection and identification of oxygen reserves underneath the Martian surface. The supplementary scientific objectives of the mission include the detection and identification of water and salt brine on Mars. The scientific instruments on-board the rover will work to detect potential abnormalities in the subsurface make-up of Mars and analyze the materials appropriately. Possible irregularities in the Martian subsurface may include gaseous, liquid or solid in subsurface deposits. These objectives were chosen because the detection of water or oxygen on the surface or subsurface of Mars and the total amount of these substances can help with the planning of human exploration missions on Mars. The areas where the rover detects water and oxygen will aid in determining the landing sites for these missions. If oxygen is found in wells in the Martian subsurface, it will help provide a breathable atmosphere in the living habitats for future Martian astronauts as well as possible propellant for spacecraft. While if water is found, it can be used for drinking, during times of low power availability and planting fruits and vegetables for food. After splitting water into its elemental parts, oxygen and hydrogen, liquid oxygen and liquid hydrogen can be used as rocket propellant on the journey back to Earth. Figure 45 depicts the chemical reaction of liquid hydrogen of liquid oxygen oxidizing liquid hydrogen to produce water and approximately 286 kilojoules used as thrust. Methane could also be utilized by future spacecraft, as it is even more dense than liquid hydrogen, if found in the subsurface; combined with oxygen it yields carbon dioxide, water, and roughly 890 kilojoules as shown in Figure 45. Detecting water and oxygen on Mars will help decrease the mass of the payload dedicated to water and oxygen on-board the spacecraft.

$$H_2 + 1/2O_2 \longrightarrow H_2O + 286{,}000 \text{ joules}$$

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + 890{,}000 \text{ joules}$$

Figure 45: The equations depict the chemical reaction of liquid hydrogen and liquid oxygen.

4.2.2 Creativity/Originality and Uniqueness/Significance

Northeast Syrtis was chosen as the landing site for the Undecim Portam mission for a variety of factors. For example, the detection of carbonates, which require water to chemically form, and Fe/Mg-phyllosilicates, which actually contain water in their chemical composition, suggest the presence of water. Additionally, the endemic volcanic activity is likely to contribute to subsurface gaseous voids, as well as heating subsurface ice deposits into liquid springs, all of which the RIMFAX is capable of detecting.

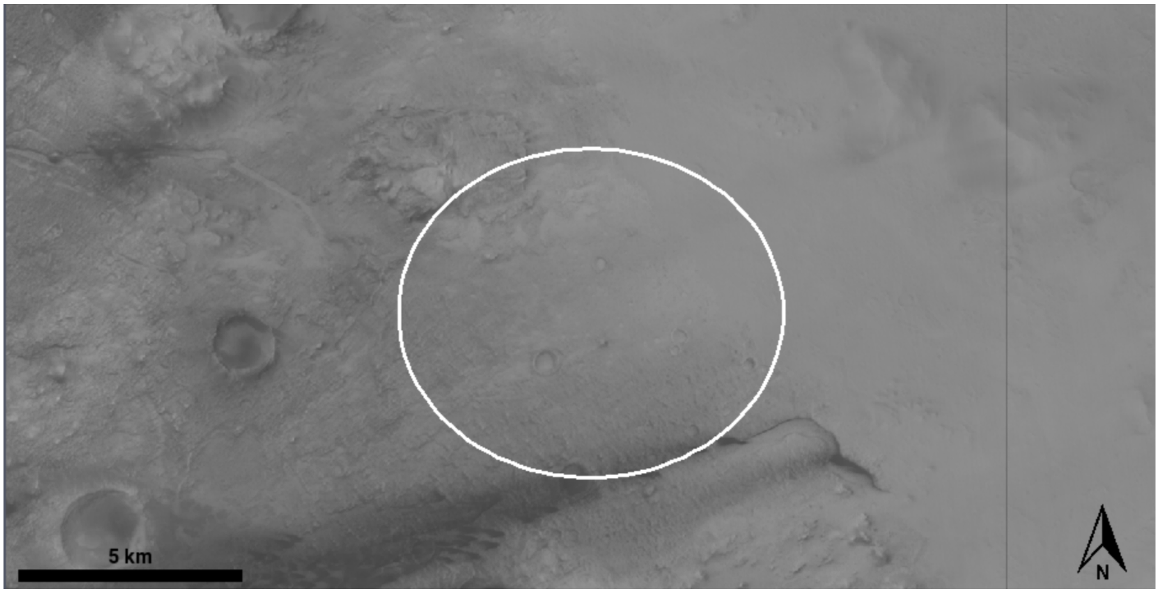


Figure 46: Northeast Syrtis Region Landing Site.

Figure 46 shows the targeted landing site for RIAMAR. The ellipse, centered at (17.497 ° N 77.835 ° E, ± 0.001), has a major axis of 8.6 km and minor axis of 7.7 km. RIAMAR is expected to land within 3 km of the center of the ellipse, so the enclosed area safely approximates the actual landing location. Table 7 shows the properties of the enclosed area. This specific location was chosen because of the relatively stable elevation and thermal inertia, which will allow RIAMAR to safely traverse on the surface. While the dust index may be relatively higher than other sites, RIAMAR's design contains many precautions to mitigate the effects of dust.

	Average	**Minimum**	**Maximum**	**Standard Deviation**
Elevation (m)	-3103.51034	-3159	-2897	56.60812
Slope	1.45025	0.06494	8.36485	1.41349
Thermal Inertia ($\mathbf{J{\cdot}m^{-2}{\cdot}K^{-1}{\cdot}s^{-\frac{1}{2}}}$)	312.25	292	335	22.4258
Albedo	0.13622	0.12819	0.14331	0.00661
Dust Index	0.96648	0.95748	0.97677	0.0059

Table 7: Properties of the Northeast Syrtis Region Landing Site.

One major contribution to the significance of the Undecim Portam mission is the fact that a radar has never been used on the actual surface of Mars. While the Mars 2020 Perseverance rover will also employ RIMFAX, Perseverance will conduct its mission on Jezero. The Undecim Portam mission will be the first time a radar has been used at Northeast Syrtis. The successful detection of a significant amount of ice, water, brines, or subsurface gaseous voids consistent with oxygen wells could lead to Northeast Syrtis being a prime candidate for future Mars missions, and possibly a potential site for human exploration.

4.2.3 Payload Success Criteria

The on-board instruments and auxiliaries that contribute towards their operation are capable of delivering the information desired by the mission. Each instrument has a specific function that directly relates to the objectives at hand and almost all serve more than a single purpose. The descent system and its components will allow the rover to have a safe touchdown while keeping the entire device intact. The rover can then deploy, start up all its instruments, and begin its path of travel. RIMFAX is the main scientific instrument used capable of directly answering the scientific objectives regarding subsurface artifacts pertaining to geologic features of water, oxygen, and brine deposits. The high top speed ensures as much area is covered as possible as intermittent stopping for data collection is not necessary due to the velocity of radio waves. The data collected from RIMFAX can be sent to the computer for computing and interpretation which can eventually be sent to Earth for further analysis. The data received can be reviewed by the team to properly assess the sub-martian makeup. To get to this point, each instrument on the rover, and the rover itself, must function accordingly so that RIMFAX may gather valid data. The method of design is the most efficient way to achieve the research criteria with today's technology.

4.2.4 Describe Experimental Logic, Approach, and Method of Investigation

After landing on the Northeast region of Syrtis Major on Mars, the rover will safely traverse the terrain using the navigation cameras on-board. The navigation cameras will guide the rover through the Martian surface while RIMFAX uses radar waves to examine the subsurface of Mars for water, oxygen and brine deposits. The radar imager will be able to detect greater than 10 meters deep and can obtain data in 10 centimeter measurement intervals [17]. The solar array on-board will power the rover and the computer will make sure the battery will not overheat. The computer will rely commands to scientific instruments so the instruments will work as needed. After obtaining the necessary data, the computer will compute the data and relay the data to the radio communication system which will then send the data via radio signals to Earth. The landing site is significant due to evidence that there was once water in the region as well as microbes, which signify life. The landing site also has relatively equal thermal inertia and elevation which is important as it is safer for the rover in level elevation.

