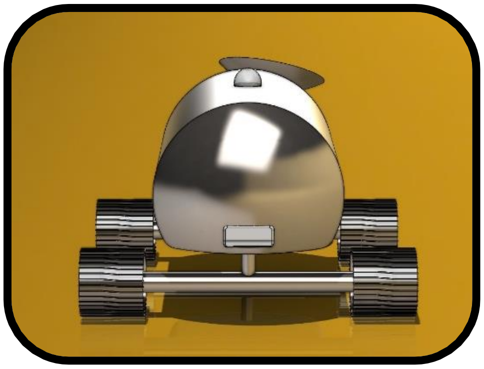
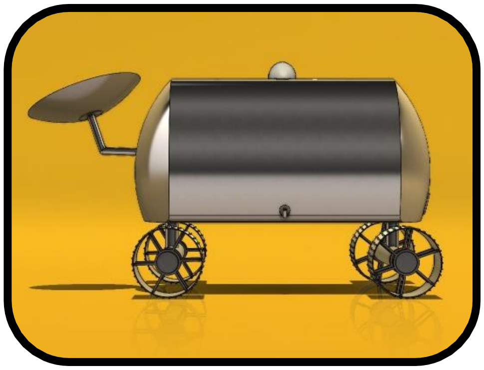
VENUS INVESTIGATION & PLANETARY EXPLORATION ROVER

2024 AIAA Request for Proposal Response: Human-Enabled Venus Robotic Exploration





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Executive Summary

The 2023 – 2024 AIAA Student Spacecraft Design Competition for Human Enabled Venus Robotic Exploration tasked participants with designing a robotic science mission that maximizes science return with humans in the loop as part of the mission operation. This emphasizes the point that a human crew in orbit would be able to optimize the collection of scientific data. A collaboration of 10 undergraduate students from the Pennsylvania State University, known as Team VIPER, created Project V.I.P.E.R., the Venus Investigation and Planetary Exploration Rover. This project outlines a mission that would effectively obtain data from the Venus surface that can be processed and utilized to deepen understanding of the Venusian atmosphere and surface, whilst also having the potential to discover applications for climate change on Earth.

The V.I.P.E.R. mission is broken up into two major phases: the interplanetary transfer and the Venus surface operation. The interplanetary transfer encompasses all aspects of the mission from the initial launch of the rocket to the descent of the rover to the surface, while the Venus surface phase covers the complete operation and control of the rover, up to the eventual disposal of the rover. The GNC, launch vehicle, and propulsion systems take the lead on the interplanetary transfer, and the power, thermal, structures, and scientific instruments are critical for the Venus surface part of the mission. The communications, ground control, and command and data handling subsystems are integrated within both parts, ensuring steady and stable contact between the Earth-based facilities, orbiting crew module, and the surface rover. The crew will be on standby during the rover's approach to ensure all systems power up correctly and diagnostics are steady prior to descent, and to monitor such systems throughout the descent itself. Once the rover reaches the surface, the crew then assumes primary control over its operations for the remainder of the mission.

The interplanetary transfer team has determined that a Hohmann transfer will be used to maximize the amount of mass that can be transferred to Venus. As determined via a trade study of multiple different options for a launch vehicle, a Falcon Heavy rocket will be used for this mission. This allows a sizable mass budget whilst also being affordable enough to fit into the overall cost budget of $1 billion USD. Due to the timeframe of this mission, the Falcon Heavy rocket may no longer be in use at the time of launch, so an alternative rocket will be selected as deemed necessary. However, such a rocket will need to be RTG-certified by the time of launch. The spacecraft bus will be inherited from previous missions, but there are a few specifications it needs to satisfy. The bus needs to house the 772.1 kg, 1.5 m x 0.86 m x 1.1 m rover and protect it through launch and transfer to Venus. It needs to receive power through the RTG and provide attitude control. It will enter the atmosphere at 10.7 km/s with an entry angle between -20.5° and -22.5° relative to the local horizon. It will then slow down to 250 m/s at an altitude of 65 km, where a 4.5 m aeroshell will be deployed until it has properly decelerated. Then the heat shield will be dropped, and a drogue parachute will be engaged, before deploying a second larger parachute. The final landing velocity will be approximately 1 m/s. The projected landing site will be on the light side of Venus at 30° S, 60° E, and the rover will head south-east, following the flat elevation of the Aino Planitia region. Based on the current orbit planned for the crew module and the slow rotation of Venus, there will be a near instantaneous communication between the rover and the crew module, with a delay of less than 0.4 seconds. To achieve this near-instantaneous communication, the crew will be placed into a Lyapunov orbit.

The rover utilizes phosphine detection, atmospheric composition, surface composition, and imaging instruments, coupled with directions from the crew module in orbit to enable the primary objective of the mission. With a live video feed and direct control over movement commands, the crew module will be able to navigate the rover over the Venusian surface with its suite of specialized instruments, providing a look into a significantly wider range of data than has previously been able to be collected. With such a small time delay between the rover and the crew, the collection of scientific data in this mission can also be extremely optimized compared to that of prior missions. Specific instruments will be taken from previously-developed technology and optimized for the V.I.P.E.R. mission such as the Venus Descent Imager, high-temperature Surface Acoustic Wave sensor, Multispectral Spectrometer, Venus Tunable Laser Spectrometer, Venus Mass Spectrometer, and Venus Atmospheric Structure Investigation. This combination of scientific instruments will be everything needed to analyze Venus more deeply as a system.

Due to the harsh conditions on the Venusian surface, the thermal, power, and structures subsystems determined that a mission duration of at least 7 days will be considered successful. The mission could potentially last longer than this, however, so long as the instruments and rover controls remain operational. Due to the impossibility of recovery without an extraordinary investment of resources, the rover will be disposed of simply by deserting it on the Venusian surface. The structures, thermal and power subsystems were designed around the scientific instruments required to accomplish the scientific mission. The power subsystem uses a combination of an RTG and sodium-sulfur batteries to generate enough power to simultaneously control the rover and collect data. The peak available power is 720 W, but estimates show the maximum power the rover will be using at any given time is only 646 W. During periods of downtime, the RTG will be able to supply enough power to keep the rover stable, as well as recharge the batteries for the eventual peak power times, during which a majority of the scientific mission and exploration will take place. The batteries' operational temperature range of 250°C – 400°C makes them viable for a short term mission such as this. The thermal subsystem, consisting of both vacuum insulation and a Stirling cooler will be able to cool the sensitive scientific instruments to as low as 50°C, and keep the rest of the rover at an acceptable operating temperature. A vacuum insulator was chosen for the passive cooling due to the risk of other insulators burning up on entry, and is supported by the pressure vessel shape chosen for the rover. The internal temperature of the rover will vary between 300°C – 350°C, while the electronics housing is capable of keeping the temperature around 50°C – 250°C. The rover's structure was designed around these other subsystems to efficiently encapsulate them, and provide protection from the immense pressure and temperatures of the Venusian surface. It is shaped cylindrically to mitigate pressure effects, and the material being used will be Ti-6Al-4V, which is able to withstand the temperature and corrosiveness of the Venus environment. The dimensions of the shell were determined to be 1.5m x 0.86m x 1.1m. Furthermore, for the windows required for use with the imager and live feed, a borosilicate composite glass fused with quartz, silica, and sapphire was chosen, being able to survive temperatures up to 1800°C and pressures up to 206 MPa. The overall mass of the rover will be 772.1 kg out of a launch vehicle-limited mass budget of 1250 kg.

The communications system, assisted by the command and data handling subsystem, will be crucial throughout both of the mission phases. Its primary goal is to maintain contact between the rover, crew module, and ground control with as little downtime as possible. It needs to be able to handle the data transfer through the thick, strongly interference-prone Venusian atmosphere. A center-feed parabolic reflector was chosen for transmitting and receiving data on both the rover and crew module. For a link margin of 1.92 dB, a rover antenna diameter of 0.49 m and a crew module antenna of 8.0 m were calculated. The maximum data rate capability for the communications relay was determined to be 100 Mbps. For the onboard command and data handling unit, it will require approximately 0.38 MIPS (18.2 Mbps) during the in-transit phase and

1.93 MIPS (92.5 Mbps) while on the Venus surface, both of which are within the operating window of the aforementioned comms system. The rover uses a silicon-carbide central processing unit which, while still a developing technology, has been shown to perform very well under simulated Venus surface conditions. The crew will communicate with ground control via the DSN, with 2 hours per day during transit being sufficient to confirm the spacecraft's trajectory as well as validate the health of all on-board systems. For the 7-day mission on the Venusian surface, 14 – 18 hours per day will be sufficient to transfer all collected data as quickly as possible back to Earth. The X-band was chosen for its ability to transmit and receive large amounts of data and information, and the orbit of the crew ensures that it will be within line-of-sight communication of the rover and DSN at all times.

Using NASA’s Project Cost Estimating Capability to perform a thorough cost analysis, it was determined that the total cost of the mission will be $963.4 million, falling just under the maximum budget of $1 billion. The biggest contributors to this budget are the flight system research and development for $493.4 million and the cost of the launch vehicle for $150 million, respectively. Development of the rover itself is estimated to cost approximately $326.6 million. Other contributing factors include areas such as project management, systems engineering, and ground control. The scientific instrument research and development will take approximately 4 years to ensure that they are viable to be implemented on the rover, and can survive under the specific power and thermal constraints. There will be another 2 years allocated to prototyping and testing, and then another 4 years to fabricate all required components. After this, the mission is planned to launch in January 2034, and it will be approximately 5 months until the primary science mission is fully underway on the Venusian surface.

A. Introduction

In recent years, Venus has become an increasingly favorable location for scientific research, facilitated by significant advances in spacecraft climate modeling and analysis technology. Coupled with the fact that the planet's runaway greenhouse effect serves as a prime example of how self-regulating climates can go wrong, there is now a greater emphasis than ever before being placed on humanity's understanding of the Venusian surface and atmosphere. However, in order to maximize the potential for any future Earth-based applications, it is necessary to study Venus as an entire system. As opposed to previous missions, in which the human team on Earth could only provide limited input to an otherwise autonomous system, placing such a team in close proximity to the planet itself would allow for near real-time control. This results in exponentially greater flexibility throughout the mission, giving the team the ability to assume direct control over the system's movement, as well as respond immediately to discoveries or issues. A human in the loop mission would enable a faster-moving surface vehicle to navigate through significantly more complex terrain than that of a non-crewed mission, and maximize scientific productivity in the harsh Venusian conditions.

As such, the 2023 – 2024 AIAA Student Spacecraft Design Competition tasked participants to design a robotic science mission that maximizes science return with humans in the loop as part of the mission operation [1]. A collaboration of 10 undergraduate students from the Pennsylvania State University, known as Team VIPER, created Project V.I.P.E.R., the Venus Investigation and Planetary Exploration Rover. This project outlines a mission to effectively obtain critical surface and atmospheric data from Venus, the results of which can be utilized to deepen understanding of the Venusian atmosphere, as well as have the potential to discover Earth-based solutions to climate change. The mission is effectively split into two primary phases: the interplanetary transfer and the Venus surface operation, with a data and communications component being integrated within both sections. The interplanetary transfer module oversees the launch and Hohmann transfer to Venus up to landing on the surface, as well as the positioning of the crew to keep them within communication's reach throughout the entire mission duration. The Venus rover encompasses the shell, the electronics inside the rover, and the various thermal- and power-related technologies required to keep the rover operational under the extremely harsh surface conditions. Finally, the data and communications module explores the means by which the rover, crew, and ground systems communicate with one another, as well as the transmission of data and commands between all involved systems.

B. Requirements Definition

The mission level and system level requirements were driven by the constraints presented in the RFP [1]. The main foci of these high level requirements are the overall mission timeline, mission cost, and high level rover design as seen in Table 1. It was determined that the launch date would fall within an appropriate launch window based on the development of the scientific instruments and other key technologies. Many instruments needed for this mission, including the Venus Mass Spectrometer, Venus Atmospheric Structure, and Venus Tunable Laser Spectrometer, are currently in development for use in high temperature and pressure environments such as Venus. This has allowed for faster development, testing, and integration, and subsequently an earlier launch date.

Table 1: Mission & System Level Requirements

Req Name	Requirement Description
Mis 1.0	The cost for the mission, including development, hardware, and operation shall be less than $1 billion
Mis 2.0	The mission shall launch no later than December 31, 2037
Mis 3.0	The mission shall complete all scientific operations by December 31, 2039
Mis 4.0	The rover shall survive on the surface of Venus for at least 7 days
Mis 5.0	The rover shall complete all scientific operations within 30 days of being on the surface of Venus
Mis 6.0	The rover shall maximize the scientific outputs throughout the duration of the mission while controlled by a crew in orbit
Mis 7.0	The launch vehicle and bus shall enable the rover to survive during transfer from Earth to Venus
Mis 8.0	The rover shall be able to communicate while in transfer to Venus
Sys 1.0	The rover shall collect atmospheric data, including pressure, temperature, and composition
Sys 2.0	The rover shall collect soil and rocky surface chemical composition data
Sys 3.0	The rover shall collect images of the Venus surface
Sys 4.0	The rover shall attempt to detect the presence to phosphine in the Venus atmosphere
Sys 5.0	The rover and bus shall weigh less than 6000 kg and more than 500 kg
Sys 6.0	The rover and bus shall fit within a 50 m^2 fairing
Sys 7.0	The rover shall have approximately 720 Watts of power to ensure consistent explorability and usage of scientific instruments, data handling, and communication systems
Sys 8.0	The rover shall have a minimum interior volume of 1.5m x 1.0m x 1.5m

Through the design process, mass and power budgets could be finalized based on the needs of all subsystems. By choosing a combination of RTG and sodium-sulfur batteries, a power system was developed that could run the rover for the duration of the mission, whilst minimizing its overall mass and volume. After analyzing the needs of the subsystems, it was determined that the rover would require no more than 720 Watts of power at any given time during the mission. The majority of the mass budget was allocated to the structure of the rover, weighing in at 431 kg. With all subsystems accounted for, the total mass of the rover is approximately 772 kg, significantly lower than the upper threshold outlined in the requirements. Similarly, instruments were chosen that could conduct the necessary scientific operations in an environment as harsh as Venus. These operations include the analysis of atmospheric and surface composition, as well as surface imaging and phosphine detection. The full mission requirements, including subsystem-level requirements, are displayed in Appendix A.

C. Concept of Operations

As previously stated, the mission is essentially split up into two major phases: the interplanetary transfer and the Venus surface concept of operations. Interplanetary transfer focuses on mission operations from launch until surface descent, while the Venus surface component covers the rover's landing to eventual disposal. In these two major parts, command and data handling (C&DH), communications, and ground systems are used heavily between the rover, the crew, and the ground systems on Earth to support the mission. The interplanetary concept of operations takes a detailed look at all the communication that makes its way to Earth, while the Venus surface concept of operations focuses on the data that gets sent to the crew module. The mission must constantly keep track of both the crew module in orbit around Venus and the rover on the Venus surface, and maintain a steady stream of communication and data transmission all the way from Venus to Earth. The crew module must also maintain a steady stream of contact with the Venus rover, and monitor diagnostics and health telemetry. Given the limitations of data transmission through the Venusian atmosphere, the presence of the orbiting crew module is integral to the success of the mission. An autonomous rover mission would simply not be feasible due to the unattainable additional processing requirements [2], and the crew module has added benefits of being able to monitor and make near-instantaneous decisions about where the rover would be able to collect the most scientific data. An in-depth analysis in Section E will subsequently prove this.

C.1 – Mission Timeline

The duration of the rover's lifespan from its launch until its inevitable death (from a functional perspective) will last ≥ 155 days. Figure 1 shows the timeline of the rover's lifespan, highlighting six key milestones. The first event is the rover's launch, which employs SpaceX's Falcon Heavy launch vehicle. Assuming a successful Hohmann transfer, the rover should reach Venus' orbit within ~146 days, soon to begin its descent to the surface the following day. Once the rover has begun its descent, it will conduct various systems checks, including rover health and telemetry verification. Once on the surface, the rover will also undergo instrument calibration and a holistic systems check prior to any data collection or transmission. After the instruments have been calibrated and system health looks promising, the rover can begin collecting data, including soil and atmospheric samples, the data from which the rover will then transfer to the crew module in orbit. The rover will continue to do this for at least 7 days, but will remain operational until the Venusian atmosphere and surface cause the rover to degrade to an unusable state.

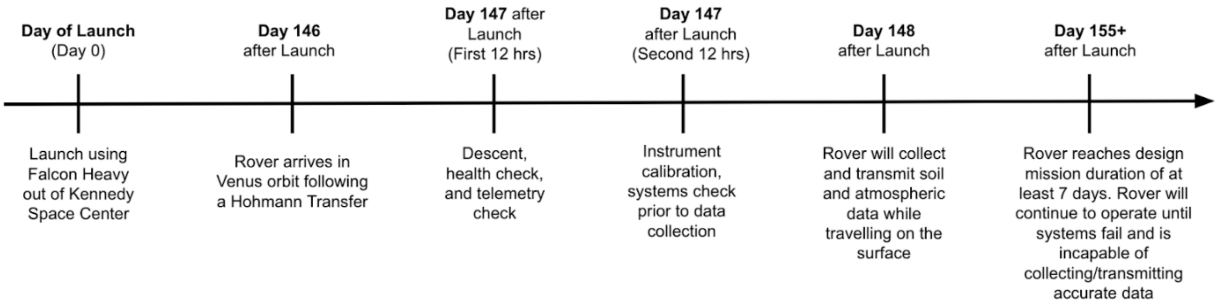


Figure 1: V.I.P.E.R. Mission Timeline

C.2 – Interplanetary ConOps

The concept of operations for the interplanetary phase is shown in Figure 2. The crew module must launch first, and ensure they are ready to establish communication with the rover. The optimal launch windows are ~19 months apart [3], which would theoretically pose challenges for the crew in terms of waiting in orbit. This, however, is not in the scope of the RFP, and the rocket launching with the rover payload assumes that the crew module will already be in the optimal orbit waiting for the rover once it arrives. The rocket with the V.I.P.E.R. payload uses a Hohmann transfer to get to orbit around Venus. Here, the crew will rendezvous with the rover in orbit to startup power systems and equipment, as well as perform diagnostics for any issues just before descent. Here it must also establish communication with the rover, which will maintain a steady stream of contact until the conclusion of the mission.

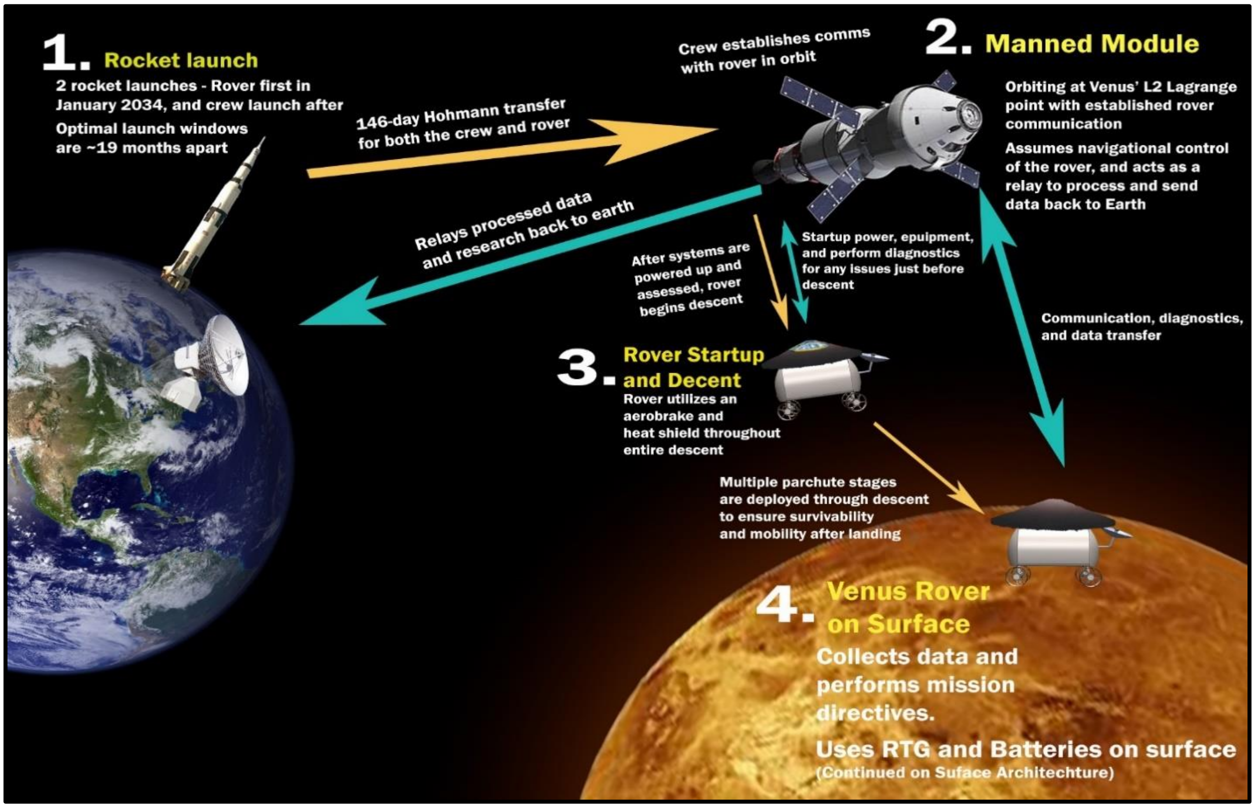


Figure 2: Interplanetary ConOps

After all systems are powered up and assessed, the rover will be ready for its descent. An aeroshell, which was previously used on the Pioneer missions, will be utilized for descent [4]. Once the spacecraft significantly decelerates, the heat shield and a drogue parachute will be used, and a second, larger parachute will also be used to slow the descent of the rover for landing. Once landed on the Venus surface, the rover will be able to start collecting data and performing its mission objectives. Due to the positioning of the crew module, there will be a no-blackout stream of communication, diagnostics and data transfer between it and the rover throughout the entire mission. The crew module will then relay processed data and research back to Earth. This communication between the crew module and ground stations, however, will not be constant. All information will first go through the DSN to get to the ground station over a period of 14 – 18 hours per day, since this is a deep space mission [5]. The data transfer must be maximized to utilize as little time of the DSN as possible while still being able to send all raw and processed data back to Earth.

C.3 – Venus Surface ConOps

The concept of operations for the Venus surface mission phase is shown in Figure 3. After landing, the rover will first power on the scientific instruments and confirm stable communication with the crew. The crew module will be giving directions and directly controlling the rover with near-negligible delay due to its Lyapunov orbit. After all the scientific instruments are calibrated and ready for use, the crew will start collecting data to satisfy the mission requirements. This entails three parts: atmospheric testing, surface composition analysis, and surface imaging. If the rover is able to collect valuable scientific data from these three categories, Venus can be analyzed fully as a system, thereby leading to a deeper understanding of Venus itself, as well as the possibility of developing potential applications for Earth-based climate change. After collecting adequate data, the rover will eventually degrade to the point where the crew module can no longer control it and collect any data. This signifies the disposal part of the mission, where the rover is left on the surface of Venus to corrode. Recovery of the rover is nearly impossible due to the Venus surface conditions [6], and there is ultimately no immediate scientific benefit to recovering the remains.

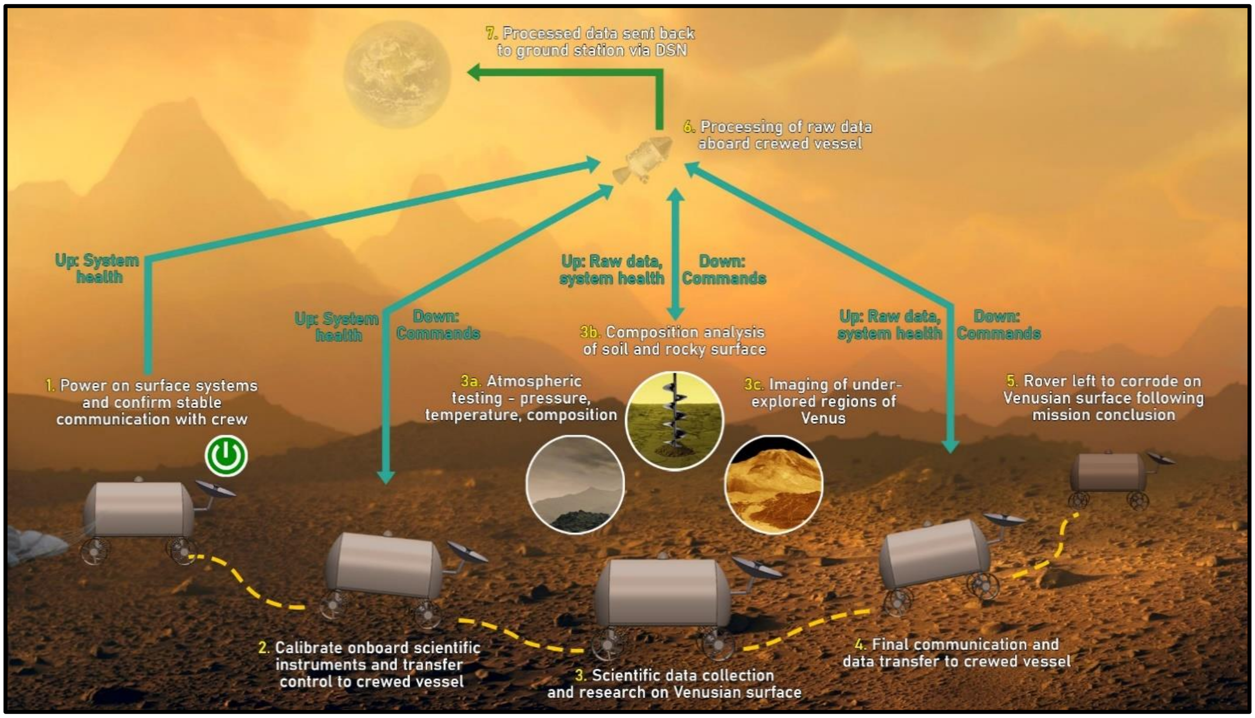


Figure 3: Venus Surface ConOps

There are a few things to note about the power, C&DH, and the communication throughout this section of the concept of operations. The rover will use a combination of a Radioisotope Thermoelectric Generator (RTG) and battery power throughout the duration of the mission; however, they will not be used simultaneously during this entire period. Due to high demands on the power system as a result of the Venusian surface conditions, the RTG will supply constant power at ~250 W (not accounting for performance losses over time), while the batteries will offer much higher power output, but only for a few hours per day. For 17 hours of the day, the RTG will supply power to the rover, as well as charge the batteries between uses. For the remaining 7 hours, batteries will supply ~500 W to account for all of the data collection, transmission, and rover system needs. This means that the majority of the science portion of this mission will occur during the 7-hour window to guarantee that there is ample power available. The rover will be constantly sending up system health information so the crew module can monitor the status of the rover. They will be able to estimate how long the rover will ultimately survive based on these system health updates, although 7 days of survival is the initial benchmark. Throughout the mission, the crew module will transmit commands down to the rover, telling it exactly where to go and when to collect data. During data collection, the rover will also send all of the raw data back to the crew module. It will continue doing this until the time of its disposal, where it will send its final data transmissions and be left to corrode. Although the rover is collecting atmospheric data and chemical composition of the surface, it will not be constantly performing these actions, and the scientific instruments will only be turned on to collect data when the crew module deems it necessary. This will be determined by the crew module and the ground control by how frequently they require the data, as well as by the amount of power available at any given time.

D. Compliance Matrix

Req Name	Requirement Description	Explanation	Complies	Section
Mis 1.0	The cost for the mission, including development, hardware, and operation shall be less than $1 billion	A cost analysis was conducted including instrument R&D, component fabrication, and mission operations, and resulted in a final cost of $963.4 million	Yes	G
Mis 2.0	The mission shall launch no later than December 31, 2037	All scientific instruments and low TRL components are intended to be developed by the end of 2029. Component integration and testing is intended to be completed by 2033. Launch will be in 2034	Yes	H
Mis 3.0	The mission shall complete all scientific operations by December 31, 2039	All scientific instruments and low TRL components are intended to be developed by the end of 2029. Component integration and testing is intended to be completed by 2033. Launch will be in 2034	Yes	H
Mis 4.0	The rover shall survive on the surface of Venus for at least 7 days	The power system on the rover is designed to last one week on the surface of Venus	Yes	E.3.3
Mis 5.0	The rover shall complete all scientific operations within 30 days of being on the surface of Venus	The power system on the rover is designed to last one week on the surface of Venus	Yes	E.3.3
Mis 6.0	The rover shall maximize the scientific outputs throughout the duration of the mission while controlled by a crew in orbit	The rover is designed to measure and record surface and atmospheric composition. The rover will also be controlled by the crew with a delay of 0.357 seconds	Yes	E.2.5 E.3.2
Mis 7.0	The launch vehicle and bus shall enable the rover to survive during transfer from Earth to Venus	The material of the rover is designed to be able to handle significant temperature fluctuations	Yes	E.3.1.1
Mis 8.0	The rover shall be able to communicate while in transfer to Venus	The rover will be minimally powered enough so that it can send back telemetry data to ground control	Yes	E.3.4.3
Sys 1.0	The rover shall collect atmospheric data, including pressure, temperature, and composition	The rover will have a Venus Tunable Laser Spectrometer, Venus Mass Spectrometer, and Venus Atmospheric Structure Investigation to measure the pressure, temperature, and composition of the atmosphere	Yes	E.3.2.4
Sys 2.0	The rover shall collect soil and rocky surface chemical composition data	The rover will have an acoustic wave sensor to measure the composition of the rocky surface	Yes	E.3.2.3
Sys 3.0	The rover shall collect images of the Venus surface	The rover will have a Venus Descent Rover Imager and Venus In Situ Surface Imager to collect images of the Venus surface	Yes	E.3.2.2
Sys 4.0	The rover shall attempt to detect the presence to phosphine in the Venus atmosphere	The rover will have a multispectral spectrometer to be able to try to detect phosphine in the Venus atmosphere	Yes	E.3.2.5
Sys 5.0	The rover and bus shall weigh less than 6000 kg and more than 500 kg	The rover is designed to weigh 772.1 kg	Yes	F
Sys 6.0	The rover and bus shall fit within a 50 m^2 fairing	The rover is designed to have an exterior volume of 1.5 m^2	Yes	E.3.1.2
Sys 7.0	The rover shall have approximately 720 Watts of power to ensure consistent explorability and usage of scientific instruments, data handling, and communication systems	The rover is designed to have both batteries and RTG to produce 720 Watts of power for the duration of the mission	Yes	E.3.3.1
Sys 8.0	The rover shall have a minimum interior volume of 1.5m x 1.0m x 1.5m	The rover is designed to hold all necessary scientific instruments, power, thermal, communications, and data handling systems which has a combined interior volume of 1.5m x 0.86m x 1.1m	Yes	E.3.1.2

E. Design Integration & Operation

E.1 – Design Introduction & Overview

The VIPER design is separated into three distinct components – launch and interplanetary transfer, the Venus rover itself, and the communications/data handling systems. The interplanetary transfer phase consists of the propulsion, GNC, and launch vehicle subsystems. The scope for this section spans from the mission's launch from Earth to the descent of the rover onto the Venusian surface, as well as ensuring that the crew has the correct orbit and orientation to reliably communicate with the rover. The Venus rover section consists of the structures, scientific instruments, power, and thermal systems. It encompasses the design of the rover's outer shell, wheels, and antenna, as well as outlines how the thermal and power subsystems are integrated into the shell to provide power and enable the use of the scientific instruments despite the extremely hostile surface conditions. Survivability of the rover is estimated to be a minimum of 7 days, with the option to extend the mission should systems remain functional, and great effort has gone into ensuring that all sensitive instruments onboard the rover have been adequately shielded from the significant temperatures and pressures of the Venusian surface. Finally, the communication and data handling component oversees any interactions between the ground systems, crew module, and rover, and includes the communication, ground systems, and C&DH subsystems. It ensures that scientific data can be collected and transferred to Earth with the greatest possible efficiency to maximize productivity under the strict time constraints. In the following design integration & operation sections, each of these three major components are described in great detail, and how they are ultimately integrated with one another to create the V.I.P.E.R. mission.

E.2 – Launch & Interplanetary Transfer

The first primary component of the mission involves the transportation of the rover payload to Venus and extends from the initial launch up until the point at which the rover successfully lands on the surface.

E.2.1 – Earth to Venus Transfer

The V.I.P.E.R. mission depends on safely traveling to Venus, and the trajectory of which is determined by the mission's constraints. The most important objective of this phase is the maximization of mass to the surface of Venus, which occurs when the fuel requirements for transfer are minimized. Thus, a Hohmann transfer will be used. Team VIPER performed a linked conic Hohmann transfer analysis, with the full derivations and conclusions of this analysis being detailed in Appendix B. The rover must escape Earth's sphere of influence, enter an orbit about the Sun that intersects with Venus's, and finally enter Venus's sphere of influence on a trajectory suitable for the landing procedure. A pure Hohmann transfer to Venus, ignoring patched conic sections, will take 146 days with a total required Δv of 5.2 km/s. The V.I.P.E.R. mission will complete an augmented version of the pure Hohmann transfer. Starting from a circular parking orbit with a radius of 20,000 km, a burn will be performed to impart 2.10 km/s of Δv on the rover [Appendix B]. This will place the spacecraft on a trajectory to collide with Venus. At Venus, a large burn will not be performed, as the atmospheric drag will provide enough deceleration for acceptable parachute deployment. The rover will enter Venus's sphere of influence on a hyperbolic trajectory that intersects with the surface. The rover will ultimately enter the Venusian atmosphere at 10.7 km/s relative to Venus [Appendix B].

E.2.2 – Launch Vehicle

The V.I.P.E.R. mission will purchase a launch vehicle. The launch vehicle must be capable of inserting the payload mass into the desired interplanetary trajectory and have enough fairing volume to safely carry the rover. Secondary factors to consider are launch vehicle reliability and cost. An interplanetary mission with a sizable payload restricts the launch vehicle options to medium- and heavy-lift rockets. Four proven rockets inside this criteria are SpaceX's Falcon 9 and Falcon Heavy, and United Launch Alliance's Delta and Atlas rocket families. A trade study was performed for all four rocket types. This trade study is shown in Table 2.

Table 2: Trade Study Results for Launch Vehicle [7, 8, 9, 10, 11]

	Weight	Goal	Falcon 9	Falcon Heavy	Delta IV M+	Atlas V HLV
Payload Mass to GTO (kg)	0.40	Max	8300	26,700	14,220	13,000
Normalized			0	1	0.322	0.255
Reliability	0.25	Max	3	2	3	2
Normalized			1	0	1	0
Fairing Volume (m^3)	0.30	Max	278	278	200	200
Normalized			1	1	0	0
Cost (Million USD)	0.10	Min	97	150	230	110
Normalized			0	0.398	1	0.098
Score			**0.650**	**0.760**	**0.379**	**0.192**

The results from the trade study indicate that the Falcon family, specifically Falcon Heavy, is preferable. In the selection matrix, payload mass to geotransfer orbit (GTO) was prioritized. This value is readily available for all of the launch vehicles investigated. Because the mass a launch vehicle can transport to Venus is correlated with the mass it can insert into a geotransfer orbit, and because SpaceX also publishes mass estimates to Mars, these values provide an acceptable reference point for a Venus mission. The estimates for Falcon 9 and Falcon Heavy suggest that they can transport 4,020 kg and 16,800 kg, respectively [7, 8]. A Hohmann transfer analysis was performed for transfers from Earth to Mars, similar to the analysis from Earth to Venus. The approximate Δv for a transfer to Mars is slightly greater than a transfer to Venus. Thus, the payloads given by SpaceX for a trip to Mars should be achievable to Venus as well. With this information, Team VIPER has set a maximum payload mass of 15,000 kg. This includes the rover and bus system.

The timeframe of the mission is relevant to the launch vehicle as well. Both SpaceX and United Launch Alliance are planning on replacing the above rockets in the next decade with the Starship and Vulcan rockets, respectively [12, 13]. The V.I.P.E.R. mission will not launch until at earliest January 2034. Ultimately, the launch vehicle does not need to be purchased in the immediate future. If new technology brings more effective, reliable, and affordable launch vehicles, the launch vehicle may change. However, for the time being, the mission has been planned around the use of the Falcon Heavy launch system.

The Falcon Heavy launch system consists of two stages. The first stage features three cores. These cores have the ability to land at the launch site or a drone ship following separation. Alternatively, a second launch option is to expend all three cores immediately after use. This will result in more mass to Venus, but will increase the price [7, 9]. However, based on the large mass margins of the V.I.P.E.R. payload, the expendable configuration will be satisfactory. The Falcon Heavy rocket was previously launched from Launch Pad 39-A at Kennedy Space Center, which is also acceptable for the mission.

A constraint on the launch vehicle not yet mentioned is radioisotope thermoelectric generator (RTG) compatibility. The Atlas V rocket has been used for all previous United States-led missions with an RTG on board. When V.I.P.E.R. is launched, the Atlas V will no longer be operational. Thus, no matter the launch vehicle selected, it will have to become RTG-certified prior to the initiation of the V.I.P.E.R. mission.

E.2.3 – Bus

The spacecraft bus has been chosen based on heritage from previous interplanetary missions. The bus needs to house the 772.1 kg, 1.5 m x 0.86 m x 1.1 m rover, and protect it through travel in space. This bus design will be contracted to an outside company for the required specifications of the mission and a majority of the components will be inherited. Power during spaceflight will be provided by the RTG onboard the rover. No major propulsion systems besides attitude control are required for the bus itself, as there is no need for any reverse braking thrust prior to entering the Venusian atmosphere.

E.2.4 – Landing

The spacecraft will enter the Venusian atmosphere at a predicted entrance velocity of 10.7 km/s [Appendix B]. This is exactly the same as the Venera 9 and Venera 10 missions, which also entered at 10.7 km/s. Also based on the Venera missions, the planned atmospheric entry angle is between -20.5° and -22.5° relative to the local horizon [14]. The spacecraft will slow to approximately 250 m/s at an altitude of 65 km [14], at which point a 4.5 m aeroshell will be deployed, which has proven to be successful during the Pioneer missions [15]. After the spacecraft has significantly decelerated, the heat shield will be dropped, and a drogue parachute will be deployed. A second larger parachute will be used to further slow the descent of the rover. This landing algorithm has been planned and analyzed by NASA. Landing simulations were run in MASTIF with the Venus Gram Atmospheric Model. The resulting landing velocity was an acceptable one meter per second (1 m/s) [15]. Several different stages of parachutes will activate and detach at different altitudes throughout the landing procedure. No propulsion will be needed during the descent as the density becomes very high towards the surface and will slow the entry craft immensely both before and after the parachutes are deployed.

E.2.5 – Crew

A key component of this mission is the efficient use of the crew. The scope of V.I.P.E.R.'s mission does not include the launch, transfer, or return of the crew; however, the location of the crew during the course of the mission is within the mission's scope. One significant constraint is that the communication delay between the rover and the crew must be less than one minute. As such, the crew will be placed in an orbit centered around the first Lagrange point of the Sun-Venus system. Team VIPER utilized the circular restricted three-body problem (CR3BP) model to find a desirable Lyapunov orbit. This orbit is displayed in Figure 4.

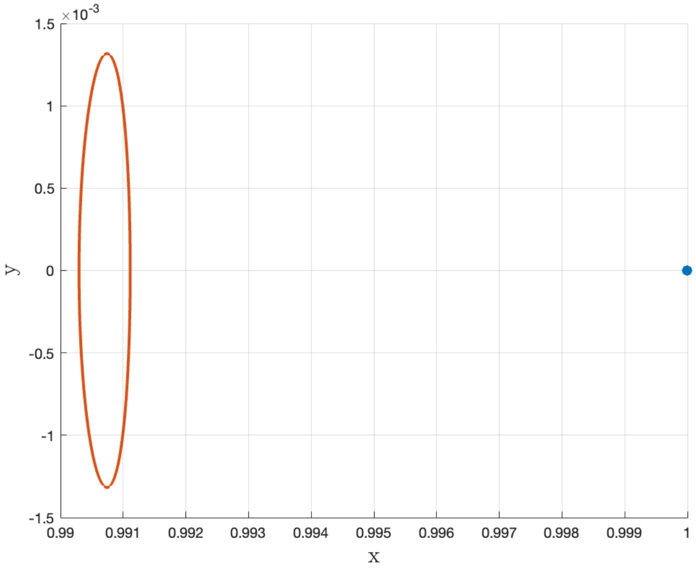


Figure 4: Crew Module Lyapunov Orbit Visualization

This orbit will ultimately result in constant communication with the rover throughout the entire mission duration. This constant communication will allow the crew to rapidly update the mission goals and parameters as data is analyzed. Based on the crew module's position, the average time delay between the crew and rover was calculated to be 0.357 seconds.