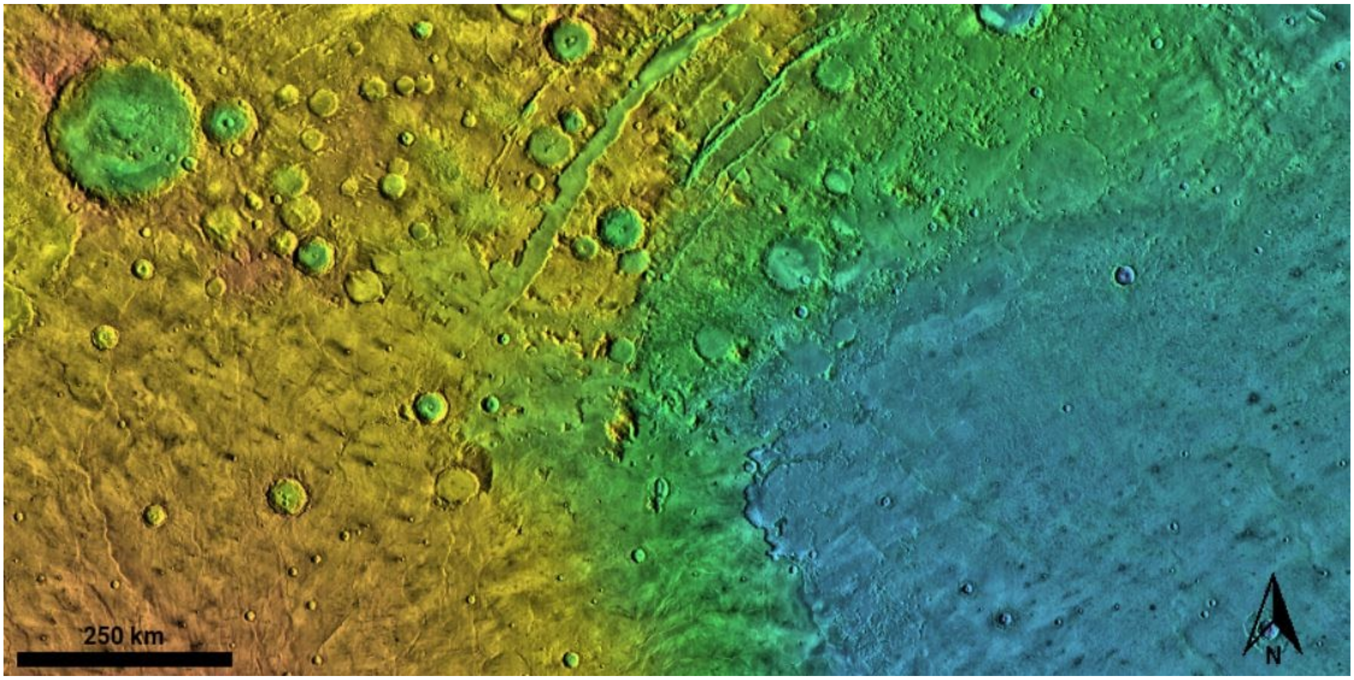


Figure 47: Northeast Syrtis Region (18 N,77E) Landing Site with color-coded elevations from MOLA data.

4.2.5 Describe Testing and Measurements, including variables and controls

Two instruments will travel on the RIAMAR rover to NorthEast Syrtis (18 ° N 77 ° E) RIMFAX and Navcam. Multiple different calibration and manufacturing tests will be done before and after launch.

Before launch, RIMFAX and Navcam will be tested in multiple locations to test reliability and create control variables before operations on the Martian surface. Past tests on RIMFAX have been undergone in Lone Mesa and Coral Pink Sand Dunes, Utah and Red Rock Canyon, CA studying limestone, quartz sand, basalt flows and clay similar to the geology of the Martian surface. Similar tests have been done on the Antarctic surface in preparation for the Mars 2020 rover. Nevertheless, for the Undecim Portam Mission there will be more extensive testing on RIMFAX in the colder environments to simulate the Martian environment. The temperature will be one control variable utilized to calibrate both instruments.

Similarly, a mock Martian surface will be built with oxygen wells and ice/water deposits underneath the surface to allow the scientists to gain a better understanding of the signals reported from water and geological deposits. RIMFAX will be tested along all of its frequencies (150 MHz to 1.2 GHz) and to its limit of 10 meters of radar penetration. The Navcam will also be tested for the autonomous navigation of the rover, by taking images and creating a calibration process once on Mars. Thus, the control variables will be the environmental and geological effects of Mars.

Once landing on Mars, there will be carefully designed steps that the team will take to calibrate the instruments. First, the Navcam will power on and begin to survey the location of RIAMAR by focusing primarily on the geometric characterization necessary for the derivation of accurate ranging and topographic data. The pictures will be sent back to scientists on Earth in order to compare the quality of test pictures with the Navcam on Earth. Once it is evident that the Navcam is functioning properly, the rover will begin to calibrate the second instrument: the RIMFAX. However, if the Navcam is not functioning properly after calibration then research will be undergone in order to determine possible areas of failure and mitigation steps needed.

The rover will begin to travel one meter forward in the direction of the desired trajectory while RIMFAX is powered on and begins data collection. Two signals will be sent out with each initial data collection, where the first reflection is to calibrate the instrument and the second will be the desired measurements/reflections to study. As a secondary way to test the data received by the first meter trajectory of the rover, besides comparison to the Earth mock data collection, the data will be compared to information taken from the SHARAD instrument, another ground penetrating radar, on the Mars Reconnaissance Orbiter. As seen in Figure 48, the SHARAD instrument gathered data in areas along the red lines in the desired landing ellipse in NE Syrtis.

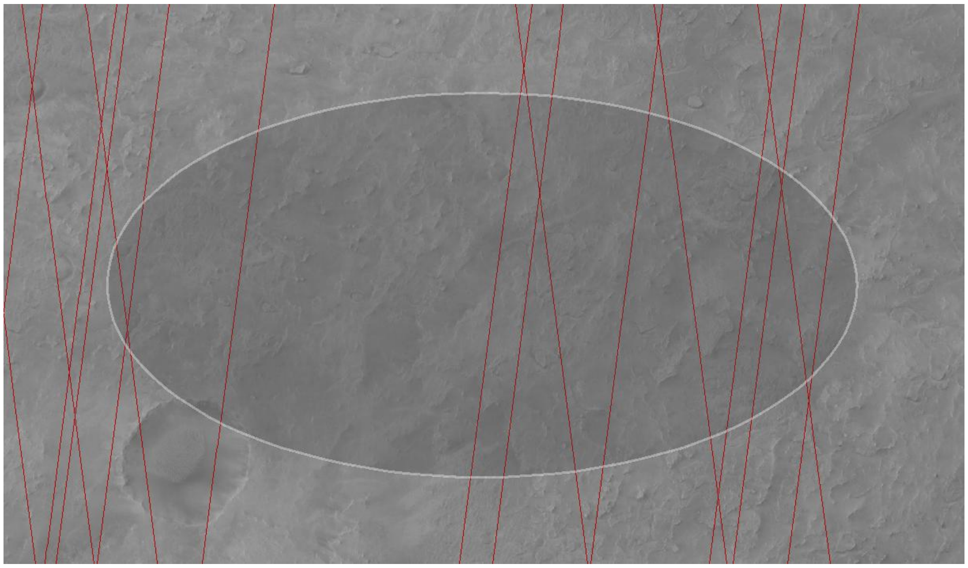


Figure 48: NorthEast Syrtis Landing Ellipse (gray-white ellipse) with SHARAD ground penetrating radar data (along red lines).

Although SHARAD operates at a lower frequency (centered at 20 MHz), both instruments could potentially detect similar subsurface properties. As seen in Figure 49, SHARAD radargram data within the landing ellipse, the topographic variations generate a lot of clutter, which makes it hard to determine the nature of the subsurface reflections. Nevertheless, the SHARAD data will be a good baseline to ensure the operation of RIMFAX. Additionally, the incomprehensible data from SHARAD allows for groundbreaking research to be done by RIMFAX in NE Syrtis to study subsurface geology. Finally, if the RIMFAX instrument passes all calibration steps then the rover will continue along in its 100 meter trajectory in order to fulfill the Undecim Portam Mission objectives. However, if it is not functioning properly after calibration then research will be undergone in order to determine possible areas of failure and mitigation steps needed.