E.3 – Venus Rover

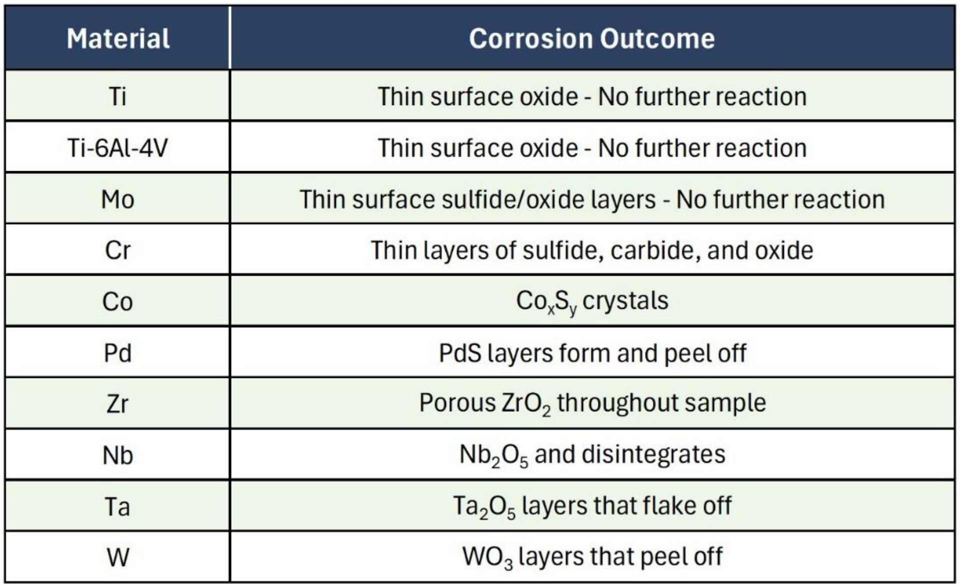
The second primary mission component constitutes the complete design of the rover, along with the onboard scientific instruments. This includes the structure of the rover itself, as well as the methods required to power it and maintain a workable temperature range.

E.3.1 – Structure

E.3.1.1 – Material Considerations

The structure of the V.I.P.E.R rover must withstand the pressure, temperature, and atmospheric corrosion experienced during descent and while on the surface. Venus's surface pressure is approximately 9.3 MPa and the maximum temperature is around 482°C (900°F). The most suitable material for Venus's atmosphere was determined to be Ti-6Al-4V. Based on a 2020 study performed in the Glenn Extreme Environments Rig (GEER), Ti-6Al-4V is sufficient both in terms of strength and corrosivity resistance [14]. Other materials that were tested were titanium (Ti) and molybdenum (Mo) as shown in Table 3. Molybdenum has an affinity for oxygen and sulfur, which, although sulfur only makes up a small part of the atmosphere, could still have a negative impact on the rover. The tests show that Mo forms a thin stable oxide layer and sulfide layer that prevents further oxidation and sulfidation. In the past, the Venera landers used titanium as their primary material, and structurally performed well. Also, Ti is already used throughout the aerospace industry, so that is why it stands out to analyze first. Ti is structurally strong enough on its own, but the aluminum (Al) component of Ti-6Al-4V increases its corrosion resistance to resist Venus's supercritical carbon dioxide, which makes up 96% of the atmosphere [14].

Table 3: GEER Study Corrosion Outcomes [14]



Material	Corrosion Outcome
Ti	Thin surface oxide - No further reaction
Ti-6Al-4V	Thin surface oxide - No further reaction
Mo	Thin surface sulfide/oxide layers - No further reaction
Cr	Thin layers of sulfide, carbide, and oxide
Co	Co_xS_y crystals
Pd	PdS layers form and peel off
Zr	Porous ZrO_2 throughout sample
Nb	Nb_2O_5 and disintegrates
Ta	Ta_2O_5 layers that flake off
W	WO_3 layers that peel off

Considering the rover will be streaming video to the crew, a high temperature, high pressure glass is required. A borosilicate composite glass fused with quartz, silica, and sapphire was selected, as it can withstand temperatures up to 1800°C and pressures up to 206 MPa, which is more than enough for Venus's surface conditions [16]. Borosilicate is a typical glass with silica and boron trioxide as its main components, and used in flasks and cookware. It has low coefficients of thermal expansion, which is good for reducing thermal stresses. On its own, borosilicate is not sufficient for Venus, but when fused with quartz, its coefficient of thermal expansion decreases. Sapphire glass is a synthetic type of sapphire, and it also optimizes the thermal capabilities and thereby increases the structural integrity of the glass [17].

E.3.1.2 – Rover Dimensions

Since the rover is landing in a high pressure environment, there will be a drastic difference in shape compared to rovers from other planetary missions. This rover will resemble a submarine, with a cylindrical body and hemispherical ends as shown by the CAD model in Figure 5. Submarines are built for high pressure environments, and the shape is critical to ensure the safety of components and crew. Cylindrical or spherical shapes work because they minimize sharp corners and edges, which are weak points when it comes to high pressures. The thickness of the rover can be determined using the hoop stress equation for a cylindrical pressure vessel, given by,

$$\sigma_H = Pd/2t \tag{1}$$

where P is the internal pressure, d is the internal diameter, and t is the wall thickness. The overall dimensions of the shell are 1.5 m x 0.86 m x 1.1 m. Dimensions were determined by optimizing the space needed to house the scientific instruments, while not leaving unnecessary empty space. Although some instruments are large, they can be modified to take up less space, and that assumption is considered for this design.

Figure 5: V.I.P.E.R. Primary Design

On the side of the rover, there is a protrusion at the bottom connecting to the interior volume with a hole facing the ground. This provides the means for the scientific instruments to collect atmospheric data. The top and front of the rover utilize the high pressure, high temperature borosilicate glass. At the top, a dome-shaped window was installed to enable a 360 degree view. In front, a rectangular window was placed for navigation and surface analysis purposes. The antenna dish used to communicate with the crew is attached to the rear of the rover. This can be adjusted to fit inside the payload bus before landing on Venus, and can move as needed while navigating the surface. The overall dimensions for the rover itself, as well as the windows and wheels, are shown in Figure 6 and Figure 7.

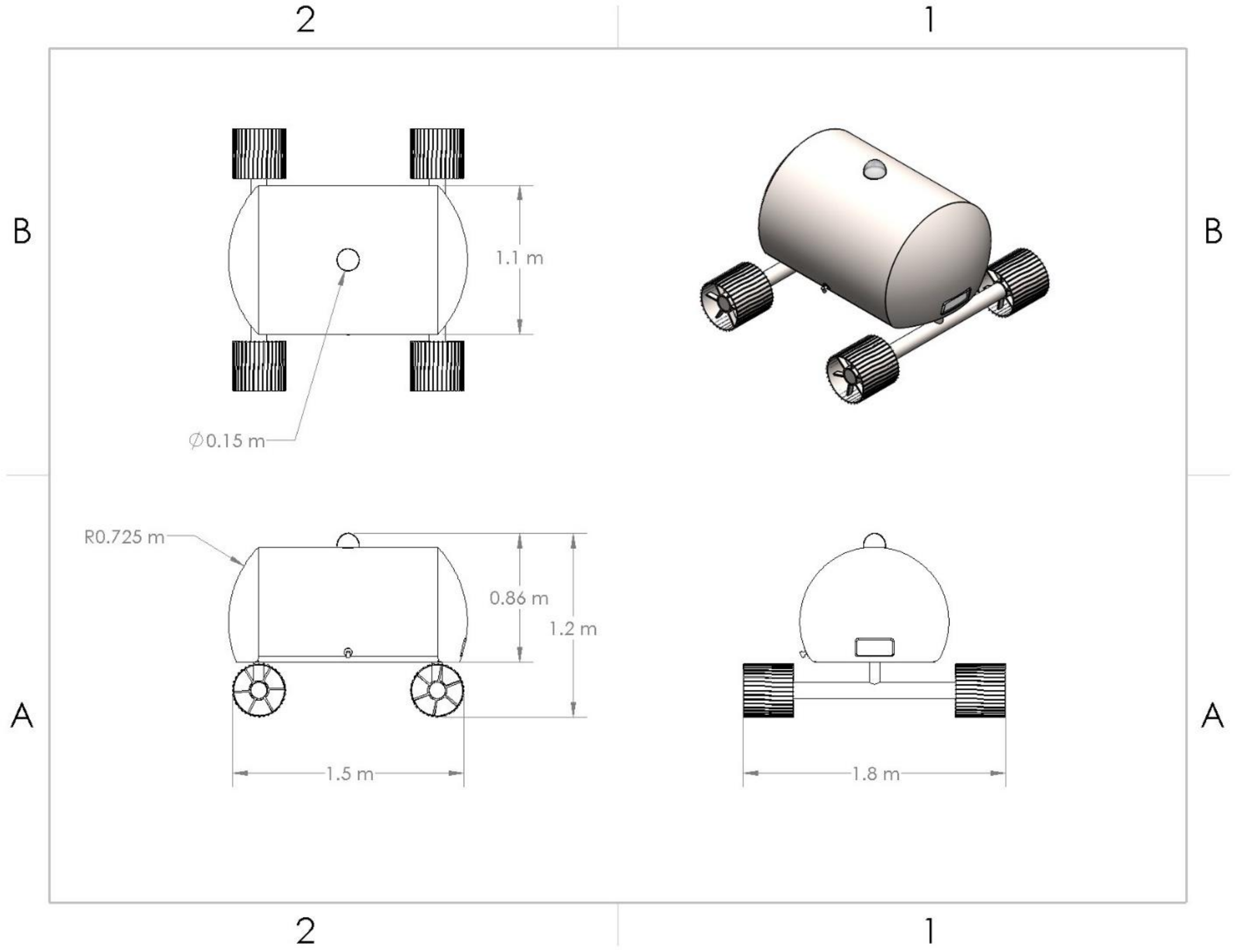


Figure 6: V.I.P.E.R. Overall Dimensions

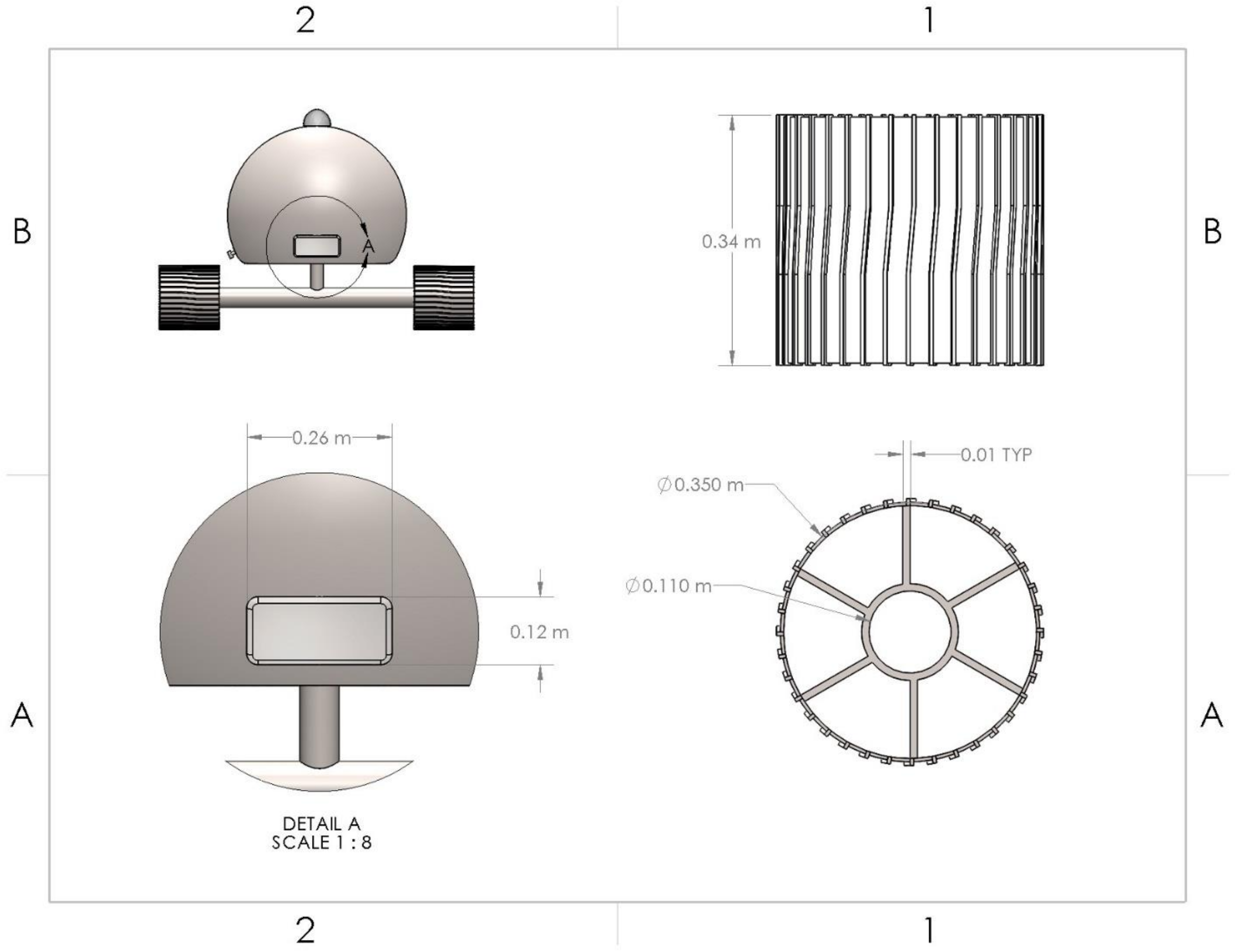


Figure 7: Imager Window & Wheel Dimensions

E.3.1.3 – Wheels

The wheels of the rover will primarily be made from Ti-6Al-4V, with other materials being considered for extra protection against fatigue from contact with the ground. Treads on the wheels will be inspired by NASA's Perseverance rover wheels, as the terrain on Mars can be comparable to Venus. There needs to be enough room for the front wheel axle to turn 90 degrees in both directions without striking the bottom of the rover, so, due to the low profile of the rover, the gap between the wheels and the rover base must be wider than usual. Since the four wheels are evenly spaced, the center of gravity of V.I.P.E.R is mostly centered, but slightly back because of the antenna and the window in front. To account for this, scientific instruments will be concentrated slightly more towards the front. Prior to launch, a robust suspension system will be developed so that each wheel can move vertically to aid in navigating more complex terrain, and soften the impact of sudden elevation changes.

Compared to Perseverance, V.I.P.E.R is significantly lighter with a wheel diameter of 35.0 cm, and a mass of 417 kg. The diameter of the wheel was determined by comparing the approximate body-to-wheel ratio of Perseverance. Therefore, because of its size and weight, it can be assumed that the maximum speed will be greater than Perseverance. Additionally, because V.I.P.E.R's crew is so close to the planet, communication with the rover will be faster and allows it to travel further distances with each command. The wheel material should be sufficient for these longer intervals of travel, and the maximum speed of V.I.P.E.R is an estimated 0.18 km/hr.

E.3.2 – Scientific Instruments

E.3.2.1 – Scientific Mission Overview

The scientific objectives defined for this mission are the following: collecting atmospheric data such as temperature, pressure, and chemical composition, collecting images and video of the surface, measuring the mass density, viscosity, permittivity, and conductivity of a surface, and detecting any remnants of phosphine in the atmosphere. With the goal of maximizing scientific outputs, it was decided that the following measurements would allow for a holistic view of Venus. Based on the current technology readiness levels (TRL) of the instruments, it would take five to six years to develop to an acceptable TRL level of 8 – 9.

E.3.2.2 – Imager

To collect live videos of the surface for the crew, the Venus Descent Imager (VenDI) can be used. This instrument will take heritage from the Mars Descent Rover. Although the original purpose of this instrument was to be used for descent, it can be repurposed as the main video feed for the crew. This instrument was chosen since it will be able to take images in both the visible and near-infrared part of the spectrum, which will help in the low light conditions on the surface. Since this instrument is still under development, the TRL can be a maximum of 4 [18]. For imaging, the Venus In Situ Surface Imager will be used. This instrument, currently being developed by the Ohio Aerospace Institute, is planned for use with future Venus surface missions. Based on analysis from the Ohio Aerospace Institute, the current TRL is between 3 and 4 [19].

E.3.2.3 – Surface Composition

The second instrument needed is a high temperature surface acoustic wave (SAW) sensor. A SAW sensor will allow the rover to measure the mass density, viscosity, permittivity, and conductivity of the surface. Developed by researchers at Northwestern Polytechnical University within the past two years, this particular instrument can operate in temperatures as high as 850°C. Since this technology has been tested in a lab at extreme temperatures, the TRL for this instrument has been determined to be a 5 [20].

E.3.2.4 – Atmospheric Composition

The third required category is a set of instruments to measure the atmospheric conditions. Currently, NASA is developing atmospheric instruments capable of operating on the surface of Venus through the DAVINCI mission. A set of three instruments will be able to measure the chemical composition, temperature, and pressure of the atmosphere whilst on the surface. These instruments are the Venus Tunable Laser Spectrometer, Venus Mass Spectrometer, and Venus Atmospheric Structure Investigation, respectively. Although these instruments were found to operate successfully in a laboratory setting, the conditions between the DAVINCI and the proposed V.I.P.E.R. mission have one critical difference: the duration of the mission. The DAVINCI mission will send a probe down from the upper atmosphere with a design lifespan of under 90 minutes. Because this proposed mission is orders of magnitude longer, the TRL for this set of instruments was decided to be a 3 [21].

E.3.2.5 – Phosphine Detection

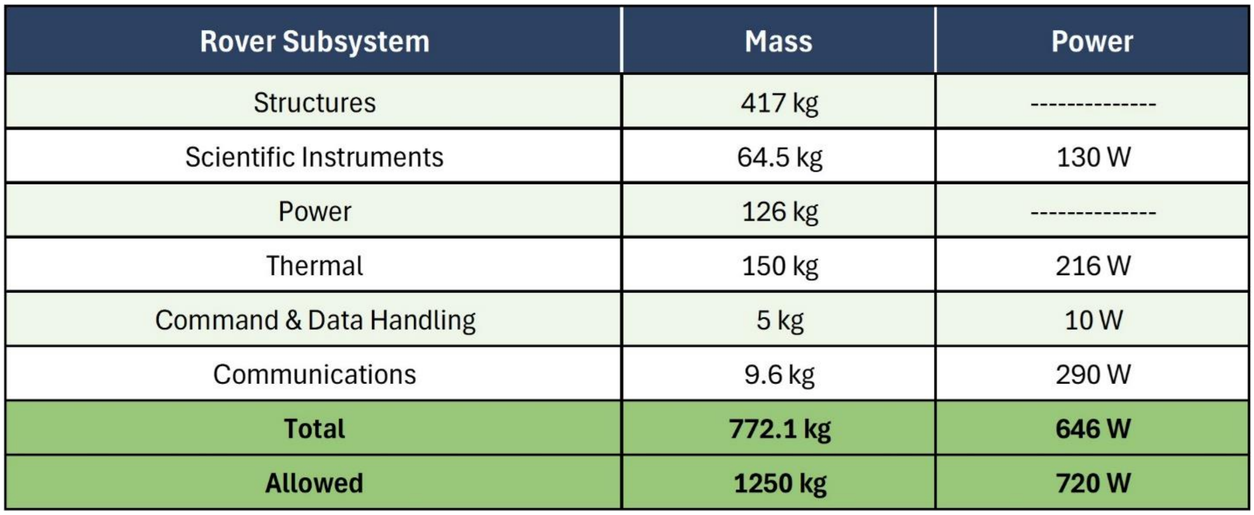
The fourth instrument needed is one that can detect phosphine traces in the atmosphere. The most recent observations of phosphine in Venus's atmosphere came from the European Space Agency's Venus Express Spacecraft. The particular device used for this mission was the multispectral spectrometer. Using this instrument, in conjunction with two phosphine detection algorithms, resulted in the conclusion that the upper limits of phosphine as originally measured by the JCW and ALMA telescope observations were overestimated by multiple orders of magnitude. However, the scope of these findings were limited to only a small region of the Venusian atmosphere [22]. By incorporating a similar instrument into the rover's design, a wider range of data could be taken to detect phosphine in the atmosphere. The current implementation of the multispectral spectrometer was designed and rated for use while in orbit, at operational temperatures of up to 40°C [23]. Because the actual operating environment is significantly different from this proposed operating conditions, the TRL is currently between 2 and 3.

E.3.3 – Power

E.3.3.1 – Subsystem Overview

The power subsystem for this mission underwent several iterations and design reviews to accommodate for increasingly prominent challenges and losses in performance. Additionally, the power system was designed in order to adequately supply power in a reliable, consistent, and safe manner. Table 4 shows a portion of the subsystem requirements outlined by Team VIPER at the beginning of this project’s lifetime. In order to meet the requirements outlined in Table 4, V.I.P.E.R. will be using a Radioisotope Thermoelectric Generator (RTG) in combination with sodium-sulfur batteries for periods of peak power consumption. The power subsystem team extensively researched various options for use on the Venusian surface, including solar arrays, batteries, RTGs, and some less-developed ideas such as power beaming using the electromagnetic spectrum [24]. However, in accordance with the power budget delineated by the team, power supply demands were much higher than originally anticipated.

Table 4: Mass & Power Budget for V.I.P.E.R. Lander



Rover Subsystem	Mass	Power
Structures	417 kg	--------------
Scientific Instruments	64.5 kg	130 W
Power	126 kg	--------------
Thermal	150 kg	216 W
Command & Data Handling	5 kg	10 W
Communications	9.6 kg	290 W
Total	**772.1 kg**	**646 W**
Allowed	**1250 kg**	**720 W**

E.3.3.2 – Power System Down-Selection

As previously mentioned, the power subsystem for the Venus rover underwent several iterations before arriving at the current configuration. Originally, batteries were going to be the sole source of power generation. However, there were several flaws with using batteries as the only source of power – the first being reliability. As of 2024, all Venus landers have used batteries as their primary source of power generation, the longest of which lasted less than 2 hours. Given that V.I.P.E.R.'s mission suggests a maximum timeline of 30 days, battery power does not give the longevity nor the reliability to be the sole source of power for the Venus rover. The next obvious choice for power supply is a solar array. However, there are several shortcomings regarding the use of solar power on the surface of Venus as well. The primary, and most debilitating, issue is the amount of solar flux that reaches the Venusian surface. From the Venera 11 & 12 missions, the estimated solar flux on the surface of Venus was 90 ± 12 W/m^2, or for context, about 9% of the solar flux that reaches the surface of the Earth [25]. This means that using solar power for the rover will simply not deliver enough power to supply all onboard components. The down-selection thus far leaves only one realistic option: employing a Radioisotope Thermoelectric Generator (RTG).

RTG technology has been around for nearly a century, and has been used heavily for missions to space [26]. However, as mentioned, previous missions to Venus's surface have relied solely on battery power and did not use RTGs. Until recently, RTGs presented several fatal flaws when working under Venusian surface conditions. For a functioning RTG, the temperature differential between the hot end and the cold end of the engine is what creates electrical power [26]. Venus makes this difficult since the ambient temperature (which represents the 'cold end' of the engine) is so high. However, using improved cooling technologies, RTGs have become a viable option for use on Venus. These methods and technologies will be expanded upon in the Thermal subsection.

E.3.3.3 – Radioisotope Thermal Generator (RTG)

While a radioisotope power system (RPS) is slightly excessive for a mission of this magnitude, it provides the most stable power delivery of all the options available. However, given the budget of $1 billion, employing an RTG is well within the scope of this mission. RTGs use General Purpose Heat Source (GPHS) modules to serve as the hot end of the engine. These modules are ~1.5 kg bricks with ~0.5 kg of condensed Pu-238, an isotope of plutonium [25, 26]. When decaying, the Pu-238 gives off significant amounts of heat, nominally producing ~250 W at the beginning of life (BOL). Figure 8 shows a cutaway view of the GPHS-RTG, further showing the components and breakdown of the engine.

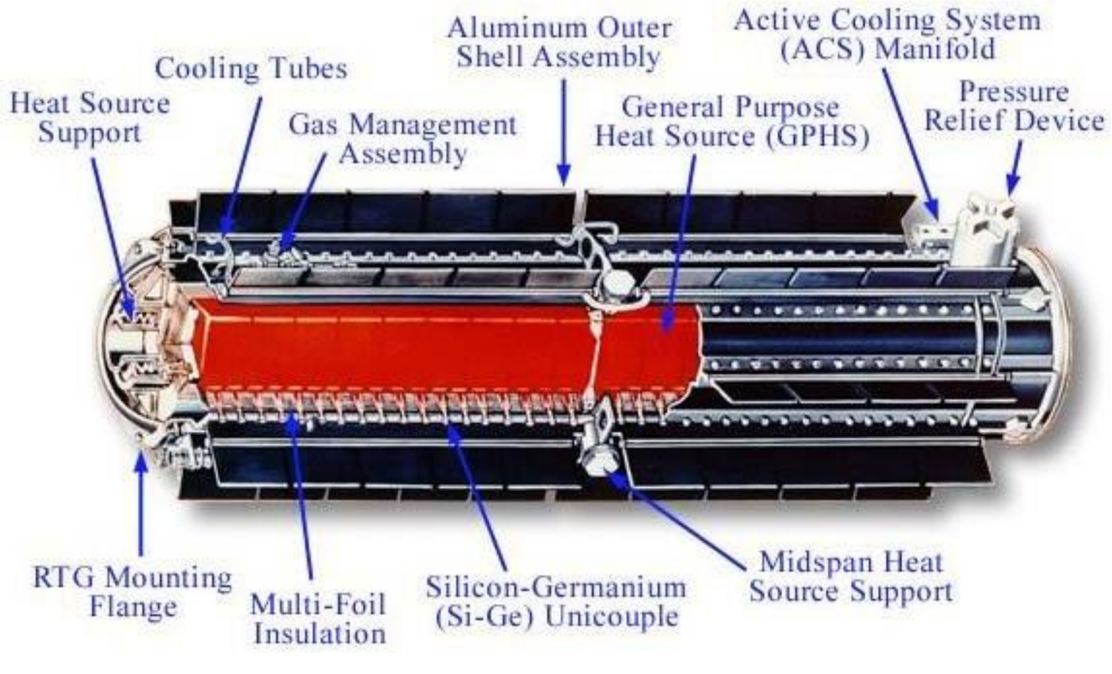


Figure 8: GHPS-RTG Component Diagram [27]

The Carnot efficiency of a heat engine depends on the temperature differential between the hot-end, T_h, and the cold-end, T_c. It can be calculated using the following equation:

$$\eta_c = 1 - \frac{T_c}{T_h} \tag{2}$$

The current hot-end material for NASA's Advanced Stirling Radioisotope Generator (ASRG) is being developed to run for 17 years at 1123 K [11], but research is currently underway to raise the operational range for the hot-end material. A realistic expectation of where the nickel-based superalloy, which makes up the hot-end material, can go is ~1200°C. Alternatively, the cold-end of the engine is expected to be slightly above Venus's ambient temperature at 500°C. Using Equation (1) with the assumed values for T_h and T_c, the expected Carnot efficiency is 47.5%.

As previously mentioned, each GPHS module can produce ~250 W of heat energy, with 216 W of required electrical power. However, after taking into account the losses due to efficiencies, an estimated ~915 W of total heat is required for the thermal and electrical requirements. Additionally, the extensive cooling solution for the rover demands a significant portion of power in order to remain operational for the duration of V.I.P.E.R.'s mission. An additional ~2900 W is needed to account for the Stirling cooler. In total, the RTG needs to produce more than 3800 W of heat energy. With each module producing a nominal 250 W of heat energy, this means that the minimum number of GPHS modules required is 15.2. Thus, V.I.P.E.R. will use 16 GPHS modules for the RTG.

The RTG technology V.I.P.E.R. intends to use has a Technological Readiness Level (TRL) of 7, as RTGs have been used in many other missions by NASA. However, none of these missions were on the surface of Venus, meaning that there is still significant research and development to be done prior to the final launch date.

E.3.3.4 – Batteries

Despite discussing many of the flaws regarding battery power on the surface of Venus, much research has been done since the majority of Venus surface missions in the late 20th century. These advancements targeted several of the primary issues with batteries, including heat exposure, battery chemistry, and improved materials [28]. These advancements make battery power a viable option as a secondary power source for missions to Venus. While the RTG is responsible for providing a consistent and stable source of power, V.I.P.E.R. will use batteries in order to offer high power for specific portions of the day. In other words, for approximately 17 hours of the day, the rover will rely solely on power from the RTG, while the remaining 7 hours will use battery power for peak loads. During the 17-hour down period, the RTG will charge the batteries so that they are ready for use during the remainder of the day. On the other hand, during the 7-hour period of battery uptime, the batteries will deliver ~500 W of power to allow for all of the scientific instruments, telecommunications, and diagnostics to work properly, without needing to worry about managing power availability.

In terms of battery chemistry, V.I.P.E.R. will use sodium-sulfur batteries. Sodium-sulfur batteries are not new to the space environment, but will present some challenges on the surface of Venus, including high sodium reactivity, limited energy density, and corrosive discharge products [29]. However, since V.I.P.E.R.'s mission requires rechargeable battery chemistry, sodium-sulfur batteries are the best option. Despite their shortcomings, NaS batteries have an operational temperature range of 250°C – 400°C, reasonable specific energy (theoretically 760 Wh/kg [28]), and a long life cycle, which makes it viable for the short-form mission V.I.P.E.R. is tasked with [30]. Additionally, with V.I.P.E.R.'s date of launch planned for 2034, but able to occur as late as 2037, further improvements in either alternative rechargeable battery chemistries or sodium-sulfur batteries specifically are likely. Thus, it is expected to see better options for batteries in the next decade or sooner. Currently, sodium-sulfur batteries have a TRL level of 7, as they have been used in many missions to space, but have not yet been employed on the surface of Venus [31].

E.3.4 – Thermal

E.3.4.1 – Subsystem Overview

The thermal subsystem is designed to keep the rover interior shell sufficiently cooled while on the surface of Venus. The fundamental issue with cooling on Venus is the extreme temperatures combined with inherent power restrictions. The solution to this is to accept high temperatures in noncritical areas, and focus thermal/power resources on smaller, more critical areas. Cooling the entire rover is impractical and unnecessary, as the rover structure is built to withstand high temperatures. This strategy will still require a significant amount of heat rejection and insulation.; however, it will allow for the most sensitive instruments to be cooled and operate efficiently.

E.3.4.2 – Thermal Technical Specifications

RTG was chosen as a primary source of power due to its potential to meet the rover's energy needs. However, it comes with the cost of producing heat on top of the already extreme surface temperature of Venus. This heat cannot be insulated against, and waste heat will need to be expelled from the rover. A combination of active and passive cooling technologies have been designed to ensure the protection of the interior of the rover. Active cooling will be utilized in the form of a Stirling cooler, working to lower the interior temperature of the rover. To negate heat coming in or leaving the rover, passive cooling will be used in the form of the interior shell's vacuum. The interior shell, which houses the electronics and scientific instruments, will contain a vacuum between it and the outer shell. A vacuum insulator was chosen because many other insulators come with the risk of burning up upon entry or breaking down under the conditions of Venus [32]. A vacuum has neither of these problems, and would be supported by the pressure vessel shape chosen for the rover. Using vacuums for insulation means that there is no limit on efficiency – the better the vacuum, the better the insulator. No vacuum is perfect, but this could allow for temperatures as low as 50°C when paired with the Stirling cooler [11]. This is important due to the sensitive nature of the electronics, which cannot be exposed to the extremes of the Venus atmosphere. Ultimately, the heat from the RTG is the major contributor to higher internal temperatures, even in the presence of a vacuum.

E.3.4.3 – Stirling Cooler

The Stirling cooler, when paired with the vacuum, is capable of keeping the interior of the rover between 50 – 250°C while operating at an exterior temperature of 500°C, which is the expected maximum temperature the rover could encounter [33]. While 50 – 250°C is a wide range, with 50°C being on the cool side and 250°C being hot, these are perfectly acceptable ranges for the selected electronics to operate at, while higher temperatures are not. The Stirling cooler will be coupled with the RTG to create a system that is more thermally efficient, and the cooler will use 216 W of power from the RTG [11]. Coupling the Stirling cooler and RTG gives an added bonus of reducing the overall rover volume, which saves mass. While in transit, the rover will need to preserve heat instead of expelling it. The Stirling cooler can be shut off intermittently to allow for the RTG to warm the rover. This can be done by setting a minimum temperature, such as 50°C, and when a temperature sensor detects it, the RTG turns on. The maximum does not need to be considered since the RTG will not be sufficiently warm to achieve this, but it should still shut off when warmed to preserve energy. A good temperature for this is approximately 125°C. While on the surface, the Stirling cooler will be running for the mission duration. The primary purpose of the Stirling cooler is to expel heat that the RTG produces, but also to expel any heat that the vacuum may let in. The Stirling cooler will specifically target communication electronics and scientific instruments, while allowing the rest of the rover's interior to remain at a higher temperature.

E.3.4.4 – Thermal Analysis

A thermal analysis was conducted via a simulation with the Stirling cooler, RTG, vacuum insulation, and surface temperature of Venus as shown in Figure 9. The temperature used in this analysis was 464°C. The internal temperature of the rover varies between 300 – 350°C, while the electronics housing is capable of keeping the temperature around an average of 100°C. As the size of the electronics housing is increased, the temperature increases, so the size must remain small compared to the overall volume of the rover. Ultimately, the simulation results fit within the intended mission requirements, and allow all onboard instruments to operate safely.

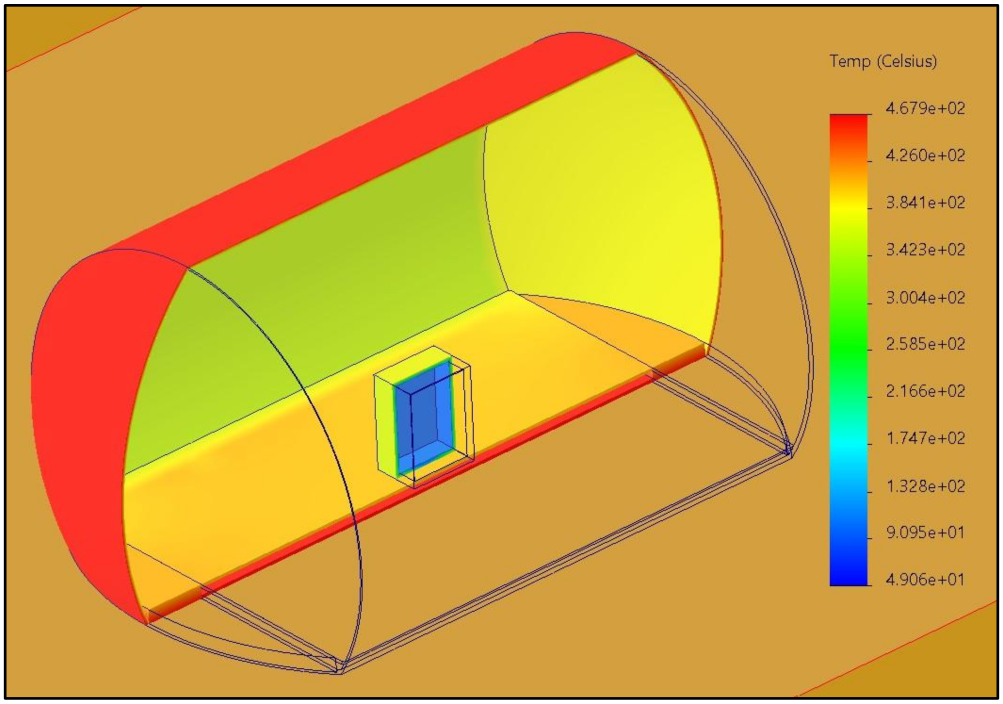


Figure 9: Rover Thermal Analysis

E.4 – Data & Communications

The final mission component focuses on the flow of data between the three primary bodies: the rover, crew module, and ground station. The internal processing architecture of the rover itself is discussed, along with the required hardware for enabling clear data transmission in spite of the extreme atmospheric conditions.

E.4.1 – Command & Data Handling (C&DH)

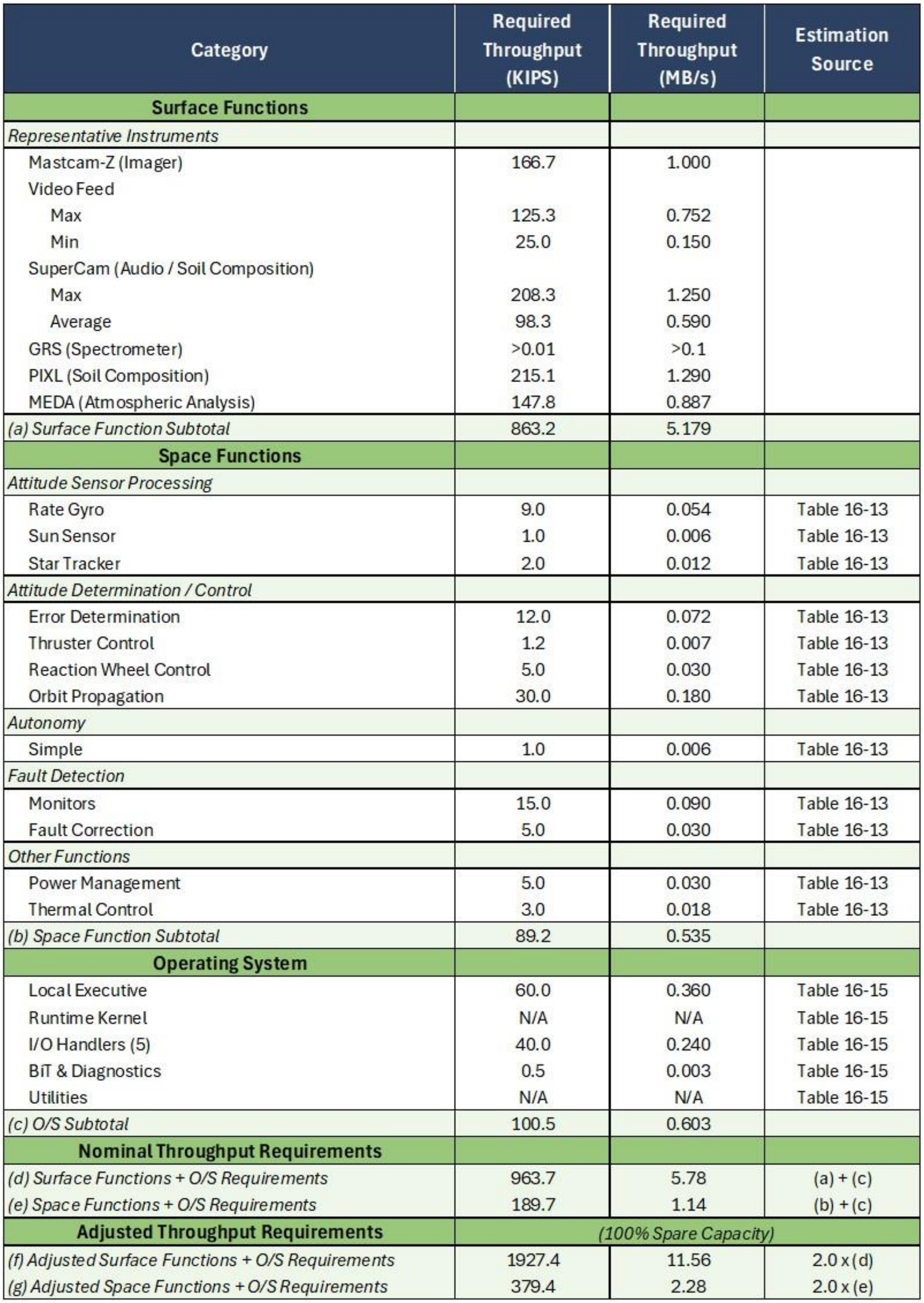
E.4.1.1 – Subsystem Overview

The command and data handling subsystem of the V.I.P.E.R. system has been designed to accommodate the needs of the onboard scientific instruments, as well as interface directly with the communications subsystem to relay scientific data and diagnostic information back to the orbiting crew module. The integrated C&DH module will be arranged in a distributed bus architecture, and draw approximately 10 W of power when at peak operation. Data throughput requirements are split into distinct in-transit and on-surface components, and, with full margins included, these two mission phases will require approximately 0.38 MIPS (18.2 Mbps) and 1.93 MIPS (92.5 Mbps), respectively.

E.4.1.2 – Data Throughput Requirements

Estimates for the data throughput observed by the command and data handling subsystem were determined both by using published data from scientific instruments, and via estimates from reference texts [2], and are shown in Table 5. Although not the exact models being used in the V.I.P.E.R. mission, these instruments are extremely comparable in practical use and have readily-available and detailed operating characteristics, making them a more than sufficient approximation. As previously stated, the mission itself is split into an initial space phase, followed by the primary scientific mission on the surface, which results in two separate values for maximum expected throughput. The space phase encompasses all of the attitude determination/control processes and onboard sensors in operation during the rover's initial transfer from its parking orbit around Earth to its final Venus intercept trajectory, while the surface phase includes the complete operation of the scientific instruments and uplink of data throughout the primary mission duration on Venus, with the operating system being the one component active during both phases. In terms of data margins, the recommended value of 100% spare capacity was selected to account for any uncertainties associated with data transfer in the reasonably untested operating conditions of the Venus surface atmosphere [2]. As a result, the final maximum estimates for the space and surface phases were 2.28 MB/s and 11.56 MB/s, respectively. It is important to note that these values only consider the scenario in which all instruments are running simultaneously, which will almost never be the case, especially during the surface phase. For example, depending on the rover's current position and/or scientific focus of the crew at any given time, only the SAW sensor and VenDI may be required to be in full operation. Therefore, with the communications subsystem able to handle up to 12.5 MB/s under normal operating conditions, all data will be able to be uplinked as it is received, with only minimal storage required in the event of weather-induced transmission losses, in which the transmitter power boost required to overcome such disturbances subsequently reduces the maximum communications throughput below comfortable margins.