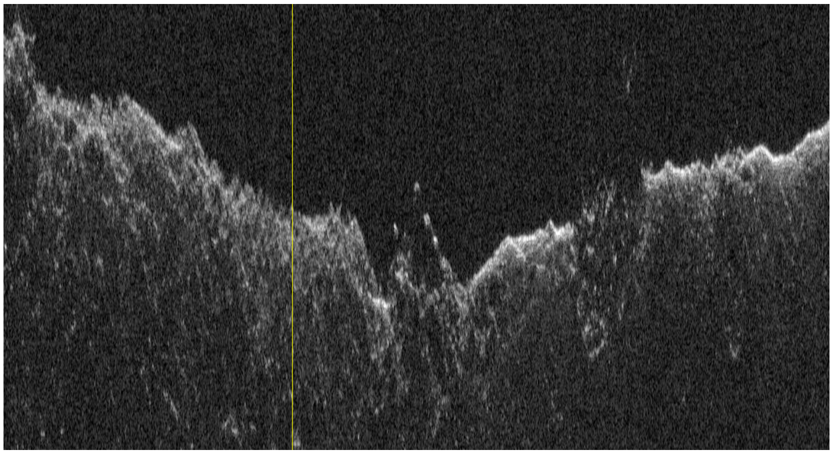


Figure 49: SHARAD ground penetrating radar data along one of the lines intersecting the landing ellipse.

4.2.6 Show expected data & analysis (error/accuracy, data analysis)

The Navcam, the engineering navigational camera, will primarily be used as the eyes of the rover as it travels in Northeast Syrtis. The camera will be used to determine the topographic geology of where the rover is located in order to stray from running into boulders or pits and to keep RIAMARA safe. Similarly, the Navcam will be able to acquire images of the morphology of the rocks around the rover to study past geologic processes on Mars. Also, the Navcam will be able to be used to understand issues or complications that arise to the instruments or equipment. If RIMFAX or any of the power equipment fails then the camera can be pointed to where the issue is coming to gain insight on how to mitigate the risk to the mission. For example, the Mars Science Laboratory (Curiosity rover) included the Navcam instrument and was able to send the following images in Figures 50-52. The Undecim Portam mission will analyze the rocks and surface geology from the images by Navcam by comparing the rocks and soils to the objects found on Earth. In this way, a greater understanding of the geological history on the surface of Mars compared to what is currently understood on Earth will be gained.

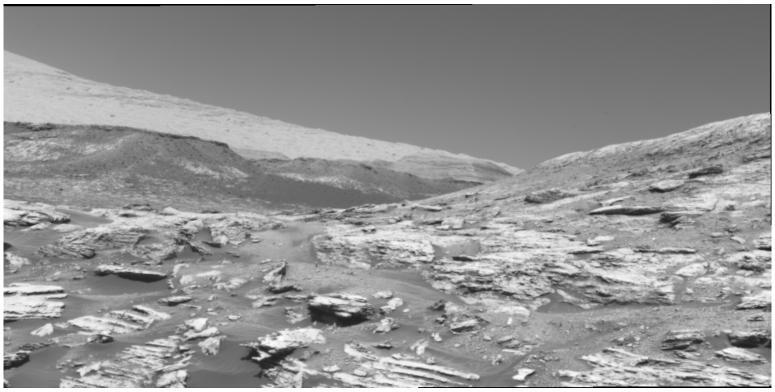


Figure 50: Image of the Martian surface taken from Navcam on the Mars Science Laboratory rover - Curiosity.

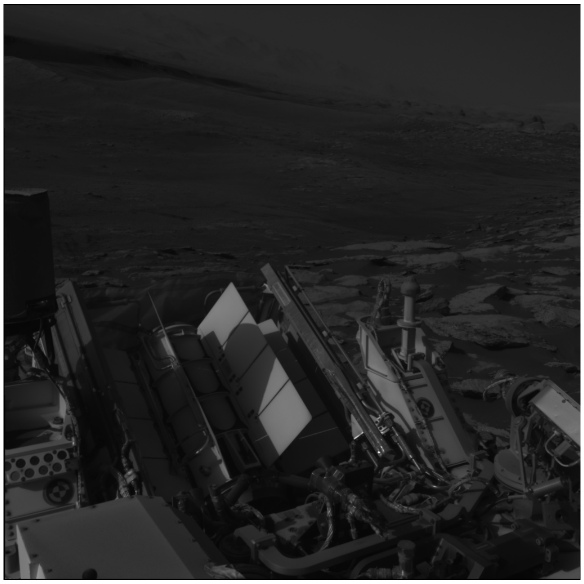


Figure 51: Image of the Curiosity rover taken from Navcam on the Mars Science Laboratory rover.

Figure 52: Image taken from Navcam to study the topological geography on the Mars Science Laboratory rover - Curiosity.

The Navcam has a 45 degree x 45 degree field of view, while the angular resolution at the center of the field of view is 0.82 mrad/pixel and the stereo baseline is 0.42 m. Using these properties, the range error for Navcam was calculated with

$$\Delta z = \frac{Z^2 \theta \phi}{b}, \tag{1}$$

where z is the estimated range error, Z is the range from the camera to the object, θ is the pixel field of view, ϕ is the sub-pixel stereo correlation accuracy, and b is the stereo baseline between the camera pairs. The ranging error Δz in Equation 1 was found for different distances in Table 8.

Distance from Navcam (m)	Ranging Error (m)
1	0.0005
2	0.002
5	0.01
10	0.05
15	0.1
20	0.2
30	0.4
40	0.8
50	1.2
60	1.7
100	4.8

Table 8: Calculated stereo range error as a function of distance from Navcam camera.

The second instrument on the RIAMAR rover is RIMFAX. By sending radio waves deep into the Martian surface between frequencies of 150 MHz to 1.2 GHz, RIMFAX will be able to detect the waves that are reflected back. These reflected waves will give insight on what lies beneath the surface, including possibly voids of gases and/or water and ice. In Figure 53, test data taken from RIMFAX on Earth can be found that provide reasonable predictions for what data from the mission should look like. Figure 54 includes images from tests on a generic GPR in Quaidam Basin in North West China. This image of data from another GPR instrument provides insight on how to study the reflections received. In Figure 54, the subsurface reflections are caused by the interactions between the clay layers and mirabilite (sulfite) mineral layers. When data is received from RIMFAX in Northeast Syrtis, the layers of sedimentary will similarly be studied to determine the composition and history of the subsurface.

Not only will the geology be studied, but the search for water and ice will need to be understood relative to how that will look through data from RIMFAX. Figure 55is an image of data taken from past Mars missions that found liquid water under the surface of the south pole. The layer that shows up with a higher intensity is supposedly determined to be liquid water due to the increased reflection. Similarly, it is known that GPR signals will propagate faster and more intensely in mediums where the dielectric permittivity is lower, as it is for a gas. Thus it can be guessed that a void of oxygen deposits or any other gas should have reflections similar to Figure 55. Also, another important idea to look for in data are signals transmitted from a more dielectric material to a less dielectric material that cause the signal to spread out and scatter.

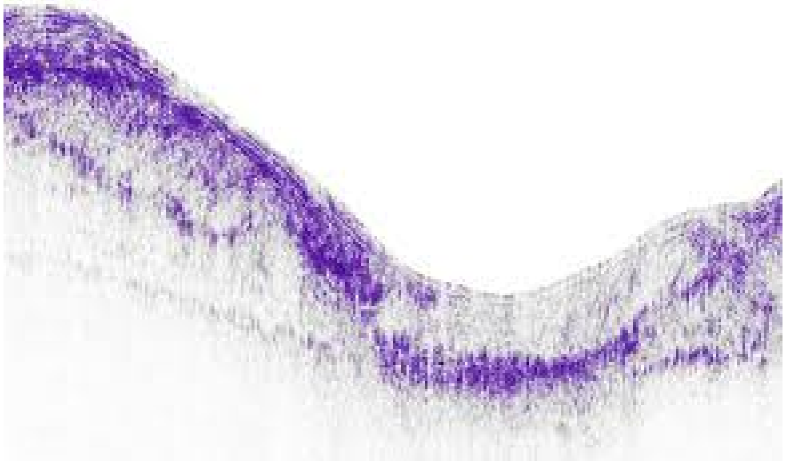


Figure 53: RIMFAX sounding from Coral Pink Sand Dunes in Utah showing subsurface sedimentary layers.

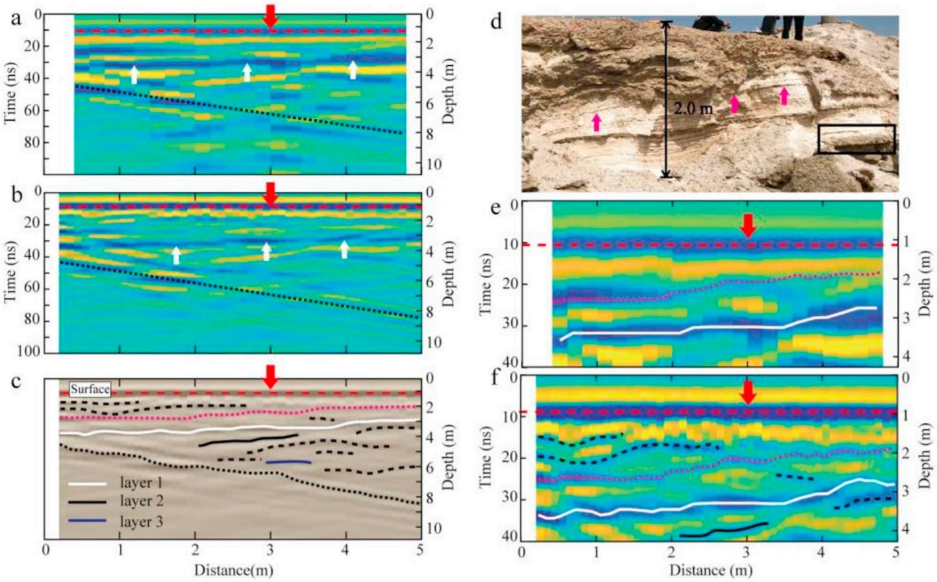


Figure 54: Ground Penetrating Radar data taken from Qaidam Basin.

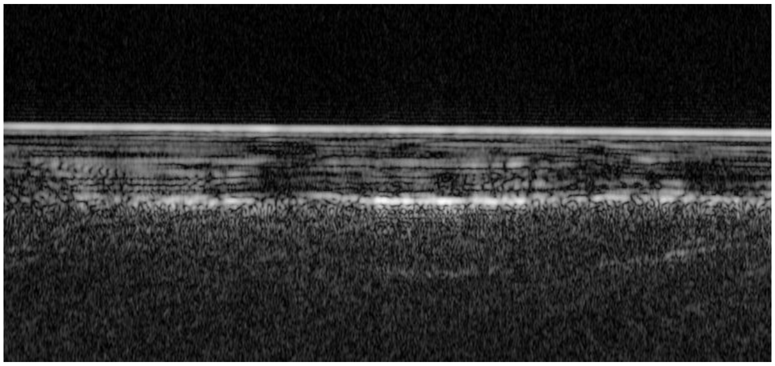


Figure 55: Possible detection of liquid water found under the surface of the South pole on Mars.

Since RIMFAX has not been tested on Mars at this point in time it is difficult to say what the exact accuracy of this instrument is for gathering data from the subsurface of Mars. Nevertheless, in searching for oxygen deposits or any void containing a gas the depth of that void will have some error. The depth of this void can be calculated using,

$$D = \frac{v_{rw}\tau}{2}, \tag{2}$$

where D is the depth, v_{rw} is the radio wave velocity and τ is the two way travel time for the data to be received by RIMFAX. Using error propagation the error in this depth was calculated to be,

$$\epsilon_D = \frac{1}{2}\sqrt{\tau^2\epsilon_{v_{rw}}^2 + v_{rw}^2\epsilon_\tau^2}, \tag{3}$$

where ϵ denotes the error in the variable indicated by the subscript. The radio wave velocity depends on the medium it travels through, however, a rough estimate is to assume the speed of light (3×10^8 m/s = 300 m/μs). According to Laparazan on ground penetrating radar measurement errors, if a single average value is chosen for vrwthen it is safe to assume an error of 8.4 m/s [22]. The two way travel time depends on the depth of the void. The error in this time is related to the frequency of the radio waves in such a way that

$$\epsilon_\tau = \frac{1}{f}, \tag{4}$$

where f is the frequency. RIMFAX operates between 150-1200 MHz and thus the lowest frequency will create the largest error, so this value was used to assume the highest amount of uncertainty. For various different two way travel times, the errors in the depth of the void were calculated and plotted in Figure 56. As predicted, the error increases linearly as the two way time increases or the depth of the void increases. Next, the average percent error for depth of voids was calculated to be approximately 3%.

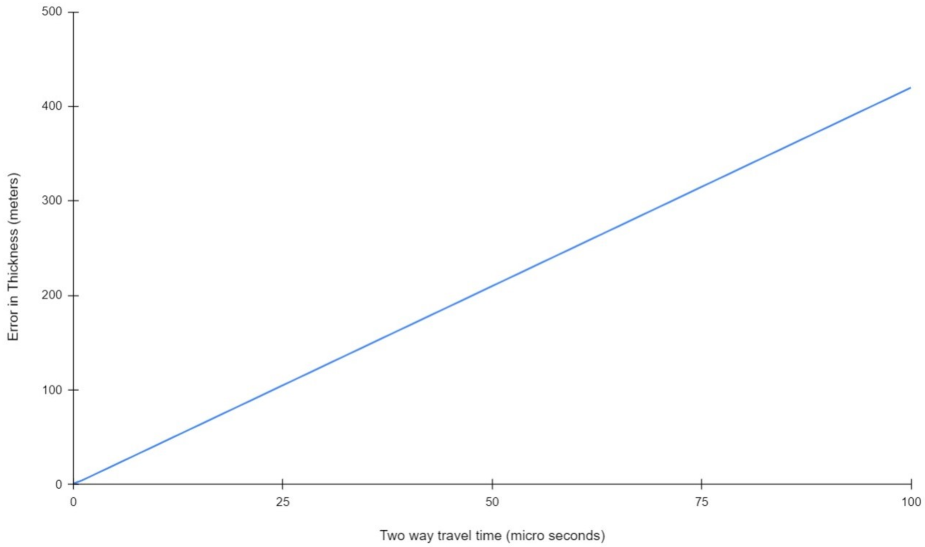


Figure 56: Plot of error in depth vs. two way travel time for RIMFAX operating at 150MHz.

5 Safety

5.1 Personnel Safety

5.1.1 Designated Safety Officer

The Undecim Portam Mission safety responsibilities were divided among two team members. Thus, it was decided to designate co-safety officers. The first co-safety officer, Farhan Virani, was primarily in charge of personnel safety and personnel hazard mitigation. Co-safety officer, Madeline Clyburn, took on the responsibilities of environmental safety and environmental hazard mitigation for the lander and payload. The personnel safety officer, Farhan, will be onsite during all of the testing.

In order to determine the potential risks for personnel during the duration of the mission, a team was assembled in order to gather and identify all of the risks per Figure 63. The team spent time walking around the facilities and identifying the potential risks for the personnel. In addition to identifying personnel hazards with the team, a survey was sent out to the personnel for feedback on hazards that they felt were missed by the safety team.

The primary research that went into the environmental safety of the lander and payload was predominantly based on past rover missions as well as research on the surface of Mars that had environmental issues (as seen in Figure 64). The Mars Exploration Rovers, Opportunity and Spirit, experimented with temperature controls, and had the opportunity to test a cleaning event on the Opportunity rover when dust covered the solar panels. Similarly, research by the National Research Council which examined the risks of robotic exploration missions to Mars offered mitigation ideas for high wind dust storms and abrasion to the equipment. Missions like the Space Environment Testbeds, or SET, have given more insight into radiation hazard mitigation. Finally, after launch and during the landing of the payload and retrieval of data, careful monitoring of radiation from solar flares and dust storms will be maintained in order to mitigate any of the following environmental hazards.