Table 5: Data Throughput Estimates



Category	Required Throughput (KIPS)	Required Throughput (MB/s)	Estimation Source
Surface Functions			
Representative Instruments			
Mastcam-Z (Imager)	166.7	1.000	
Video Feed			
Max	125.3	0.752	
Min	25.0	0.150	
SuperCam (Audio / Soil Composition)			
Max	208.3	1.250	
Average	98.3	0.590	
GRS (Spectrometer)	>0.01	>0.1	
PIXL (Soil Composition)	215.1	1.290	
MEDA (Atmospheric Analysis)	147.8	0.887	
(a) Surface Function Subtotal	863.2	5.179	
Space Functions			
Attitude Sensor Processing			
Rate Gyro	9.0	0.054	Table 16-13
Sun Sensor	1.0	0.006	Table 16-13
Star Tracker	2.0	0.012	Table 16-13
Attitude Determination / Control			
Error Determination	12.0	0.072	Table 16-13
Thruster Control	1.2	0.007	Table 16-13
Reaction Wheel Control	5.0	0.030	Table 16-13
Orbit Propagation	30.0	0.180	Table 16-13
Autonomy			
Simple	1.0	0.006	Table 16-13
Fault Detection			
Monitors	15.0	0.090	Table 16-13
Fault Correction	5.0	0.030	Table 16-13
Other Functions			
Power Management	5.0	0.030	Table 16-13
Thermal Control	3.0	0.018	Table 16-13
(b) Space Function Subtotal	89.2	0.535	
Operating System			
Local Executive	60.0	0.360	Table 16-15
Runtime Kernel	N/A	N/A	Table 16-15
I/O Handlers (5)	40.0	0.240	Table 16-15
BiT & Diagnostics	0.5	0.003	Table 16-15
Utilities	N/A	N/A	Table 16-15
(c) O/S Subtotal	100.5	0.603	
Nominal Throughput Requirements			
(d) Surface Functions + O/S Requirements	963.7	5.78	(a) + (c)
(e) Space Functions + O/S Requirements	189.7	1.14	(b) + (c)
Adjusted Throughput Requirements	*(100% Spare Capacity)*		
(f) Adjusted Surface Functions + O/S Requirements	1927.4	11.56	2.0 x (d)
(g) Adjusted Space Functions + O/S Requirements	379.4	2.28	2.0 x (e)

E.4.1.3 – Material Considerations

In order to combat the extreme surface conditions on Venus and ensure that a one-week mission duration is feasible, the rover will utilize a silicon-carbide (SiC) central processing unit. Of all the previous missions to the surface of Venus, the longest observed mission duration with conventional silicon processors lasted only two hours [34]. However, compared to these standard silicon chips, which have been employed on lunar / outer planetary missions for decades, and begin to experience critical semiconductive degradation at temperatures exceeding 300°C, silicon-carbide processors have been proven to operate at temperatures upwards of 500°C for over 500 continuous hours [35]. In a 2016 study conducted by the NASA Glenn Research Center, two SiC JFET ring oscillator integrated circuits were placed in the Glenn Extreme Environments Rig (GEER) under simulated Venus surface atmospheric conditions for 521 continuous hours (21.7 days), and experienced near zero performance degradation over the entire test period [35], as shown in Figure 10. With the mean surface temperature of Venus being a comparatively lower 460°C, and the rover interior temperature being reduced even further by the Stirling cooler, a silicon-carbide processor will thus allow for virtually uninterrupted data processing capabilities over an extended period of time, in conditions where a standard silicon processor simply could not function.

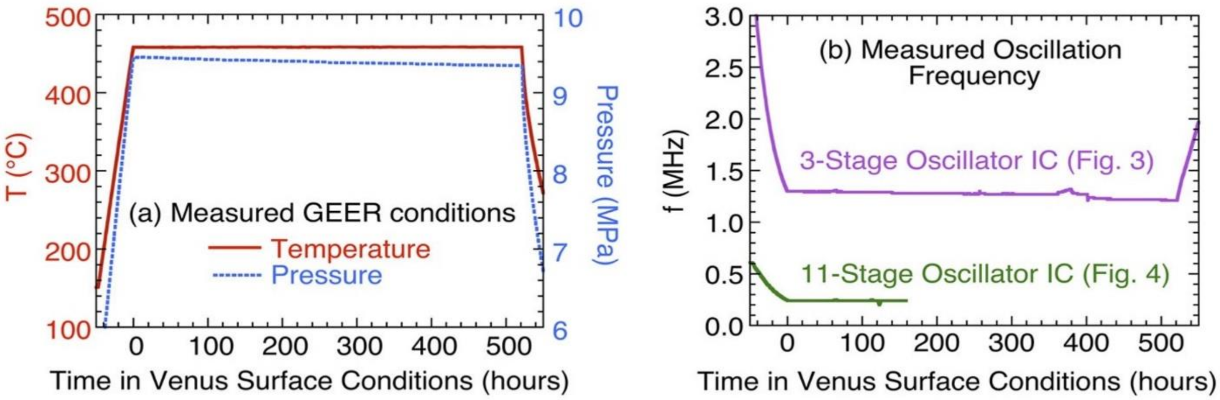


Figure 10: SiC Processor Performance Evolution under Venus Atmospheric Conditions [35]

E.4.1.4 – Technology Limitations & Solutions

One important aspect to note, though, is that current SiC technology is inferior to common Si components in terms of size, manufacturing cost, and complexity, with channel lengths in particular being on the order of μm, a magnitude that is comparable to decades-old Si circuits [34]. This results in speeds that are noticeably reduced compared to that of an industry standard like the RAD750, which is capable of reaching upwards of 240 MIPS [36], or even its predecessor, the RAD6000. The results of a 2022 study on the viability of SiC-based processing architectures designed for Venus surface exploration are shown in Figure 11. On average, the two main processors involved in the test, the SiC T4 and SiC V1, were 23.1 and 16.6 times slower than that of the RAD6000 Si processor, respectively, with the absolute best case scenario observed still being 6.25 times slower [34]. The other three SiC processors included in the test were simply modifications to the SiC V1, mostly in relation to cache size and whose specifications are shown in Table 6, but did not have appreciable differences in their normalized throughput. However, given a timeframe of slightly under 10 years until the expected launch date in 2034, it would not be inappropriate to assume that this technology can be developed to a level that is suitable for the mission, especially with targeted R&D efforts. Furthermore, considering the RAD750 itself already vastly exceeded the required throughput, SiC technology will not need to replicate the exact level of performance shown by Si chips to still remain practical for use on the rover.

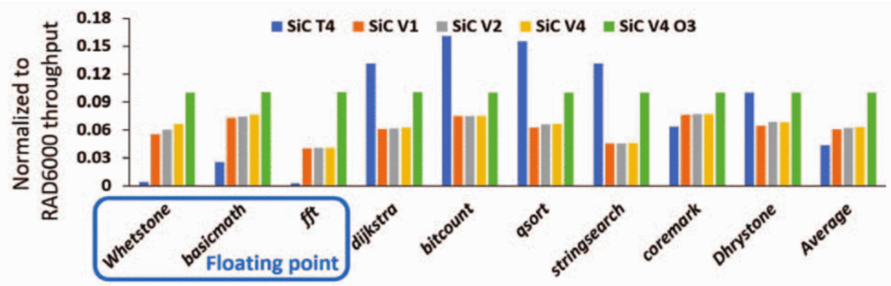


Figure 11: Normalized Throughput Benchmarks for SiC Processors [34]

Table 6: CPU Specifications & Design Parameters [34]

Processor	Clock Freq	I/D Cache Size	Gem5 CPU Model
Si RAD750	200 MHz	32 kB each	DerivO3 (Out-of-Order)
Si RAD6000	20 MHz	4 kB each	DerivO3 (Out-of-Order)
SiC T4	8 MHz	4 kB each (250 mm^2)	TimingSimple (1 Stage, ALU only)
SiC V1	2 MHz	1 kB each (250 mm^2)	Minor (In-Order)
SiC V2	2 MHz	2 kB each (testing)	Minor (In-Order)
SiC V4	2 MHz	4 kB each (RAD6000)	Minor (In-Order)
SiC V4 O3	2 MHz	4 kB each (RAD6000)	DerivO3 (Out-of-Order)

E.4.1.5 – Crew Module & Storage

Unlike the rover, because high-temperature operation is of no concern to the orbiting crew module, the use of the RAD750 processor is not only possible, but an extremely favorable option. Due to its extensive use on past satellites and space missions, the associated risk is extremely low compared to that of a more recently-developed technology like SiC circuitry. Additionally, as mentioned previously, the processing speed of the RAD750 is exponentially greater than anything achievable by current SiC processors, thereby making the use of such processors wholly unnecessary in the absence of specialized conditions. The RAD750 will allow for the maximum transfer of data between the rover and crew as deemed possible by the communications system, with a reduced potential for failure or loss of information. The crew module will also be equipped with approximately 10 terabytes of data storage, as, because the timing of data transfer between it and the Earth is quite flexible compared to its interactions with the surface rover, it will be expected to hold sizable amounts of accumulated data for an extended period of time. The storage requirements for the rover itself, on the other hand, are determined by the transmitting capabilities of the communications subsystem, and have been set at 16 GB. Under normal conditions, the transmitter will be able to uplink all data to the crew module at once; however, in the event of unexpected interference events, this may no longer be possible. Because the live video feed and diagnostic information will be the only data that must be uplinked continuously, this storage allows sufficient margins for scientific results to accumulate onboard until a more optimal transfer window becomes available.

E.4.1.6 – Viability of Complex Autonomy Integration

A potential point of contention is whether or not the rover C&DH subsystem would be more efficient if it were instead designed to accomplish all required tasks without external input and guidance from the crew. While this would certainly simplify the overall mission logistics and eliminate the risk associated with a human crew, it would ultimately not be feasible for the given mission parameters. Compared to the current simple autonomy processes onboard the rover, the introduction of a completely autonomous system architecture would significantly increase the required data throughput for the on-surface component of the rover's operation. While only about 6.0 kB/s (1.0 KIPS) is needed to troubleshoot basic sensor issues or analyze diagnostic information, a system that would allow the rover to independently navigate the mostly unmapped and unpredictable surface of Venus, particularly with the extreme efficiency required to make the most of the limited mission duration before fatal system degradation, would demand upwards of 1.2 MB/s (20 KIPS) [2]. Therefore, with a communications system that can handle up to 12.5 MB/s, and a current maximum expected throughput of 11.56 MB/s, the addition of complex autonomy would push the latter above the capabilities of the former. Despite the previously-stated assumption that not all instruments would be running concurrently, which would, in theory, bring the average throughput back within the operating window of the comms antenna, this does not consider the decreased performance observed during inclement weather events, and generally leans towards unsafe margins. The only way to truly integrate complex autonomy into the rover would either be to raise the onboard storage capacity to account for the now-inability to transfer all data at once, or increase the size of the antenna itself. However, both of these options would raise the overall mass, power, and cost, with the margins for the latter two in particular already being relatively slim, thereby ensuring that neither is a viable solution. As a result, given the current rover design and constraints associated with the operational environment, the presence of the crew is strictly necessary to ensure that an amount of scientific data significant enough to warrant the mission's existence can be collected.

E.4.2 – Ground Control

E.4.2.1 – Subsystem Overview

The ground control subsystem is responsible for maintaining Earth-based, crew, and rover communication networks throughout the duration of the mission. In order to properly maintain this communication network, the ground control subsystem will be split into multiple parts, with each contributing to the overall success of the mission. The Mission Operation Center (MOC) is tasked with commanding and monitoring spacecraft performance, as well as requesting and receiving mission data. The mission will be reliant on the Deep-Space Network (DSN), so the MOC will be located at NASA's Jet Propulsion Laboratory in Pasadena, California where the DSN is managed and operated. The DSN comprises three locations in Goldstone, California, Madrid, Spain, and Canberra, Australia, each separated in longitude by 120 degrees to provide constant communication with each part of the mission, independent of their location with respect to Earth [37]. The MOC works in tandem with the Spacecraft Operation Control Center (SOCC), which is responsible for commanding the spacecraft bus and any other systems related to spacecraft and rover health and performance. The SOCC generates mission-relevant commands for the spacecraft, and sends it to the MOC for direct communication. Lastly, there is the Payload Operation Control Center (POCC). The POCC monitors the payload during flight to Venus and for the duration of the rover's lifespan. The POCC is responsible for analyzing telemetry and mission data as well as generating commands for all scientific instruments. It is important to note that both the SOCC and POCC do not directly communicate with the spacecraft, rover, or crew module. They simply generate commands, relay the commands to the MOC, and wait for the MOC to directly communicate with the intended recipient through the DSN. Any information sent back from the crew module will first be received at the DSN, which will relay the information to the MOC, and the MOC will distribute the data to either the POCC or SOCC, depending on the content of the data. The payload will be designed by Lockheed Martin, and for ease of communication, the SOCC and POCC will be co-located at the Lockheed Martin headquarters in Denver, Colorado.

E.4.2.2 – Communication Network & Budgeting

The success of the mission is heavily reliant on a strong communication network between the DSN, rover, crew, spacecraft, and the ground control subsystem. Each DSN location is equipped with one 70 m antenna as well as multiple 34 m antennas that allow for radio communication [38]. Radio communication must take place within a specific band in the radio spectrum, and new technologies have allowed for communication with the S, X, or K bands, as opposed to the Ultra-High Frequency bands used in older missions [39]. The communication network will use the X-band, operating at a frequency of 10 GHz with a bandwidth of 1 GHz. The choice to operate in the X-band ensures that large amounts of data can be transmitted from the rover to the crew, and eventually from the crew to Earth for analysis. The location of the crew module in orbit, together with Venus's extremely slow rotational period, will allow for near constant communication with the rover and crew. This will not be the only mission using the DSN, however, so 24/7 communication is an unrealistic expectation. Although real-time adjustments will need to be made to accommodate the transfer of mission data, 14 – 18 hours per day will be sufficient for mission success. Data communication between the crew module and the rover is much more of a priority due to the extremely harsh surface conditions present on Venus. The rover will aim to transmit as much data as quickly as possible to the crew before the rover encounters any catastrophic hardware or software malfunctions. During the rover's 147-day journey to Venus, the spacecraft bus will be in contact with the DSN for 2 hours each day. These two hours will be used to confirm the spacecraft's trajectory as well as validate the health of all on-board systems. The mission will use the DSN for a total of 520 hours at an estimated cost of $1648.92 per hour (based on NASA's Mission Operations and Communications Services) and so the total cost for the mission will be approximately $860,000 [40].

E.4.2.3 – RF Attenuation from Atmospheric Conditions

Despite the relatively straightforward choices detailing the DSN and ground control subsystem, as well as the communication bands and budgeting, there is still an important challenge that needs to be overcome. Although most other subsystems are concerned with mitigating potential issues caused by the surface temperature and pressure, the ground control subsystem (alongside the closely-related communication subsystem) must understand how the atmospheric conditions on Venus will impact the communication network. As mentioned in Section E.4.2.2, the X-band was chosen for its ability to transmit and receive large amounts of data and information. The X-band operates through line-of-sight communication, meaning that data signals can only be sent if the two communicating stations (in this case, the DSN and the crew, or the crew and the rover) can clearly view each other without any obstructions [41]. Since the evenly-spaced DSN locations allow for communication at any location in space, the line of communication between the DSN and crew will only experience minimal attenuation as radio waves pass through Earth’s atmosphere. Slight attenuation is to be expected, and this will not cause any major issues within the communication network. Communication between the rover and the crew, however, is much more of a concern. The atmosphere of Venus is dominated by carbon dioxide (CO_2), nitrogen (N), sulfur dioxide (SO_2), and large clouds of sulfuric acid (H_2SO_4) [42]. This has the potential to significantly interfere with the communication network. Sulfuric acid clouds can easily obstruct the line-of-sight between the rover and the crew and CO_2, N, SO_2, and H_2SO_4 are all strong absorbers of radio waves [43]. Fortunately, these absorbers are not evenly distributed throughout the atmosphere of Venus, and there is a range of suitable locations that will allow for effective communication, as shown in Figure 12 and Figure 13.

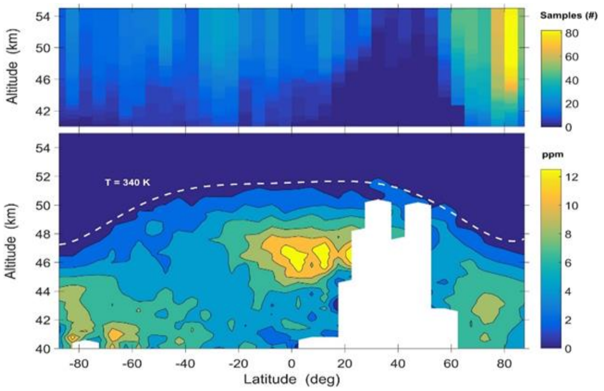


Figure 12: Variation of H_2SO_4 with Altitude & Latitude [43]

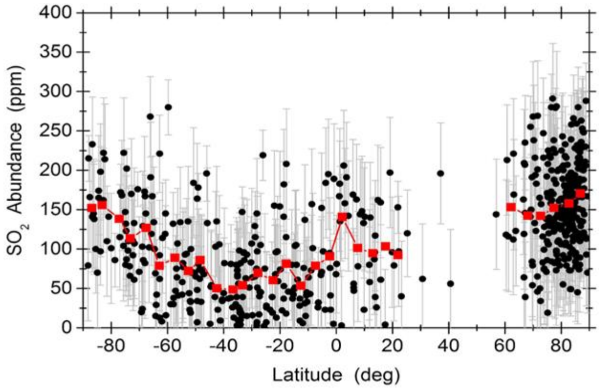


Figure 13: Variation of SO_2 with Latitude [43]

Both figures show a clear trend between regions of high absorptivity and latitude. Latitudes of 20° – 60° can be ignored due to a lack of sufficient data, but despite this, there is still a noticeable low-abundance region of absorbers found between -40° to 15° latitude. There is no correlation between longitude and abundance, so there is no landing preference for either side of Venus. Maximizing data communication requires the minimization of RF propagation through RF absorbers, and so the -40° to 15° latitude range will be prioritized for landing, operation, and exploration.

E.4.2.4 – Landing Site & Rover Pathing

The mission landing site and exploration path will be on the light side of Venus (to maximize photo and video clarity) and within the range of -40° to 15° latitude (to maximize communication efficiency). The mission launch will begin on January 1st, 2034, and after the 147-day journey, the rover is expected to touch down on May 28th, 2034, before exploring the surface of Venus until at least June 4th, 2034. By using the Systems Tool Kit (STK) software to determine the sun coverage from May 28th to June 4th, as shown in Figure 14, combined with the topography of Venus in Figure 15, a suitable location for landing and exploration was determined. The rover will be in complete sun coverage for the duration of the mission, which will aid in navigation while also providing high quality videos and images. The landing site and rover pathing will be within the range for minimum absorption from CO_2, N, SO_2, and H_2SO_4, which will allow for minimal data loss during rover to crew communication. The rover will touch down at 30° S, 60° E (marked with a circled X in Figure 15) and will head south-east, following the flat elevation of the Aino Planitia region. This region is between the desired latitude range and should minimize potential issues while traversing the surface of Venus, as it has nearly zero changes in elevation.