5.1.2 List of Personnel Hazards

There are many different personnel hazards that could threaten the safety of the team members during the mission. The two safety officers have identified the following hazards. During the manufacturing process, many hazards can occur to affect the personnel. Some major hazards for the personnel are inhalation of toxic fumes and materials, dropping of dangerous chemicals on oneself, and overexertion of the body. These can occur when the manufacturing process occurs in a small environment or without the use of proper equipment. In the creation of the vehicle structure, the personnel will be using many high powered tools in order to create the final product. These tools both have the possibility of injuring the personnel and they are very energy intensive. Whether they may have very sharp points or very fast moving parts, one can easily get injured. Using around 1,200 watts, an average power tool already uses around $\frac{1}{3}$ of a house's AC power consumption, having a multitude of power tools plugged in simultaneously has the possibility of causing power problems in the facilities. Having tight deadlines, fulfilling mission guidelines can sometimes be very stressful. This can lead to overall personnel unhappiness and lower levels of productivity.

Unfortunately, with the circumstances of the world today, another major hazard is the spread of disease among the personnel. In a closed environment such as a manufacturing environment or mission control room, the spread of disease is very possible. The safety officers have plans to mitigate the risk these hazards pose to personnel in Table 9.

5.1.3 Personnel Hazard Mitigation

Hazard	**Cause(s) of Hazard**	**Effect(s) of Hazard**	**Hazard Mitigation**
Inhalation of toxic fumes and materials	Soldering electrical components, cutting of materials, welding of metal components	Irritation of airways, eyes, and skin. Sores of the throat and swelling of the nose	Workers will be wearing masks and glasses in order to protect from the inhalation of toxic fumes. Additionally, personnel will use adjustable solder smoke absorber remover fume extractor fans while soldering and welding to mitigate the amount of toxic fumes inhaled in addition to PPE.
Cutting or burning oneself	Soldering electrical components, cutting of materials, welding of metal components	Bleeding from the cut. Burning from the burnt spot. Swelling of the affected spot	Workers will be wearing protective clothing in order to prevent harm to themselves. Additionally, we will have first aid kits located on site for the treatment of small burns and cuts.
Over-exertion of body	Carrying heavy materials and parts without the use of proper tools and techniques	Soreness and pain of muscles	Provide machinery and tools to carry heavy materials and parts.

Spread of disease amongst personnel	Through a cough or sneeze, a worker can spread an infectious disease to people around	Workers physical well being is hurt and productivity is hurt as a result	Education on proper hygiene methods, distribution of PPE material to workers, easily accessible hand sanitizer.
Dropping of dangerous chemicals on oneself	Use of chemicals in the manufacturing process	Poisoning, itching, burning, and physical harm to the body	Mandatory use of protective clothing and masks in order to protect against potential exposure to chemicals. Additionally, the site will have showers and eyewash stations for use in emergencies.
Electrical hazards	Improper use of machinery or tools and outlets such as plugging in too many piece of equipment	Blowing a fuse and sometimes even messing up the tool or machinery that was plugged in	Proper training on good practices when working with high power electronics. Having a professional inspect the uses of electricity

Table 9: List of hazards and hazard mitigation steps for personnel safety of the Undecim Portam mission.

5.2 Lander/Payload Safety

5.2.1 Environmental Hazards

There are many different environmental hazards that could threaten the safety of the lander and payload during the mission. One such hazard that has caused problems on past missions to Mars is dust buildup. Past research found that over a thousand dust storms were observed within 2000 km of the Northeast Syrtis landing site during a 5.78 Martian year period. These dust storms have proven in the past to cause malfunctions to rovers by layering of dust cutting off power sources from the sun or abrasion to the equipment from the wind blown particles. Another hazard to avoid in order to refrain from damage to the scientific payload is extreme temperature fluctuations. Due to Mars' very thin atmosphere the surface temperature varies from -73 degrees Celsius to 20 degrees Celsius throughout the day and night. Thus, it is important to ensure that all of the instruments and equipment can withstand the extreme cold and the moderately warm temperatures. RIMFAX has been designed and tested to work well in extreme Arctic temperatures, however it is necessary to have backup precautions. Finally, another small environmental hazard is solar flares. Solar flares are from sunspots on the sun that create bursts of energetic particles that could possibly travel all the way to the Martian surface or intercept the payload as it is landing. These energetic particles can interfere with the electrical wiring and equipment that are necessary to the rover's mission. The safety officers have thus created plans to mitigate the risk these environmental hazards pose to Undecim Portam in Table 10.

5.2.2 Environmental Hazard Mitigation

Hazard	**Cause(s) of Hazard**	**Effect(s) of Hazard**	**Hazard Mitigation**
Solar Flares	Sudden outburst of energy from sunspots on the sun	Increased release of radiation from the sun damaging or destroying the electronics	Instruments and equipment will be layered with either aluminum or titanium to slow energetic particles. Instruments will also be equipped with extra computer chips and electronics in the event that shorts a circuit or scrambles data

Dust Buildup	Dust storms on Mars with winds of up to 60 miles per hour create airborne dust particles	Layers of dust form on the solar panels reducing the power output	Monitoring weather statistics before launch to delay depending on dust storm prevalence and purposeful slope design to solar panels such that wind can remove dust from the panels reducing buildup
Abrasion by Wind Blown Particles	Suspended airborne dust caused by wind and dust storms	Abrasion by saltation to equipment on rover altering data	Increased monitoring of weather statistics during data collection and strategic placing of instruments to create barrier from dust particles
Extreme Temperature Fluctuations	The distance of Mars from the sun, the eccentricity of the orbit of Mars, and the thin atmosphere of Mars	Malfunction of electronics and instruments, possibly producing larger error in data	Utilizing excess heat from electronics of rover, the instruments will be warmed when in lower temperatures, similarly gold paint will be used on the rover to reduce energy radiated from the electronics

Table 10: List of hazards and hazard mitigation steps for environmental safety of the payload and lander for the Undecim Portam mission.

6 Activity Plan

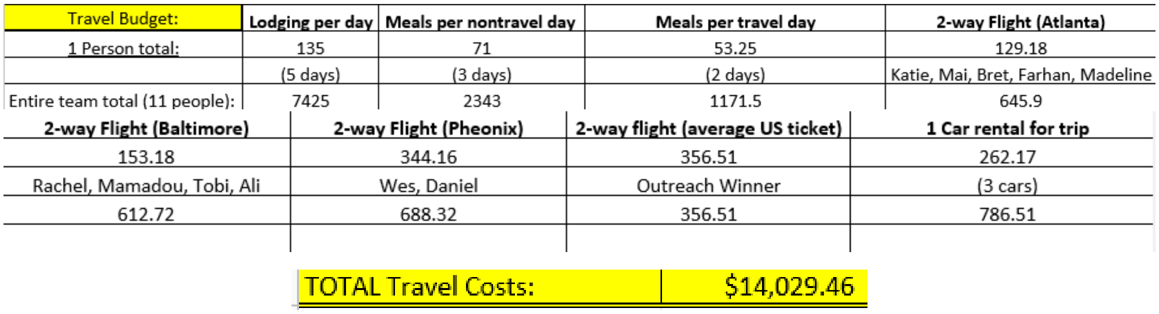
6.1 Budget

This budget plan consisted of analyzing different sets of data to identify all costs in the process from the start in May 2020 to the end of the mission in May 2023. With an initial allotted amount of $100,000,000 for the large mission concept it was helpful to trace precisely what will be expended for a 3-year plan from design to scientific analysis. In an effort to stay well below budget, it was necessary to find out how much money should be spent on science and engineering objectives while keeping in mind that the science drives the design. The main science objective was to locate oxygen wells under the surface of Mars while the budget goal was to obtain the maximum quantity of science with the apportioned amount given while ensuring that personnel were properly paid and covering all other expenses with regards to travel and other engineering needs.

The personnel plan consists of eleven employees each based at a salary cap of $80,000,00 with a fringe rate of 0.28%, expending to $3,376,824.00 over a span of three years. The three chosen interns will work during the data analysis phase of the mission in the summer of 2022. These interns will be each paid a stipend of $7,300 [19]. The science for the mission requires two instruments to perform scientific analysis. The first instrument being used is the RIMFAX ground penetrating radar instrument. Using the instrument budget for the Mars 2020 rover, which included the RIMFAX instrument, the total cost of the instruments was divided by the total number of instruments on this mission ($130/7) to approximate the cost of RIMFAX as $18,500,000; which rounding up for any error was expensed at $20,000,000 [23]. The second instrument being utilized is the Navcam camera, which is expensed at $10,000,000.

The engineering department's budget is currently $22,500,000 for expenses on materials and supplies including mechanical systems and dimensional size of the project [13]. Equipment needed to design the project expensed to $225,835.60, this expense consists of welding machines, computer-aided design programs (Siemens NX) and other mechanical tools. With an additional 50% manufacturing margin of \$11,369,448.86, the total direct cost including personnel, science, engineering, and overall margin sums to \$64,102,785.17 plus an additional total facilities and administrative expense of \$9,424,154.71. This expense is 10% of the modified total direct cost of \$64,215,677.51 and subcontracts (instruments) utilized. Facilities and administrative costs are all the assets and personnel that projects use to do their work such as the engineering and science lab space.

Finally, it was also necessary to budget travel expenses for the launch from Cape Canaveral, Florida. The lodging and meals were expensed relative to a December 4, 2021 launch date with lodging at \$135 per day over a period of five days, meals at \$71 for three non-travel days, \$53.25 for two travel days [49]. It was assumed that all eleven team members will travel to the launch from each prospective university (i.e. five team members will travel from Atlanta to Orlando, four will travel from Baltimore, and two will travel from Phoenix). All flights were booked through Spirit airlines with economy seat tickets; see Figure 57 for prices of each two-way flight [46]. Also, the winner of the outreach writing essay will win a flight to Cape Canaveral for the launch which was estimated to cost on average \$356.51 [4]. Finally, rental cars were budgeted to use from the Orlando airport to Cape Canaveral through Enterprise at \$52.43 per day per compact car rented [5]. With eleven team members it was necessary to assume the rental of three cars. As a result, total travel costs resulted in \$14,029.46 for lodging, meals, and flights.

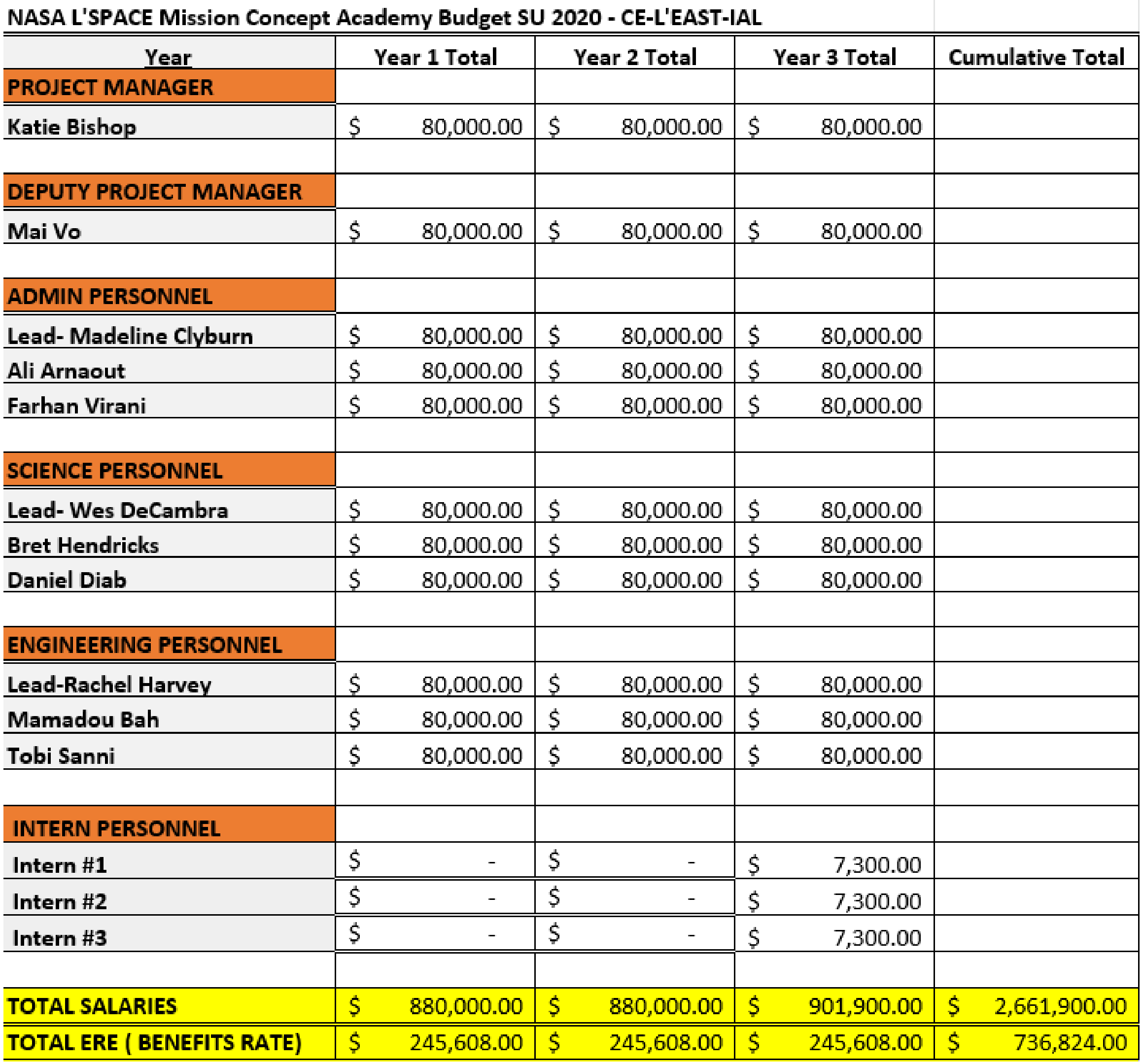


Travel Budget:	Lodging per day	Meals per nontravel day	Meals per travel day	2-way Flight (Atlanta)	2-way Flight (Baltimore)	2-way Flight (Pheonix)	2-way flight (average US ticket)	1 Car rental for trip
1 Person total:	135	71	53.25	129.18	153.18	344.16	356.51	262.17
	(5 days)	(3 days)	(2 days)	Katie, Mai, Bret, Farhan, Madeline	Rachel, Mamadou, Tobi, Ali	Wes, Daniel	Outreach Winner	(3 cars)
Entire team total (11 people):	7425	2343	1171.5	645.9	612.72	688.32	356.51	786.51

TOTAL Travel Costs:	\$14,029.46

Figure 57: Screenshot of the Travel budget plan to Cape Canaveral for the launch of Undecim Portam in December 2021.