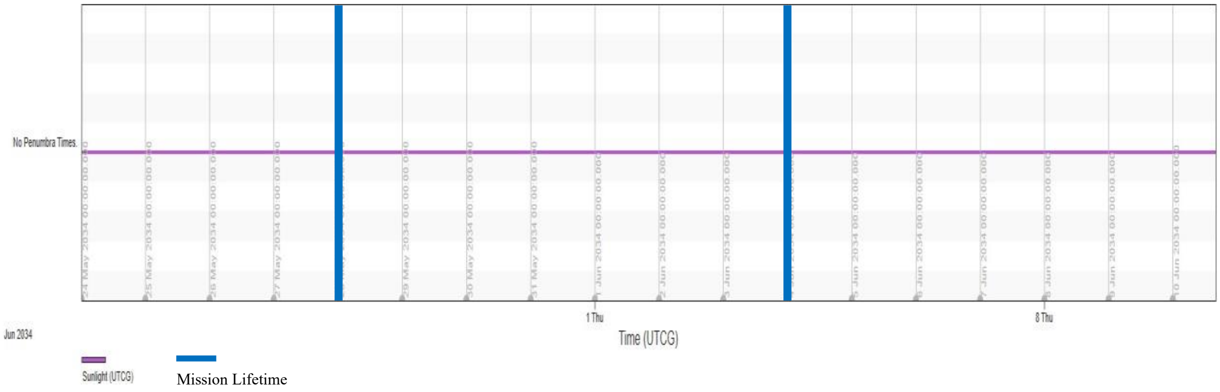


Figure 14: STK-Predicted Sun Coverage During Landing and Exploration

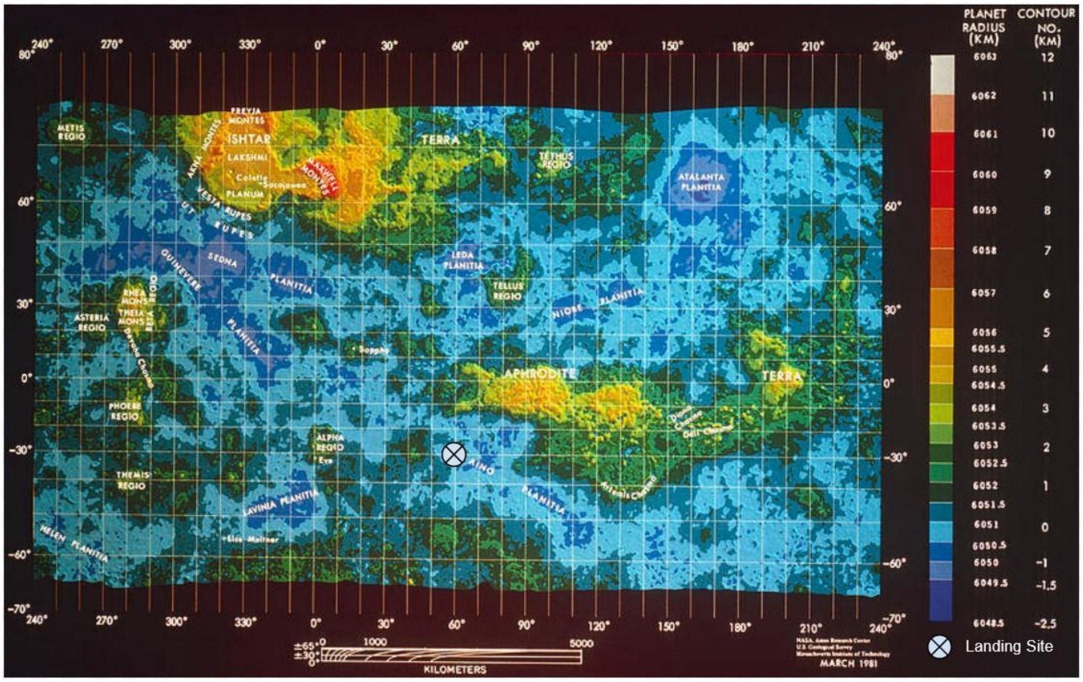


Figure 15: Topography of Venus Including Landing Site [44]

E.4.3 – Communications

E.4.3.1 – Subsystem Overview

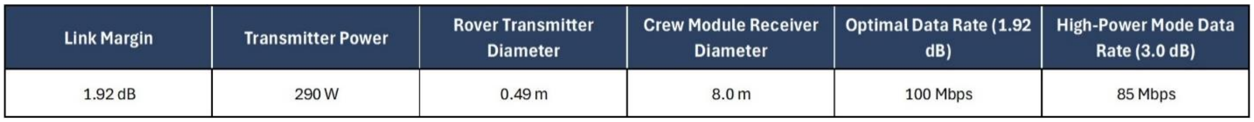
The communications subsystem enables the rover to transmit the collected data to the crew module (uplink) and for the crew to send commands down to the rover (downlink). As previously outlined in the ground control section, the primary obstacle with transferring data from Venus is the presence of an extremely thick atmosphere. Because of this, and since the rover has such limited power, a high gain antenna is necessary to both maximize data rates and minimize transmitter power [2]. Therefore, a center-feed parabolic reflector was chosen for transmitting and receiving data on the rover and crew module.

With such a hostile environment present on the surface of Venus, the communications subsystem also benefits greatly from having a crew in orbit. Having such a crew allows for quick and precise commands to be sent to the rover, enabling the rover to complete tasks significantly faster than if a similar crew was sending commands from Earth. Faster task completion means that the rover will collect more scientific data on average, therefore optimizing the mission as a whole. Furthermore, the rover's safety is markedly improved through this arrangement. In the event of sudden environmental shifts, such as storms or volcanic activities, an orbital crew can respond more rapidly and potentially more effectively than their Earth-based counterparts or fully-autonomous systems, thereby safeguarding the rover from unforeseen hazards.

E.4.3.2 – Uplink (Rover to Crew)

Using the ATSV (trade space visualizer) software to optimize the communications system, the values for transmitter power, transmitter antenna diameter, receiver antenna diameter, and data rate were found for a link margin of 1.92 dB, and are shown in Table 7. Even though a typical link margin for transmitting data is around 3 dB, which provides a margin in case the communication system and/or environment are not completely optimal, 1.92 dB was deemed an acceptable compromise given the external factors. Having a link margin of 1.92 dB still allows for some margin of error, though, meaning that an acceptable data rate and transmitter power can be maintained in the event of additional atmospheric disturbances.

Table 7: Comms Values Obtained from ATSV



Link Margin	Transmitter Power	Rover Transmitter Diameter	Crew Module Receiver Diameter	Optimal Data Rate (1.92 dB)	High-Power Mode Data Rate (3.0 dB)
1.92 dB	290 W	0.49 m	8.0 m	100 Mbps	85 Mbps

Due to structural limits on the rover, the parabolic antenna will have a diameter of 0.49 m. To survive the extreme surface temperatures, the rover antenna will be made of titanium and weigh approximately 9.6 kg (as calculated in Appendix C).

If atmospheric disturbances become too intense, the crew has the option to directly adjust the transmitter power from 290 W to a maximum of 316 W, giving a link margin of 2.3 dB while holding data rates constant at 100 Mbps. Increasing the power to a maximum of 316 W will still allow the rover to be under the allowable power budget of 720 W. If this power increase is still inadequate to achieve minimal data error, the data rates can then be lowered to 85Mbps, resulting in a link margin of 3 dB.

E.4.3.3 – Downlink (Crew to Rover)

Movement of the rover will be determined by three commands, a joystick command (for desired direction), a wheel-power command (for rover speed), and a duration-of-movement command. This will be done by one of the crew members while viewing the video feed transmitted by the rover. An example of this process would be as such: the joystick is moved forward and to the left to set the rover wheels' direction, low power to the wheels is set so that the rover will move slowly, and a two second duration is requested for power delivery to the wheels. Before the movement command is ultimately sent to the rover, the command will be run through a simulation to ensure a desired output is achieved. Due to the simulation step size, the rover may only receive these three commands once or twice per minute. This would mean that 12 Kwords (4 Kwords per command) [2] of data is being sent every 60 seconds, which would translate to a data rate of 3.28 kbps. To achieve the desired link margin of 20 dB for commands, the crew module transmitter power would need to be 0.465 W.

Given the extreme surface conditions on Venus, one of the main reasons for having a crew nearby with direct control over the rover is so that they can react to and make quick decisions in situations where the rover may be in danger. If there is an emergency situation in which the rover needs to move relatively quickly, there may not be enough time to accomplish this with the default simulation step. In this case, the crew would be able to send a maximum of 4 movements per minute (3 commands each) to the rover, therefore increasing the data rate to 13.1 kbps. For this data rate, the crew module transmitter power would need to be boosted to 1.89 W to achieve the desired link margin of 20dB. These values are shown in Table 8.

Table 8: Parameters for Downlink Transmission

Link Margin	Normal Transmitter Power	Emergency Conditions Transmitter Power	Rover Receiver Diameter	Crew Transmitter Diameter	Normal Data Rate	Emergency Conditions Data Rate
20 dB	0.465 W	1.86 W	0.49 m	8.0 m	3.28 kbps	13.1 kbps

F. Mission & Operation Summary

Requirements for the mass and power of the V.I.P.E.R. mission were estimated and broken down by subsystem, as shown in Table 9. The current upper mass limit, governed by the capabilities of the selected Falcon Heavy launch vehicle, has been set at 1250 kg. Additionally, based on the selection of power subsystem components, the maximum allowed power the rover can use at any given time is 720 W. The selection process for the specifications and methods of powering the rover took into heavy considerations each of the subsystems' requirements, and has been updated multiple times to accommodate their power needs. As stated, the current combination of batteries and RTG power give the rover a peak power of 720 W, albeit with a limited duration before the batteries need to be recharged in a lower-power configuration.

Table 9: Mission Mass & Power Breakdown

Rover	Mass (kg)	Power (W)
Structures	417	-----
Chassis and Axles	369	-----
Wheels	48	-----
Scientific Instruments	64.5	130
Imagers	14.6	35
Soil Composition	30.5	25
Atmospheric Composition	13.5	45
Phosphine Detection	5.9	25
Power	126	-----
RTG	56	-----
Batteries	70	-----
Thermal	150	216
Stirling Cooler	150	216
C&DH	5	10
Silicon-Carbide Single Board System	1	9
Hard Disk Drive	4	1
Communications	9.6	290
Antenna	9.6	290
Total	**772.1**	**646**
Allowed	**1250**	**720**

The mass budget can be broken down by subsystem. The majority of the rover's mass goes into the structures subsystem. This is to be expected because it constitutes the entirely of the rover's shell and wheels, and comes out to be 417 kg. The scientific instruments use a total of 64.5 kg across the multitude of their components. The power subsystem uses 126 kg in the form of the radioisotope thermoelectric generator and high-temperature batteries. The thermal subsystem only has one primary component, that being the Stirling cooler, which contributes 150 kg. The C&DH and communications subsystems use the least amount of mass at 5 kg and 9.6 kg, respectively. Ultimately, the total mass sums to be 772.1 kg. This is well-within the requirement of 1250 kg, as defined by the capabilities of the selected launch vehicle.

Like the mass budget, the power budget can also be broken down by each subsystem. The scientific instruments use 130 W across all the components necessary for testing on the Venusian surface. This 130 W will only be required if every instrument is active concurrently; in reality, though, only some of them will be active at any given time. For the majority of the time, none will be active. The power subsystem does not require any power as it is itself the power source. The only component from the thermal subsystem to use power is the Stirling cooler, which requires 216 W. This system needs to be running for the entire mission duration in order to keep the rover interior sufficiently cool. The command and data handling subsystem uses a maximum of 10 W when transmitting. Likewise, the communications subsystem uses a maximum of 290 W. This brings the total maximum power to 646 W, which is safely below the maximum allowable power of 720 W coming from the combination of RTG and batteries.

G. Cost Estimate

The budget for Project V.I.P.E.R. was calculated using NASA's proprietary Project Cost Estimating Capability (PCEC) software. The individual subsystem masses, functional properties, and development requirements, together with the overarching characteristics of the mission such as class, orbit type, and lead organization experience, were combined to generate a fairly realistic model of the costs associated with executing such a mission, as shown in Table 10. These costs are divided amongst ten primary components, those being: Project Management, Systems Engineering, Safety and Mission Assurance, Science/Technology, Payload, Flight System/Spacecraft, Mission Operations System, Launch Vehicle/Services, Ground Data System, and System Integration/Assembly/Test/Check Out. While Education and Public Outreach is also considered a major component of the PCEC, it was deemed to be of negligible concern in the scope of the mission, and has thus been excluded from the budget. Within these components, costs are also further divided into recurring and non-recurring costs, with a few exceptions, in order to differentiate between R&D-related expenditures and those associated with actual production.

As expected, the flight system accounts for a significant portion of the allotted budget, requiring $494.3 million out of the total $963.4 million. This encompasses all facets of the spacecraft itself, including the individual subsystems of the rover (with the exception of the scientific instruments), as well as the bus that will transport them to the surface. The launch vehicle also comprises a notable portion of the budget at approximately $150 million. It should be noted that this value was manually adjusted to better reflect the real-life cost of the Falcon Heavy, as opposed to the price that was generated on a purely mass-based scale. The remaining budget consists of the operational facilities, as well as the costs associated with all research and development efforts over the next 10 years.

Table 10: V.I.P.E.R. Cost Budget

WBS #	Level	Line Item Name/Description	Non-Recurring	Design & Development	System Test Hardware	Flight Unit	Recurring Production	Non-Allocated	Operations	TOTAL
0	**1**	**System Name**	**$ 243.8**	**$ -**	**$ -**	**$ -**	**$ 532.8**	**$ 170.6**	**$ 16.3**	**$ 963.4**
1.0	2	Project Management	**$ 13.2**	$ -	$ -	$ -	**$ 19.5**	**$ -**	**$ -**	**$ 32.8**
2.0	2	Systems Engineering	**$ 21.8**	$ -	$ -	$ -	**$ 36.7**	**$ -**	**$ -**	**$ 58.5**
3.0	2	Safety and Mission Assurance	**$ 5.8**	$ -	$ -	$ -	**$ 15.9**	**$ -**	**$ -**	**$ 21.7**
4.0	2	Science/Technology	**$ -**	$ -	$ -	$ -	**$ -**	**$ 19.7**	**$ -**	**$ 19.7**
5.0	2	Payload(s)	**$ 15.0**	$ -	$ -	$ -	**$ 26.6**	**$ -**	**$ -**	**$ 41.6**
5.01	3	Payload Management	**$ 3.1**	$ -	$ -	$ -	**$ 4.6**	**$ -**	**$ -**	**$ 7.7**
5.02	3	Payload System Engineering	**$ 4.6**	$ -	$ -	$ -	**$ 7.7**	**$ -**	**$ -**	**$ 12.2**
5.03	3	Payload Product Assurance	**$ 0.6**	$ -	$ -	$ -	**$ 1.7**	**$ -**	**$ -**	**$ 2.4**
5.x	3	Payload I&T	**$ 6.7**	$ -	$ -	$ -	**$ 12.6**	**$ -**	**$ -**	**$ 19.3**
6.0	2	Flight System / Spacecraft	**$ 149.3**	$ -	$ -	$ -	**$ 345.0**	**$ -**	**$ -**	**$ 494.3**
6.01	3	Flight System Project Management	**$ 10.8**	$ -	$ -	$ -	**$ 16.0**	**$ -**	**$ -**	**$ 26.8**
6.02	3	Flight System Systems Engineering	**$ 15.4**	$ -	$ -	$ -	**$ 26.0**	**$ -**	**$ -**	**$ 41.4**
6.03	3	Flight System Product Assurance	**$ 4.7**	$ -	$ -	$ -	**$ 12.9**	**$ -**	**$ -**	**$ 17.7**
6.10	3	Spacecraft	**$ 89.9**	$ -	$ -	$ -	**$ 236.6**	**$ -**	**$ -**	**$ 326.6**
--	4	Structures & Mechanisms	**$ 12.0**	$ -	$ -	$ -	**$ 117.1**	**$ -**	**$ -**	**$ 129.2**
--	4	Thermal Control	**$ 5.4**	$ -	$ -	$ -	**$ 37.3**	**$ -**	**$ -**	**$ 42.7**
--	4	Electrical Power & Distribution	**$ 19.1**	$ -	$ -	$ -	**$ 42.1**	**$ -**	**$ -**	**$ 61.1**
--	4	GN&C	**$ 4.0**	$ -	$ -	$ -	**$ 6.5**	**$ -**	**$ -**	**$ 10.5**
--	4	Communications	**$ 9.0**	$ -	$ -	$ -	**$ 14.3**	**$ -**	**$ -**	**$ 23.3**
--	4	C&DH	**$ 38.6**	$ -	$ -	$ -	**$ 7.2**	**$ -**	**$ -**	**$ 45.8**
--	4	Entry, Descent, and Landing	**$ 1.8**	$ -	$ -	$ -	**$ 12.2**	**$ -**	**$ -**	**$ 14.0**
--	5	Parachutes	**$ 1.2**	$ -	$ -	$ -	**$ 3.0**	**$ -**	**$ -**	**$ 4.1**
--	5	Thermal Protection System	**$ 0.7**	$ -	$ -	$ -	**$ 9.2**	**$ -**	**$ -**	**$ 9.9**
6.x	3	Flight System I&T	**$ 28.4**	$ -	$ -	$ -	**$ 53.5**	**$ -**	**$ -**	**$ 81.9**
7.0	2	Mission Operations System (MOS)	**$ 10.0**	$ -	$ -	$ -	**$ 35.0**	**$ -**	**$ 16.3**	**$ 61.3**
--	3	MOS/GDS Development (Phase B-D)	**$ 10.0**	$ -	$ -	$ -	**$ 35.0**	**$ -**	**$ -**	**$ 45.0**
--	3	Mission Ops & Data Analysis (Phase E)	**$ -**	$ -	$ -	$ -	**$ -**	**$ -**	**$ 16.3**	**$ 16.3**
8.0	2	Launch Vehicle/Services	**$ -**	$ -	$ -	$ -	**$ -**	**$ 150.0**	**$ -**	**$ 150.0**
9.0	2	Ground Data System (GDS)	**$ -**	$ -	$ -	$ -	**$ -**	**$ 0.86**	**$ -**	**$ 0.86**
10.0	2	System Integration, Assembly, Test & Check Out	**$ 28.7**	$ -	$ -	$ -	**$ 54.0**	**$ -**	**$ -**	**$ 82.7**
11.0	2	Education & Public Outreach	**$ -**	$ -	$ -	$ -	**$ -**	**$ -**	**$ -**	**$ -**

FY2023, $M

Total	Budget	Margin
$ 963.4	**$ 1,000.0**	**$ 36.6**

The uncertainty margins associated with the mission itself, together with compensation for unexpected problems that may arise during R&D, were modeled via a triangular distribution, varying within a range of $75 million from the nominal value of $963.4 million. The adjusted cost was simulated using 1000 iterations, and the results were subsequently plotted on an S-Curve chart, as shown in Figure 16. Because the total cost calculated via the PCEC functions as the origin of the distribution, the mean naturally lines up very closely with the point estimate. In terms of reserves, neither the 35% or 50% points are visible in the figure, as they are vastly outside the scope of both the graph and the maximum budget of $1 billion specified in the original Request for Proposal. Due to the extremely complex nature of this mission, in which a majority of the physical components and surrounding infrastructure either do not exist yet, or must be significantly modified to be at all practical for the conditions on Venus, it would be nearly impossible to maintain such high margins. However, in the absence of severe complications leading up to the launch in 2034, Team VIPER is confident that the remaining $36.6 million will be enough to account for any developmental uncertainties and unavoidable delays that may occur.

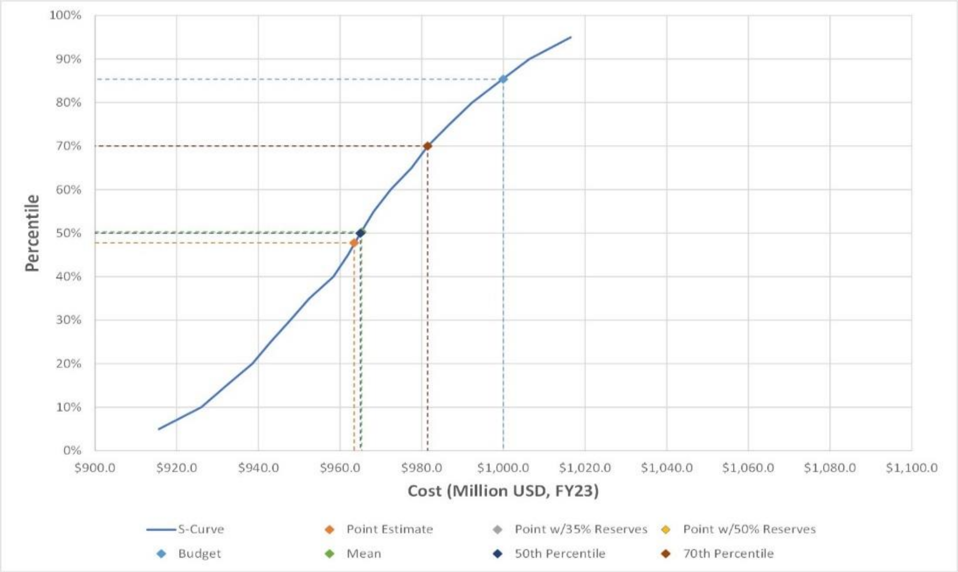


Figure 16: Mission S-Curve Results

H. Mission Schedule

The V.I.P.E.R. mission schedule, as seen in Table 11, outlines the timeframes for component research and development, subsystem and system testing, and mission operations. The main technologies that require significant R&D are the scientific instruments. Some instruments, such as the Venus Descent Rover Imager and Acoustic Wave Sensor, are currently being developed for environments similar to Venus, and are therefore already resistant to extreme temperatures and pressures. Due to their more advanced developments, they are predicted to take approximately two years to reach an appropriate technology readiness level. Other instruments, such as the atmospheric instruments, are in earlier phases of development and require an additional year of development. The detection of phosphine was previously completed by orbiters around Venus using a multispectral spectrometer. Because the operating conditions were so much different than those found on Venus, the TRL for this instrument was placed at a 2 – 3, the lowest of all the instruments. Such a low TRL level resulted in the longest development time of four years. The R&D time for each instrument was determined based on the time required for similar instruments. In addition, the lower TRL threshold of each instrument was selected to add a buffer for the R&D portion of the timeline. Additional information on the TRL of each instrument can be found in Section E.3.2.

The mission operation on Venus can be broken down into much smaller intervals due to the relatively short duration of the proposed mission. An arrival to the Venusian atmosphere on May 28, 2034 was chosen since it correlates to the landing zone being on the light side of Venus. It was determined that it would take approximately one day for descent, landing, and instrument calibration. This would allow for scientific operations to begin on May 29, 2034. Rover operation on Venus will last from approximately May 29, 2034 at midnight to a minimum of June 5, 2034 at midnight. Any scientific operations past that date will be considered additional data, as it is outside the scope of what has been defined as a successful mission.