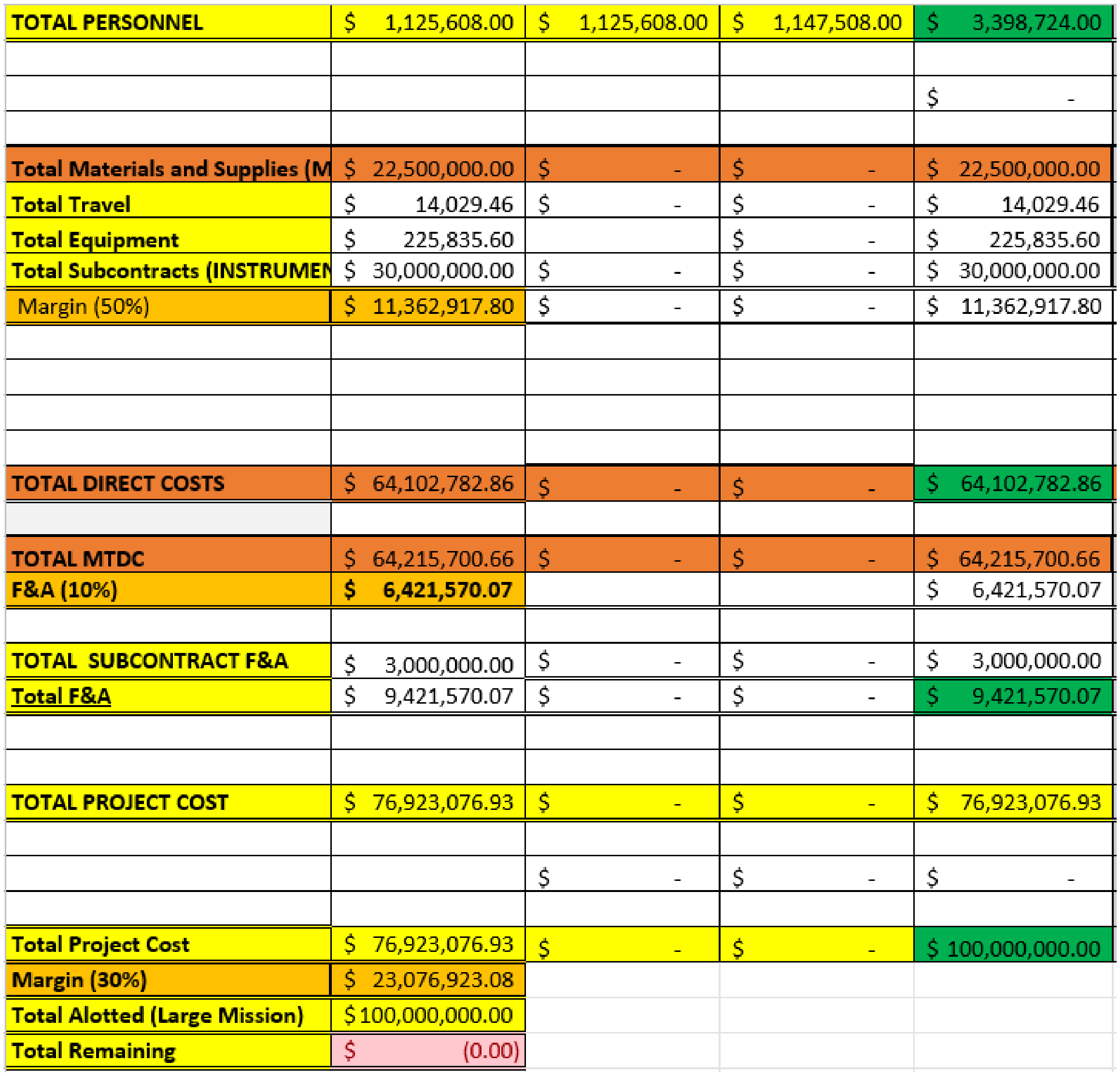
By combining all of our expenses including total personnel costs, scientific instruments, engineering costs, and a 50% margin rate for manufacturing, the direct costs total to \$64,102,628.17. With an additional facilities and administration rate of 10% equaling \$9,421,567.75, the total project cost equates to \$76,923,076.92. An additional 30% margin is added to this total project cost for budgeting purposes equaling a total of \$100,000,000.00.



NASA L'SPACE Mission Concept Academy Budget SU 2020 - CE-L'EAST-IAL

Year	Year 1 Total	Year 2 Total	Year 3 Total	Cumulative Total
PROJECT MANAGER				
Katie Bishop	$ 80,000.00	$ 80,000.00	$ 80,000.00	
DEPUTY PROJECT MANAGER				
Mai Vo	$ 80,000.00	$ 80,000.00	$ 80,000.00	
ADMIN PERSONNEL				
Lead- Madeline Clyburn	$ 80,000.00	$ 80,000.00	$ 80,000.00	
Ali Arnaout	$ 80,000.00	$ 80,000.00	$ 80,000.00	
Farhan Virani	$ 80,000.00	$ 80,000.00	$ 80,000.00	
SCIENCE PERSONNEL				
Lead- Wes DeCambra	$ 80,000.00	$ 80,000.00	$ 80,000.00	
Bret Hendricks	$ 80,000.00	$ 80,000.00	$ 80,000.00	
Daniel Diab	$ 80,000.00	$ 80,000.00	$ 80,000.00	
ENGINEERING PERSONNEL				
Lead-Rachel Harvey	$ 80,000.00	$ 80,000.00	$ 80,000.00	
Mamadou Bah	$ 80,000.00	$ 80,000.00	$ 80,000.00	
Tobi Sanni	$ 80,000.00	$ 80,000.00	$ 80,000.00	
INTERN PERSONNEL				
Intern #1	$ -	$ -	$ 7,300.00	
Intern #2	$ -	$ -	$ 7,300.00	
Intern #3	$ -	$ -	$ 7,300.00	
TOTAL SALARIES	$ 880,000.00	$ 880,000.00	$ 901,900.00	$ 2,661,900.00
TOTAL ERE (BENEFITS RATE)	$ 245,608.00	$ 245,608.00	$ 245,608.00	$ 736,824.00

Figure 58: Screenshot of the Undecim Portam mission budget plan.



TOTAL PERSONNEL	$ 1,125,608.00	$ 1,125,608.00	$ 1,147,508.00	$ 3,398,724.00
				$ -
Total Materials and Supplies (M	$ 22,500,000.00	$ -	$ -	$ 22,500,000.00
Total Travel	$ 14,029.46	$ -	$ -	$ 14,029.46
Total Equipment	$ 225,835.60		$ -	$ 225,835.60
Total Subcontracts (INSTRUMEN	$ 30,000,000.00	$ -	$ -	$ 30,000,000.00
Margin (50%)	$ 11,362,917.80	$ -	$ -	$ 11,362,917.80
TOTAL DIRECT COSTS	$ 64,102,782.86	$ -	$ -	$ 64,102,782.86
TOTAL MTDC	$ 64,215,700.66	$ -	$ -	$ 64,215,700.66
F&A (10%)	**$ 6,421,570.07**			$ 6,421,570.07
TOTAL SUBCONTRACT F&A	$ 3,000,000.00	$ -	$ -	$ 3,000,000.00
Total F&A	$ 9,421,570.07	$ -	$ -	$ 9,421,570.07
TOTAL PROJECT COST	$ 76,923,076.93	$ -	$ -	$ 76,923,076.93
		$ -	$ -	$ -
Total Project Cost	$ 76,923,076.93	$ -	$ -	$ 100,000,000.00
Margin (30%)	$ 23,076,923.08			
Total Alotted (Large Mission)	$100,000,000.00			
Total Remaining	$ (0.00)			

Figure 59: Continued screenshot of the Undecim Portam mission budget plan.

6.2 Schedule

The schedule shown in Figure 60 shows the entire mission from development to the end of the mission on Mars. Development starts in May 2020 with the Preliminary Design Review in July 2020. From there, further analysis is required with a Critical Design Review projected in October 2020. Design and development then starts in October 2020 and the mission is projected to have a launch date in December 2021, with a landing date in June 2022.

Surface operations would occur soon after with the mission terminating in May 2023 due to budget constraints. However, to factor in a buffer time-frame in the case that design and development takes longer than expected, we project the next launch date to occur in March 2022, with a landing date in September 2022. The mission will start later than anticipated, but landing in September still gives the team adequate time to perform the operations needed to accomplish the mission objectives while maintaining the mission end date of May 2023.

Figure 60: Undecim Portam Mission schedule from 2020–2023.

6.3 Outreach Summary

UNDECIM PORTAM MISSION : MARS 2021

WHERE ARE WE GOING?

THE UNDECIM PORTAM MISSION WILL BE TRAVELING TO NORTH EAST SYRTIS. LOCATED IN THE NORTHERN HEMISPHER OF MARS. THIS LANDING SITE IS LOCATED NEAR A LARGE MARTIAN VOLCANO – SYRTIS MAJOR.

WHY ARE WE GOING?

PAST MISSIONS TO MARS HAVE INDICATED AN INCONSISTENCY IN THE PRESENCE OF OXYGEN IN THE MARTIAN ATMOSPHERE. WE BELIEVE THAT VOLCANIC ACTIVITY UNDER THE SURFACE HAS CAUSED THE RELEASE OF OXYGEN FROM DEPOSITS FOUND UNDERGROUND.

HOW ARE WE GOING?

RIAMARA – RESOURCE INVISTIGATION FOR THE ARRIVAL OF MARS ARRIVAL AND RESEARCH

NAVCAM – NAVIGATIONAL CAMERA TO FIND OUR WAY AROUND THE SURFACE OF MARS

RIMFAX – GROUND PENETRATING RADAR TO SEARCH FOR OXYGEN DEPOSITS

WHAT WILL WE LEARN?

A GREATER UNDERSTANDING OF THE MARTIAN ATMOSPHERE WILL BE GAINED AND THE PRESENCE OF OXYGEN WILL BE STUDIED.

FUTURE MISSIONS TO MARS WILL BE ABLE TO DRILL AND LEARN HOW TO HARVEST THESE OXYGEN DEPOSITS TO SAVE MONEY AND MASS FOR HUMAN EXPLORATION TO AND FROM MARS.

Figure 61: Example info-graphic to expand awareness on the Undecim Portam mission objectives to the general public.

The Undecim Portam mission will have the RIAMAR rover travel to the landing site Northeast Syrtis where it will search for oxygen wells under the surface of Mars using the ground penetrating radar. This will allow for a deeper understanding of the inconsistencies in the presence of oxygen and methane in the atmosphere of Mars and pave the way for future missions to drill to these possible oxygen deposits.

This objective is what fuels the outreach program because it offers benefits to not only scientists and engineers but also the general public. The goal of outreach is to raise awareness on the mission, inspire future generations in space exploration, and increase public support in space missions. In order to raise awareness on our mission objectives, informative graphics (similar to the one depicted in Figure 61) will be posted on all social media platforms such that the general public is aware of the mission objectives and how they can be involved. One such way the public will be involved is through a campaign called "A Trip to Mars with RIAMAR." Through this campaign anyone in the world can submit their photo that will be sent on the RIAMAR rover through a USB microchip, so that one can send themselves on a virtual trip to Northeast Syrtis.

According to the National Science Board, 18% of American first year college students begin to pursue a degree in a STEM field [39]. This statistic could be larger as the number of STEM related careers in American society consistently increases. This number is widely known to depend on the academic preparation and awareness received in elementary through high school education. Thus, reaching out and inspiring the younger generations is a large part of the Undecim Portam mission's outreach plan. By visiting K-12 schools, the research team will inspire the future astronauts, engineers, and scientists of America by doing demonstrations and hands-on activities on our mission objectives. Some of the activities include but are not limited to an activity on drilling to find subsurface oxygen wells while students brainstorm and design their own drills, a lesson on finding life on Mars and the implications that come along with that discovery, and talks on what a career at NASA is like. A large effort will be put into visiting Title 1 (or low-income) schools to educate students that otherwise might never have the opportunity to learn about space exploration opportunities and missions in their normal school curriculum.

On a similar note, high schoolers will have the opportunity to partake in a competition that involves writing an essay on how NASA and the scientific community should deal with the discovery of extraterrestrial life found on Mars if a discovery is ever made. The winning essay will be chosen based on the following objectives: quality of writing, advanced and innovative ideas, and scientific accuracy. The winner will be awarded an all paid for flight and front-row seat to view the mission launch, plus an opportunity to meet the Undecim Portam team.

Finally, another way that the future generations will be inspired to contribute to the Undecim Portam mission is internship opportunities. During the data collection and scientific analysis phase of the mission, it will be useful to have a diverse perspective on the results while also providing research experiences for undergraduate college students in STEM fields. Three undergraduate students majoring in Biology, Chemistry, and Geology will be offered positions to help work on the analysis of the oxygen deposit data and the implications this brings towards the possibility of life on Mars.

6.4 Program Management Approach

In order to approach the complex problem of designing and engineering a payload to fulfill scientific objectives for landing a lunar mission on Mars, the team had to rely on each other as well as a strict timeline. The team from the beginning split up into separate groups with little overlap in assignments besides between the administrative teams and other teams. By the project managers setting all the deadlines ahead of time, the individual teams could identify how to space out their work in order to best succeed. Additionally, for every Tuesday PDR deadline, there was an internal deadline for teams to have their parts done by Friday night, so that the management team could spend three days editing the PDR sections to perfection and going back and forth with the teams on suggestions. This helped to create an environment where there would be no late work submitted and sufficient time for peer review.

In regards to meetings, every Sunday the whole team met for an hour to discuss their progress as well as provide a space for collaboration and communication on necessary topics. This ensured that the whole team was on the same page which was essential in being able to successfully complete the project. Sub-teams broken into engineering, science, administration, and management met additionally at least another time per week but sometimes more when necessary. During sub-team meetings, leads assigned work to their teammates and ensured that everyone was doing their part. Additionally, slack was used to effectively communicate through channels for everyone as well as individual sub-team channels and a leads channel.

For the most part, members were just on one team, except for those on the administrative team. Due to the nature of the administrative work, many of the teammates on this sub-team wanted to also serve in a capacity on the engineering or science team. By having this overlap, it made many of the administrative tasks such as budgeting and safety a lot easier as the administrative team already understood where science and engineering was coming from when drafting these items and was able to bounce ideas off their teammates more easily.

The project manager and deputy project manager made the decision to not micromanage each sub-team as everyone on the team was highly intelligent and hardworking. Instead, the management team took the leadership approach of being there to really support the sub-teams as well as the leads from a high level providing anything they needed as the project became more busy at the end. Management worked to set the team up for success through leading the weekly team meetings, reviewing the PDR sections thoroughly and quickly as soon as they were completed by the sub-teams, and being the communication link between teams whenever it appeared that a conclusion was not being reached. Management ensured that deadlines are being met by individual reminders or team-wide notices.

As with every project, there were sometimes disagreements between engineering and science, and this is where the management team often stepped in as a non-biased third party to figure out a solution everyone could agree on in order to move forward with the project. This occurred with the budget as well as objectives, but the team was able to overcome these differences and move forward. When sub-teams need to communicate to one another, the leads took it upon themselves to communicate with one another and move forward with a conclusion.

7 Conclusion Summary

This PDR introduced the next generation of Mars exploration with our mission - Undecim Portam - to search for oxygen wells on Northeast Syrtis on Mars. Our goal was to better understand the history and geography of Mars as well as find evidence for seasonal oxygen and methane atmosphere swells through sub-surface analysis and photography. These goals pave the way for future exploration on Mars, where oxygen deposits could be utilized to resupply missions dramatically lowering the barrier to the means of attainable manned voyage and other relevant scientific discoveries.

The team plans on conducting the Critical Design Review starting October 2020 and planning for test readiness review in March of 2021. With an organized schedule and lots of hard work, this timeline is viewed as extremely realistic and will set the team on track to launch in December 2021. After launch, the landing should occur in June 2022. The Undecim Portam mission will enter the Martian atmosphere about Northeast Syrtis and deploy a parachute for deceleration followed by the separation of the aeroshell and heat shield from the probe. Then, a skycrane will gently lower the lander and flyaway. The lander will begin to move forward, conducting radar sensing with a modified RIMFAX sensor to collect information about the landscape and possibly underground oxygen wells. After the mission is concluded, the data will be transmitted back to earth for detailed analysis by the scientific team.

Our payload and lander is one of a kind and represents the hopes, dreams, and tireless effort of each of the people who contributed to its success so far. Our lander represents a bold solution to the first steps to finding oxygen wells and precious minerals on Mars to enable human exploration and human habitation in the future. It highlights the ability we have as humans to come together to solve the impossible, explore the unknown, and habitat beyond our home on earth. Our mission also represents how a team of incredibly dedicated engineers, scientists, physicists, and mathematicians came together to solve an incredibly challenging problem in the midst of a global pandemic.

8 Acknowledgements and References

The Ce-L'EAST-ial team would like to thank everyone who assisted in the development of the Undecim Portam Preliminary Design Review. The team is very thankful to mentor, Hannah Stickel, for the extra effort and time she invested in consistently meeting with the team over zoom, answering all of our questions, and giving constructive criticism on this PDR. Thank you to Dann Garcia and Sheri Boonstra for leading the Mission Concept Academy and providing the team with the experience of learning from some of NASA's inspiring leaders. Finally, a huge thank you to everyone involved with the L'SPACE Program for giving the team the opportunity to be involved in such an amazing program that has provided the knowledge of many valuable skills.

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