Table 11: V.I.P.E.R. Mission Development Schedule

Section	Task	Start	End	2024				2025				2026				2027				2028				2029				2030				2031				2032				2033				2034			
				Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	**Instrument Research and Development**																																														
1.1	Venus Descent Rover Imager	1/1/2024	12/31/2025	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																				
1.2	Venus In Situ Surface Imager	1/1/2024	12/31/2026	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																
1.3	Acoustic Wave Sensor	1/1/2024	12/31/2025	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																				
1.4	Venus Tunable Laser Spectrometer	1/1/2024	12/31/2026	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																
1.5	Venus Mass Spectrometer	1/1/2024	12/31/2026	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																
1.6	Venus Atmospheric Structure Investigation	1/1/2024	12/31/2026	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																																
1.7	Multispectral Spectrometer	1/1/2024	12/31/2027	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																												
2	**Instrument Prototyping and Testing**																																														
2.1	Venus Descent Rover Imager	1/1/2026	12/31/2026									🟩	🟩	🟩	🟩																																
2.2	Venus In Situ Surface Imager	1/1/2027	12/31/2027													🟩	🟩	🟩	🟩																												
2.3	Acoustic Wave Sensor	1/1/2026	12/31/2026									🟩	🟩	🟩	🟩																																
2.4	Venus Tunable Laser Spectrometer	1/1/2027	12/31/2027													🟩	🟩	🟩	🟩																												
2.5	Venus Mass Spectrometer	1/1/2027	12/31/2027													🟩	🟩	🟩	🟩																												
2.6	Venus Atmospheric Structure Investigation	1/1/2027	12/31/2027													🟩	🟩	🟩	🟩																												
2.7	Multispectral Spectrometer	1/1/2028	12/31/2028																	🟩	🟩	🟩	🟩																								
3	**System Level Fabrication, Integration, and Testing**																																														
3.1	Component Fabrication	1/1/2029	12/31/2031																					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
3.2	Instument Fabrication	1/1/2029	12/31/2031																					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
3.3	Environmental Testing	1/1/2032	12/31/2033																																	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
4	**Mission Operation**																																														
4.1	Launch	1/1/2034	5/28/2034																																							🟩	🟩		
4.2	Rover Arrival, Startup, and Descent	5/28/2034 0:00:00	5/28/2034 12:00:00																																								🟩		
4.3	Rover Operation on Venus	5/28/2034 12:00:00	6/5/2034 0:00:00																																								🟩		
4.3.1	Power-On / Confirm Stable Communication with Crew	5/28/2034 12:00:00	5/28/2034 12:01:00																																								🟩		
4.3.2	Scientific Instrument Calibration	5/28/2034 12:01:00	5/29/2034 0:00:00																																								🟩		
4.3.3	Scientific Operations - Determination of Soil / Atmospheric Composition	5/29/2034 00:00:00	6/4/2034 23:59:59																																								🟩		
4.3.4	Rover Disposal	6/5/2034	6/5/2034																																								🟩		

I. Conclusion

Team VIPER's solution to the 2023 – 2024 AIAA Student Spacecraft Design Competition employs a surface rover in conjunction with an orbiting crew module to efficiently collect a large, robust quantity of scientific data on the Venusian surface. With a near-instantaneous communication delay of 0.357 seconds, the crew module is able to avoid issues and respond to items of interest under circumstances an autonomous rover may not be prepared to handle. Without the presence of such a crew module, the mission would not be able to collect nearly as much useful data, both due to the communication distance between Earth and Venus, as well as the limited capabilities of the current command and data handling system to accommodate autonomous processing functions.

An in-depth orbital analysis was conducted to prove that a Hohmann transfer can adequately transport a payload with the mass and size specifications of the V.I.P.E.R. mission to Venus, as well as to determine the Lyapunov orbit required for the crew module to be in constant communication with the rover. Facilitated by recent advances in spacecraft climate modeling and analysis technologies, scientific instruments will be specially designed for survival on the Venusian surface, and will be optimized to collect as much scientific data as possible given the limited mission duration. The use of a specialized Ti-6Al-4V titanium alloy for the shell of the rover, together with the implementation of a coupled RTG/Stirling cooler system to power and cool the scientific instruments, enables V.I.P.E.R. to operate for at least seven days in the midst of extreme pressures and temperatures.

Careful selection of technology readiness levels and analysis of typical research and development timelines show that this mission will theoretically be able to launch by January 2034, with a total cost of $963.4 million out of an allotted $1 billion, as determined via the use of a detailed cost estimating model. With Project V.I.P.E.R., Venus will finally be able to be studied as a full system, and valuable information about the climate and atmosphere on the Venusian surface will ultimately allow researchers to better understand the long term effects of greenhouse gases for potential use with various Earth-based applications.

Appendix A – Complete Mission Requirements Definition

Most of the mission level requirements were developed by information taken directly from the RFP [1]. These include the general timeline of the mission and the requirement that a crew in orbit will need to be utilized. An additional requirement, Mis 7.0, was generated to account for the duration of the mission before arriving at Venus, while Mis 8.0 was added to account for the communication between the rover and the ground system whilst in transit. The system level requirements stemmed from the mission level requirements, but avoid going directly to a component level. These system level requirements can be broken into two main categories: the characteristics for the scientific part of the mission, and the rover's mass, size, and power budgets. With the system level requirements in mind, the subsystem requirements could then be created.

Significant research had to be conducted for each of the subsystems before the development of their respective requirements. The initial subsystem-level requirements focused entirely on the scientific instruments, as they constitute the entire purpose of the mission. After defining those requirements, the power, thermal, structures, and C&DH subsystems could begin to form their requirements around what was outlined by the scientific instrument and system level requirements. Some of the remaining subsystems, mainly launch vehicles and ground systems, were then able to start generating requirements with minimal dependence on the prior subsystems, based more on the higher-level requirements. All remaining subsystems were then able to be developed based on the needs of the already present subsystems. As further research was done, better estimates were able to be made for each of the quantitative requirements. There are several inter-subsystem interactions that need to be considered while creating the requirements, the most important of which are thermal, power, and structures. Because of the extreme environment on the Venusian surface, being able to keep the rover powered for the duration of the mission while simultaneously allowing all subsystems to operate fully is the most prominent challenge. As a result, those subsystems in particular have to interact directly with almost all others to determine their individual needs and adequately accommodate them. In addition, any and all communication-based subsystems, namely command & data handling, communications, and ground control, all work closely together and thus have many requirements that directly depend on one other.

Req Name	Parent Req	Traceability	Requirement	Rationale	Relevant Subsystem
Mis 1.0	N/A	Mis 1.0	The cost for the mission, including development, hardware, and operation shall be less than $1 billion	This requirement is driven by the RFP	All
Mis 2.0	N/A	Mis 2.0	The mission shall launch no later than December 31, 2037	This requirement is driven by the RFP	LV, GNC
Mis 3.0	N/A	Mis 3.0	The mission shall complete all scientific operations by December 31, 2039	This requirement is driven by the RFP	All
Mis 4.0	N/A	Mis 4.0	The rover shall survive on the surface of Venus for at least 7 days	This requirement is driven by the RFP. A mission length of 7 days was chosen due to power constraints	Pow, Str, T, LV
Mis 5.0	N/A	Mis 5.0	The rover shall complete all scientific operations within 30 days of being on the surface of Venus	This requirement is driven by the RFP	Pow, Str, T, CDH, PSI
Mis 6.0	N/A	Mis 6.0	The rover shall maximize the scientific outputs throughout the duration of the mission while controlled by a crew in orbit	This requirement is driven by the RFP	PSI, Com, CDH
Mis 7.0	N/A	Mis 7.0	The launch vehicle and bus shall enable the rover to survive during transfer from Earth to Venus	The rover must be delivered safely to Venus with full operationability. The rover must also be able to send telemetry data so the health of the rover can be monitored while in transit.	Com, CDH
Mis 8.0	N/A	Mis 8.0	The rover shall be able to communicate while in transfer to Venus	The rover can't lose any functionality while in transfer to Venus and must send back telemetry data so the rover's health can be monitored	All
Sys 1.0	Mis 6.0	Mis 6.0 - Sys 1.0	The rover shall collect atmospheric data, including pressure, temperature, and composition	This requirement is driven by the need for robust scientific data	PSI
Sys 2.0	Mis 6.0	Mis 6.0 - Sys 2.0	The rover shall collect soil and rocky surface chemical composition data	This requirement is driven by the need for robust scientific data	PSI
Sys 3.0	Mis 6.0	Mis 6.0 - Sys 3.0	The rover shall collect images of the Venus surface	This requirement is driven by the need for robust scientific data	PSI
Sys 4.0	Mis 6.0	Mis 6.0 - Sys 4.0	The rover shall attempt to detect the presence to phosphine in the Venus atmosphere	Using radar, phosphine could be discovered that could indicate potential signs of life	PSI
Sys 5.0	Mis 1.0	Mis 1.0 - Sys 5.0	The rover and bus shall weigh less than 6000 kg and more than 500 kg	The rover must be heavy enough to be able to reach the surface of Venus but also needs to be minimized to reduce launch, power, and fuel costs	Str
Sys 6.0	Mis 2.0	Mis 2.0 - Sys 6.0	The rover and bus shall fit within a 50 m^2 fairing	The rover must fit within the launch vehicle	Str
Sys 7.0	Mis 4.0	Mis 4.0 - Sys 7.0	The rover shall have approximately 720 Watts of power to ensure consistent explorability and usage of scientific instruments, data handling, and communication systems	The crew must have enough power for the entire duration of the mission	Pow
Sys 8.0	Mis 6.0	Mis 6.0 - Sys 8.0	The rover shall have a minimum interior volume of 1.5m x 1.0m x 1.5m	The rover needs to be able to hold all scientific instruments, power, communication, and electronics without worry of interference between the subsystems	Str, Pow, PSI, CDH, T
T 1.0	Mis 4.0	Mis 4.0 - T 1.0	The rover shall withstand Venus surface temperature conditions as high as 464°C	The rover must withstand extreme conditions to carry out the scientific mission	T
T 2.0	Mis 4.0	Mis 4.0 - T 2.0	The thermal system shall be integrated within the structural system	The thermal system needs to be placed strategically and soundly	Str
T 3.0	Mis 6.0	Mis 6.0 - T 3.0	The scientific instruments shall be kept at or below 500°C	The rover must withstand extreme conditions to carry out the scientific mission. Because the power system will produce heat and the extreme ambient temperatures, the interior of the rover will still be at extreme temperatures	T, Str, PSI
T 4.0	Mis 4.0	Mis 4.0 - T 4.0	The power source shall be stored in compartment with an internal temperature of under 800°C	The rover must maximize its efficiency to collect all scientific data within its time spent on Venus and withstand the extreme conditions of Venus	T, Str, Pow
T 5.0	Mis 8.0	Mis 8.0 - T 1.0	The power source shall be stored in compartment with an internal temperature of under 500°C	This requirement is driven by the RFP	LV, T, Str
PSI 1.0	Sys 1.0	Mis 6.0 - Sys 1.0 - PSI 1.0	The rover shall collect atmospheric data using spectrometry	Spectrometers and spectrographs were used in past missions to find atmospheric data	N/A
PSI 2.0	Sys 2.0	Mis 6.0 - Sys 2.0 - PSI 2.0	The rover shall analyze the composition of the surface of Venus	To learn more about the composition and history of Venus, the surface has to be analyzed	N/A
PSI 3.0	Sys 3.0	Mis 6.0 - Sys 3.0 - PSI 3.0	The rover shall be able to take video with resolution of at least 480×640	Good imaging is needed for crew operation and scientific mission	N/A
PSI 4.0	Sys 4.0	Mis 6.0 - Sys 4.0 - PSI 4.0	The rover shall try to detect and analyze phosphine in the Venus atmosphere	The James Clerk Maxwell Telescope has recently detected phosphine on Venus using this instrument	N/A
PSI 5.0	Mis 1.0	Mis 1.0 - PSI 5.0	The total cost of all scientific instruments, including research and development, shall stay below $25 million	The mission must stay within the budget while allowing funding for other subsystems. In addition, there are no proven technologies for Venus's surface so significant research will need to be conducted for each instrument	N/A
PSI 6.0	Sys 8.0	Mis 6.0 - Sys 8.0 - PSI 6.0	All scientific instruments shall be able to be used without exposure to the Venus atmosphere	The Venus atmosphere would cause significant damage to the scientific instruments	PSI
PSI 7.0	Sys 3.0	Mis 6.0 - Sys 3.0 - PSI 7.0	The rover shall be able to take images with a resolution of at least 480x640	The rover will have a separate imager dedicated for imaging rather than video for the crew	N/A
CDH 1.0	Mis 7.0	Mis 7.0 - CDH 1.0	The rover shall be able to receive commands from the crew with a latency of less than 10 seconds	Communication must be minimally delayed as so the crew can control the rover accurately	Com
CDH 2.0	Mis 7.0	Mis 7.0 - CDH 2.0	The rover shall be able to send data to the crew at a rate of at least 10 MB/s	The rate of transmission must be able to approach the rate of science data collection in order to minimize onboard storage requirements	Com
CDH 3.0	Mis 8.0	Mis 8.0 - CDH 3.0	The commands sent to and from the rover shall be verified before being implemented	All data must be verified to reduce errors on the rover	Com
CDH 4.0	Mis 4.0	Mis 4.0 - CDH 4.0	All subsystems shall have the ability to exchange data autonomously of human input	The rover must have some level of autonomous function in the event of communication loss	Com
CDH 5.0	Mis 4.0	Mis 4.0 - CDH 5.0	The crew shall have the ability to remotely monitor the rover's health	The crew must monitor the rover's health as to ensure the safety and full function of the rover	Com

Req Name	Parent Req	Traceability	Requirement	Rationale	Relevant Subsystem
Pow 1.0	Mis 4.0	Mis 4.0 - Pow 1.0	The power system shall withstand 464°C	The power system must function in the Venus atmosphere	T
Pow 2.0	Mis 8.0	Mis 8.0 - Pow 2.0	The power system shall function while in its transfer from Earth to Venus	The bus might need to make adjustments to its orbit between Earth and Venus	LV, T
Pow 3.0	Mis 4.0	Mis 4.0 - Pow 3.0	The rover shall have a power reserve in case of malfunction	A backup power system is needed in case of primary power failure	N/A
Pow 4.0	Sys 7.0	Mis 4.0 - Sys 7.0 - Pow 4.0	The power system shall supply at least 100 W of power to the rover	The rover must need to have enough power in order to properly function	N/A
Pow 5.0	Mis 6.0	Mis 6.0 - Pow 5.0	The power system shall function at full operability during all periods of the day while on Venus	To ensure maximum scientific output, the rover must function at all times	N/A
Str 1.0	Mis 4.0	Mis 4.0 - Str 1.0	The material chosen for the exterior of the rover shall be able to withstand 464°C temperature and 92 Bar	The rover must be able to operate under the surface conditions of Venus	T
Str 2.0	Mis 6.0	Mis 6.0 - Str 2.0	The interior of the rover shall be completely sealed off from the outside environment	The Venus atmosphere would cause significant damage to all components within the rover, especially the scientific instruments	T
Str 3.0	Mis 6.0	Mis 6.0 - Str 3.0	The rover shall be able to transverse the Venus surface at a maximum speed of 0.18 km/h	The rover needs to travel into minimally explored terrain, meaning it needs to go fast enough to explore large areas but not too fast to minimize any potential accidents	N/A
Str 4.0	Mis 8.0	Mis 8.0 - Str 4.0	The bus of the rover shall be able to withstand temperatures of 550 K while transferring from Earth to Venus	The bus needs to survive the vacuum of space while transferring from Earth to Venus	T
Str 5.0	Mis 8.0	Mis 8.0 - Str 5.0	The bus shall have the ability to protect from vibrations and radiation while in space	The bus must protect the rover during transfer to ensure that the rover is fully operational while on Venus	LV
LV 1.0	Mis 2.0	Mis 2.0 - LV 1.0	The launch vehicle shall have a history of success	The launch vehicle must be reliable as to ensure a reliable delivery to the transfer orbit	N/A
LV 2.0	Mis 1.0	Mis 1.0 - LV 2.0	The launch vehicle shall cost less than $200 million	The launch vehicle must be within the given budget	N/A
LV 3.0	Sys 5.0	Mis 1.0 - Sys 5.0 - LV 3.0	The launch vehicle shall be able to deliver at least 2000 to Venus orbit	The launch vehicle must be able to deliver the weight of the rover to the proper altitude	Str
LV 4.0	Sys 6.0	Mis 2.0 - Sys 6.0 - LV 4.0	The launch vehicle shall have a payload volume of at least 150 m^3	The launch vehicle must be able to house the size of the rover	Str
LV 5.0	Mis 4.0	Mis 4.0 - LV 5.0	The launch vehicle shall produce loads under 8 g	The launch vehicle must not cause any damage to the rover during launch	Str
GNC 1.0	Mis 6.0	Mis 6.0 - GNC 1.0	The orbit of the crew shall result in at least 70% of time being overtop of the Rover	A highly eccentric orbit will allow for minimal blackout periods for the crew and rover	Com
GNC 2.0	Mis 4.0	Mis 4.0 - GNC 2.0	The rover shall enter Venus's atmosphere at less than -20.5 and -22.5 degrees and 11 km/s	Only certain atmosphere entry angles and speeds result in acceptable thermal loads to the vehicle	Str, Prop
GNC 3.0	Mis 3.0	Mis 3.0 - GNC 3.0	The bus shall be able to adjust its trajectory while in its transfer orbit	Must be able to correct for error	Prop
GNC 4.0	Mis 4.0	Mis 4.0 - GNC 4.0	The orientation of the bus shall point toward Venus and rotate at least 1 rph angular velocity	To ensure an entry that doesn't damage the rover	Prop
GNC 5.0	Mis 4.0	Mis 4.0 - GNC 5.0	The speed of impact with Venus shall be no greater than 2 mph	Must land at a speed acceptable to structures team	Prop
Prop 1.0	GNC 3.0	Mis 3.0 - GNC 3.0 - Prop 1.0	The thrusters shall be able to adjust the orbit of the bus while in orbit	Electronics and other components can be damaged by the sun and cosmic radiation	GNC
Prop 2.0	GNC 5.0	Mis 4.0 - GNC 5.0 - Prop 2.0	The parachute shall be able to slow the descent of the rover onto the surface at a speed of 1 m/s	The velocity of the descent is slow enough so that no damage is sustained to the rover	GNC
Prop 3.0	Sys 7.0	Mis 4.0 - Sys 7.0 - Prop 3.0	The parachutes shall use less than 20 W of power to deploy	Parachute deployment based on pressure reading during decent. Little power will be needed to deploy.	Pow
Prop 4.0	Mis 1.0	Mis 1.0 - Prop 4.0	The parachutes shall cost less than $3.6 million	Cost estimation from NASA PCEC	N/A
Prop 5.0	Mis 2.0	Mis 2.0 - Prop 5.0	Launch vehicle shall be able to generate enough lift to exit Earth's orbit	Launch vehicle must be able to leave Earth's orbit	GNC, LV
Com 1.0	Mis 6.0	Mis 6.0 - Com 1.0	The crew shall be able to communicate with the ground control for 14-16 hours everday	The crew must be able to send back processed data to and receive information from Earth	GC
Com 2.0	Mis 6.0	Mis 6.0 - Com 2.0	The rover shall be in constant communication with the crew	To ensure maximum scientific output, the rover must function at all times	N/A
Com 3.0	Mis 6.0	Mis 6.0 - Com 3.0	The time delay between the crew and rover shall be less than 60 seconds	To ensure maximum scientific output, the rover must function at all times	N/A
Com 4.0	Sys 7.0	Mis 4.0 - Sys 7.0 - Com 4.0	The communication system on the rover shall use less than 316 Watts of power	The communication system needs to be strong enough to reach back to the crew but needs to still minimized to ensure a small power supply	Pow
Com 5.0	CDH 5.0	Mis 4.0 - CDH 5.0 - Com 5.0	The rover shall transmit telemetry at a rate of 85-100 Mbps under normal operating conditions	The health of every component of the rover needs to be monitored while in operation	N/A
GC 1.0	Com 1.0	Mis 6.0 - Com 1.0 - GC 1.0	The crew shall have communication between the SOCC, POCC, and MOCC	To be able to save computational space, the crew may send processed data back to Earth. The crew also needs to be in contact with Earth to receive any commands or information	Com
GC 2.0	Mis 3.0	Mis 6.0 - Com 1.0 - GC 2.0	The rover and crew module will utilize the X-band for regular communication	The crew will need to receive data from the rover to reduce the need for DTE communication from the rover	Com
GC 3.0	Mis 3.0	Mis 3.0 - GC 3.0	The ground control shall maintain synchronization of time between the crew, payload, and ground	Proper synchronization is needed to ensure the success of the mission	Com
GC 4.0	Com 1.0	Mis 6.0 - Com 1.0 - GC 4.0	The mission will use the X-band, with a frequency of 10 GHz, for communication between the DSN, rover, spacecraft, and crew module.	Establish a connection with the DSN for interplanetary communication	Com
GC 5.0	Mis 3.0	Mis 3.0 - GC 5.0	The DSN will communicate for 2 hours each day during the spacecrafts journey to Venus. The MOC, POCC, and SOCC will communicate for 14-18 hours with the crew and rover each day.	Must section off time slots due to other missions using the same locations	Com

Appendix B – Orbital Analysis

Orbital analysis was performed by Team VIPER to determine how the rover would reach Venus. The main purpose of the analysis was to obtain results accurate enough to design the rover around. The following assumptions were made: the Earth and Venus orbit the Sun in circular orbits, their orbits are in the same plane, only one body's gravitational influence must be accounted for at any time (i.e. linked conics), and the rover starts in a circular parking orbit around with Earth with a radius of 20,000 km. The mass and distance properties of the system are shown in Table 12.

Table 12: Sun, Earth, & Venus System Parameters

Body	Mass (kg)	μ of System (km^3 / s^2)	Distance from Sun (km)	Body Radius (km)
Sun	$1.99 \bullet 10^{30}$	$1.33 \bullet 10^{11}$	--------	--------
Earth	$5.97 \bullet 10^{24}$	$3.99 \bullet 10^{5}$	$1.50 \bullet 10^{8}$	6378.0
Venus	$4.87 \bullet 10^{24}$	$3.25 \bullet 10^{5}$	$1.08 \bullet 10^{8}$	6052.0

First, the Sun-centered Hohmann transfer trajectory is found. The transfer orbit must have an apoapsis distance of $1.50 \bullet 10^{8}$ km (Earth departure) and a periapsis distance of $1.08 \bullet 10^{8}$ km (Venus arrival). This transfer is shown in the Sun-centered conic plot of Figure 17. The semi-major axis of the orbit is given by the equation,

$$a_{Hohmann} = \frac{1}{2}(r_a + r_p) \tag{3}$$

and is equal to $1.29 \bullet 10^{8}$ km. The energy of the transfer orbit can then be determined using an equation of the form,

$$\varepsilon_{Hohmann} = -\frac{\mu_S}{2a_{Hohmann}} \tag{4}$$

where μ_s is the gravitational parameter of the sun, and results in a value of -515 kJ/kg. The required velocity at Earth departure, or apoapsis of the transfer orbit, can be derived from the Vis-Viva relation, given by,

$$v_{a,Earth} = \sqrt{\mu_S\left(\frac{2}{r_a} - \frac{1}{a_{Hohmann}}\right)} \tag{5}$$

and yields a velocity of 27.25 km/s. This value must be compared to the velocity of the Earth in the Sun-centered frame at this point, which can be found by noting that, in this case, both the radius and semi-major axis are equal to the distance between the Earth and Sun (under the previous assumption of a circular orbit). Substituting a_{Earth} into Equation (5) for r_a and $a_{Hohmann}$ gives a velocity v_{Earth} = 29.78 km/s.

Given $\Delta v_E = v_{Earth} - v_{a,Earth}$ = 2.53 km/s, the rover must therefore leave the Earth's sphere of influence moving at 2.53 km/s relative to the Earth in the direction opposing Earth's motion. With this information, the Earth linked conic problem can be solved. To determine the energy of the departing rover in the Earth centered frame, an equation of the form,

$$\varepsilon_{hyper} = \frac{(\Delta v_E)^2}{2} - \frac{\mu_E}{\infty} \tag{6}$$

where μ_E is the gravitational parameter of the Earth, can be used, and results in a departure energy of 3.20 kJ/kg. The distance value is approximated as ∞ in order for the rover to escape the Earth on a hyperbolic trajectory. This trajectory is shown in the Earth linked conic plot of Figure 17. As stated in the initial assumptions, it is assumed that the rover has previously been placed into a circular parking orbit with a radius of 20,000 km. The semi-major axis of the departing rover can thus be found with the equation,

$$a_{hyper,E} = -\frac{\mu_E}{2\varepsilon} \tag{7}$$

and is equal to -1.24 • 10^5 km. The velocity of the rover before the burn, as well as the hyperbolic velocity after the burn, is calculated using a form of Equation (5) given by,

$$v_{a,i} = \sqrt{\mu_S\left(\frac{2}{r_p} - \frac{1}{a_i}\right)} \tag{8}$$

where r_p = 20,000 km for both cases. For the velocity prior to burn, the rover is still in its circular parking orbit, so a_1 = 20,000 km and the resultant velocity $v_{a,1}$ = 4.47 km/s. After the burn, the semi-major axis $a_2 = a_{hyper}$, which results in a velocity $v_{a,2}$ = 6.57 km/s. Thus, given $\Delta v_{req} = v_{a,2} - v_{a,1}$, the amount of Δv required to escape Earth's sphere of influence on a trajectory for Venus is 2.10 km/s.

Finally, the rover velocity at Venus arrival must be calculated. The rover's velocity in the Sun-centered frame when it intersects with Venus is given by the equation,

$$v_{p,Venus} = \sqrt{\mu_S\left(\frac{2}{a_{Venus}} - \frac{1}{a_{Hohmann}}\right)} \tag{9}$$

while the velocity of Venus itself in the sun-centered frame is the case where both values of semi-major axis are equal to a_{Venus}. This results in velocities $v_{p,Venus}$ = 37.84 km/s and v_V = 35.09 km/s for the arriving rover and Venus, respectively. Therefore, the rover will enter Venus's sphere of influence at relative velocity δv_V = 2.75 km/s.

Making use of Equations (6) and (7), and replacing the Earth-based parameters with the Venus-based δv_V and μ_V, the energy of the incoming hyperbolic orbit and subsequent semi-major axis are found to be 3.77 kJ/kg and -4.30 • 10^4 km, respectively. These values ultimately allow the velocity of the rover when it enters the Venusian atmosphere to be calculated, which is a critical aspect of the landing sequence. The atmospheric entrance velocity is given by,

$$v_{entry,V} = \sqrt{\mu_V \frac{2}{r_V} - \frac{1}{a_{hyper,V}}} \tag{10}$$

where r_V is the radius of Venus, representing the radial distance of the rover when it passes through the upper atmosphere, and is calculated to be 10.72 km/s. The hyperbolic trajectory on Venus approach is also shown in Figure 17.

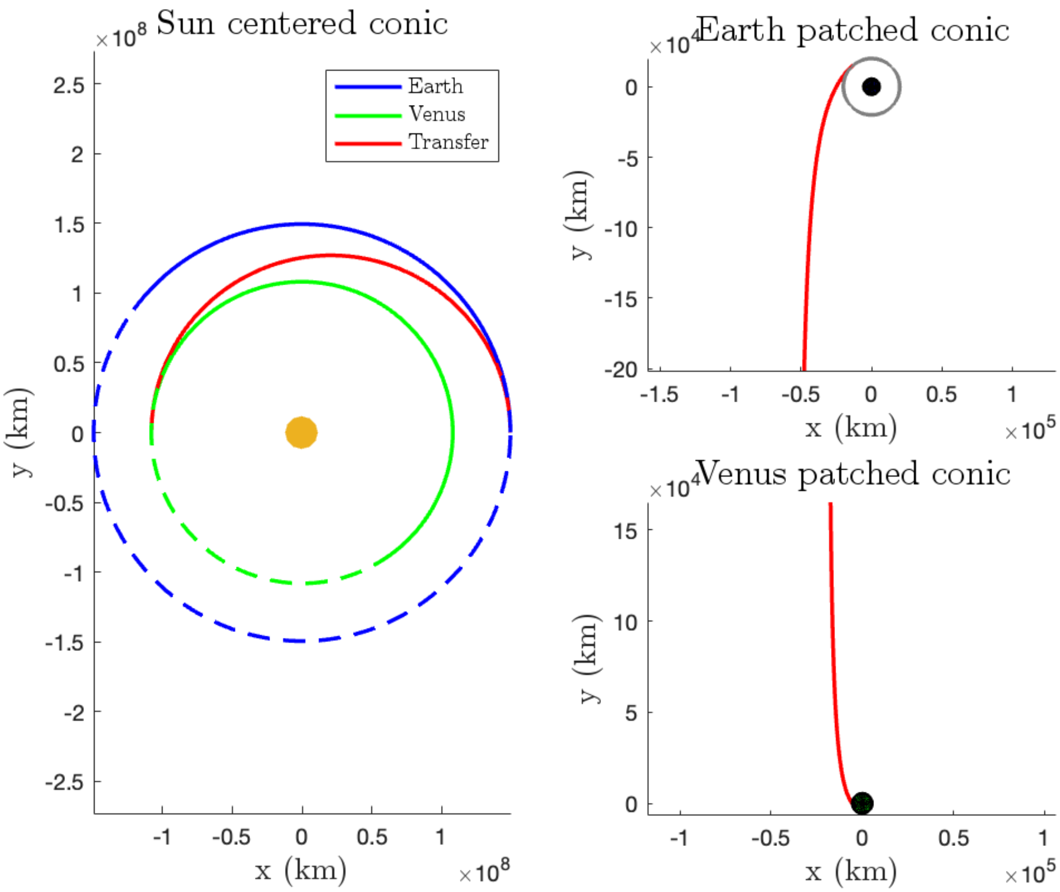


Figure 17: Linked Conic Section & Orbital Transfer Diagram

Appendix C – Communications Antenna Mass Calculation

Given that the average masses of a 2-foot and 3-foot aluminum parabolic antenna are 6.5 kg and 8.5 kg, respectively [45], and assuming that each antenna is made entirely out of aluminum, it is possible to calculate the volume of aluminum that is used for each antenna. These volumes, found by dividing the mass of the antenna by the density of aluminum, which is equal to 2710 kg/m^3, were determined to be $V_{2\text{-ft}}$ = 0.003952 m^3 and $V_{3\text{-ft}}$ = 0.003137 m^3. Using these values, it is then possible to establish a linear relationship between the antenna diameter and volume to estimate the volume of an antenna with an arbitrary diameter. This linear relationship is derived through the point-slope formula,

$$V - V_1 = m(D - D_1) \tag{11}$$

where

$$m = \frac{V_2 - V_1}{D_2 - D_1} \tag{12}$$

and V_1 and D_1 are the volume and diameter of the smaller 2-foot antenna, respectively. V_2 and D_2 are therefore the volume and diameter of the larger 3-foot antenna, and plugging all known values into Equation (11), the linear relationship now becomes,

$$V = 0.0024D + 0.00094 \tag{13}$$

The V.I.P.E.R. mission makes use of a titanium parabolic antenna, with a diameter of 0.49 m being required to satisfy the mission communications parameters. Substituting this value into Equation (13) yields a required volume of 0.002118 m^3, and given that the density of titanium is 4540 kg/m^3, the estimated mass of the antenna is approximately 9.616 kg.

References

[1] AIAA, "2023-2024 AIAA Undergraduate Team Space Design Competition," AIAA, 2023. [Online]. Available: https://www.aiaa.org/docs/default-source/uploadedfiles/membership-and-communities/university-students/design-competitions/2023-24-aiaa-space-system-design-competition_human-enabled-venus-robotic-exploration.pdf?sfvrsn=aee1eefd_0. [Accessed 21 January 2024].

[2] J. Wertz and W. Larson, Space Mission Analysis and Design, El Segundo, CA, CA: Microcosm Press, 1999.

[3] "Cosmic Train Schedule," [Online]. Available: http://www.clowder.net/hop/railroad/EV.htm. [Accessed 31 March 2024].

[4] D. R. Williams, "Pioneer Venus Project Information," NASA, 10 December 2018. [Online]. Available: https://nssdc.gsfc.nasa.gov/planetary/pioneer_venus.html. [Accessed 27 March 2024].

[5] J. Walker, "Deep Space Network," NASA, 21 March 2024. [Online]. Available: https://www.nasa.gov/communicating-with-missions/dsn/#:~:text=The%20Deep%20Space%20Network%E2%80%94or%20DSN%E2%80%94is%20NASA%E2%80%99s%20international%20array,of%20the%20solar%20system%20and%20the%20larger%20universe.. [Accessed 2 April 2024].

[6] D. Bolles, "Venus Facts," NASA, 2024. [Online]. Available: https://science.nasa.gov/venus/venus-facts/. [Accessed 27 March 2024].

[7] SpaceX, "Falcon User's Guide," September 2021. [Online]. Available: https://www.spacex.com/media/falcon-users-guide-2021-09.pdf. [Accessed 29 November 2023].

[8] United Launch Alliance (ULA), "Atlas V Launch Services User's Guide," March 2010. [Online]. Available: https://www.ulalaunch.com/docs/default-source/rockets/atlasvusersguide2010a.pdf?sfvrsn=f84bb59e_2. [Accessed 1 December 2023].

[9] United Launch Alliance (ULA), "Delta IV Launch Services User's Guide," June 2013. [Online]. Available: https://www.ulalaunch.com/docs/default-source/rockets/delta-iv-user's-guide.pdf. [Accessed 30 November 2023].

[10] J. Davis, "Preview: Succeed or fail, SpaceX's Falcon Heavy Test Sure to be a Blast," The Planetary Society, 1 February 2018. [Online]. Available:

https://www.planetary.org/articles/20180201-falcon-heavy-demo-preview. [Accessed 1 December 2023].

[11] G. Landis, R. Dyson, S. Oleson, J. Warner, A. Colozza and P. Schmitz, "Venus Rover Design Study," in *AIAA SPACE 2011 Conference & Exposition*, Long Beach, CA, USA, 2011.

[12] "Starship," SpaceX, 2023. [Online]. Available: https://www.spacex.com/vehicles/starship/. [Accessed 29 November 2023].

[13] "Vulcan," United Launch Services (ULA), 2023. [Online]. Available: https://www.ulalaunch.com/rockets/vulcan-centaur. [Accessed 1 December 2023].

[14] D. Lukco, D. J. Spry, P. G. Neudeck, L. M. Nakley, K. G. Phillips, R. S. Okojie and G. W. Hunter, "Experimental Study of Structural Materials for Prolonged Venus Surface Exploration Missions," *Journal of Spacecraft and Rockets,* vol. 57, no. 6, 2020.

[15] M. V. Keldysh, "Venus Exploration with the Venera 9 and Venera 10 Spacecraft," *Icarus,* vol. 30, no. 4, pp. 605-625, 1977.

[16] Rayotek, "High Temepature Sight Glass Windows," Rayotek, 2023. [Online]. Available: https://rayoteksightwindows.com/products/high-temp-sight-glass-windows.html. [Accessed 15 February 2024].

[17] "Introduction and Characteristics of Sapphire Glass," Hyperion Optics, [Online]. Available: https://www.hypoptics.com/introduction-and-characteristics-of-sapphire-glass.html. [Accessed 10 April 2024].

[18] M. Gilmore, "Seeing Venus Tessera Terrain with the Vendi Camera on DaVinci," in *Geological Society of America - Connects 2021*, Portland, OR, USA, 2021.

[19] J. Balcerski, "Venus In Situ Surface Imager (VISSI)," 2023. [Online]. Available: https://www1.grc.nasa.gov/wp-content/uploads/18-PICASO18_2-0033_Balcerski.pdf. [Accessed 20 February 2024].

[20] G. Pei, M. B, J. Luo and J. Deng, "High Temperature Surface Acoustic Wave Sensor with Strain Isolation Structure," in *21st International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers)*, Orlando, FL, USA, 2021.

[21] "DAVINCI Mission," NASA, [Online]. Available: https://ssed.gsfc.nasa.gov/davinci/mission. [Accessed 26 November 2023].

[22] J. Greaves, A. Richards, W. Bains, P. Rimmer and H. Sagawa, "Phosphine Gas in the Cloud Decks of Venus," *Nature Astronomy,* vol. 5, no. 7, pp. 655-664, 2020.

[23] D. Nevejans, E. Neefs, E. Van Ransbeeck, S. Berkenbosch and R. Clairquin, "Compact High-Resolution Spaceborne Echelle Grating Spectrometer with Acousto-Optical Tunable Filter Based Order Sorting for the Infrared Domain from 22 to 43 µm," *Applied Optics,* vol. 45, no. 21, p. 5191, 2006.

[24] E. Brandon, "Power Beaming for Long Life Venus Surface Missions," NASA, 10 April 2019. [Online]. Available: https://www.nasa.gov/general/power-beaming-for-long-life-venus-surface-missions/. [Accessed 28 March 2024].

[25] G. A. Landis, "Power Systems for Venus Surface Missions: A Review," *Acta Astronautica,* vol. 187, pp. 492-497, 2021.

[26] C. D. Barklay, "The History of the Invention of Radioisotope Thermoelectric Generators (RTGs) for Space Exploration," *The Technology of Discovery: Radioisotope Thermoelectric Generators and Thermoelectric Technologies for Space Exploration,* 17 February 2023.

[27] C. B. Vining and G. L. Bennett, "Power for Science and Exploration: Upgrading the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG)," in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Nashville, TN, USA, 2010.

[28] F. Odoi-Yorke, R. Opoku, F. Davis and G. Yaw Obeng, "Optimisation of Thermal Energy Storage Systems Incorporated with Phase Change Materials for Sustainable Energy Supply: A Systematic Review," *Energy Reports,* vol. 10, pp. 2496-2512, 2023.

[29] A. Lowry, "High Energy, Long Cycle Life, and Extreme Temperature Lithium-Sulfur Battery for Venus Missions," NASA, [Online]. Available: https://techport.nasa.gov/view/92914. [Accessed 3 April 2024].

[30] D. E. Glass, J. Jones, A. V. Shevade, D. Bhakta, E. Raub, R. Sim and R. V. Bugga, "High Temperature Primary Battery for Venus Surface Missions," *Journal of Power Sources,* vol. 449, 2020.

[31] C. G. Manning, "Technology Readiness Levels," NASA, 27 September 2023. [Online]. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/. [Accessed 22 February 2024].

[32] D. Salazar, G. A. Landis and A. J. Colozza, "Non-Cooled Power System for Venus Lander," in *AIAA Propulsion and Energy Forum*, Cleveland, OH, USA, 2014.

[33] C. Sagan, "SAO/NASA Astrophysics Data System (ADS)," *Astronomical Journal,* vol. 65, pp. 352-353, 1960.

[34] H. Kim, J. Bagherzadeh and R. G. Dreslinski, "SiC Processors for Extreme High-Temperature Venus Surface Exploration," in *2022 Design, Automation & Test in Europe Conference & Exhibition*, Antwerp, Belgium, 2022.

[35] P. G. Neudeck, R. D. Meredith, L. Chen, D. J. Spry, L. M. Nakley and G. W. Hunter, "Prolonged Silicon Carbide Integrated Circuit Operation in Venus Surface Atmospheric Conditions," *AIP Advances,* vol. 6, no. 12, 2016.

[36] R. W. Berger, D. Bayles, R. Brown, S. Doyle, A. Kazemzadeh, K. Knowles, D. Moser, J. Rodgers, B. Saari, D. Stanley and B. Grant, "The RAD750 - A Radiation Hardened PowerPC Processor for High Performance Spaceborne Applications," in *2001 IEEE Aerospace Conference*, Big Sky, MT, USA, 2001.

[37] H. Monaghan, "What is the Deep Space Network?," NASA, 30 March 2020. [Online]. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/what-is-the-deep-space-network/#:~:text=The%20DSN%20consists%20of%20three,%3B%20and%20near%20Canberra%2C%20Australia. [Accessed 1 December 2023].

[38] J. Lazio, "The Deep Space Network Radio Astronomy User Guide," California Institute of Technology, 3 April 2021. [Online]. Available: https://deepspace.jpl.nasa.gov/files/DSN_Radio_Astronomy_Users_Guide.pdf. [Accessed 30 November 2023].

[39] S. Caldwell, "State-of-the-Art Small Spacecraft Technology - Ground Data Systems and Mission Operations," NASA, 27 May 2023. [Online]. Available: https://www.nasa.gov/smallsat-institute/sst-soa/ground-data-systems-and-mission-operations/. [Accessed 1 December 2023].

[40] NASA, "NASA's Mission Operations and Communications Services," 1 October 2014. [Online]. Available: https://deepspace.jpl.nasa.gov/files/6_NASA_MOCS_2014_10_01_14.pdf. [Accessed 17 February 2024].

[41] "Line-of-Sight Propagation," IEEE, [Online]. Available: https://technav.ieee.org/topic/line-of-sight-propagation. [Accessed 26 March 2024].

[42] P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," *Icarus,* vol. 51, no. 2, pp. 322-333, 1982.

[43] J. Oschlisniok, B. Hausler, M. Patzold, S. Tellman, M. K. Bird, K. Peter and T. P. Andert, "Sulfuric Acid Vapor and Sulfur Dioxide in the Atmosphere of Venus as Observed by the Venus Express Radio Science Experiment VeRa," *Icarus,* vol. 362, 2021.

[44] D. Bolles, "Pioneer Venus Orbiter Map of Venus," NASA, 7 May 2019. [Online]. Available: https://technav.ieee.org/topic/line-of-sight-propagation. [Accessed 5 April 2024].

[45] L-Com, "4950 MHz to 7125 MHz, 2-foot collapsible Parabolic Antenna, 2x2 MIMO, 30 dBi, RPSMA," Infinite Electronics International, 2023. [Online]. Available: https://www.l-com.com/4950-mhz-7125-mhz-2-foot-collapsible-parabolic-antenna-2x2-mimo-30-dbi-rpsma-2-pack-hg4971dp-30dc-rsp?gad_source=1. [Accessed 25 February 2024].