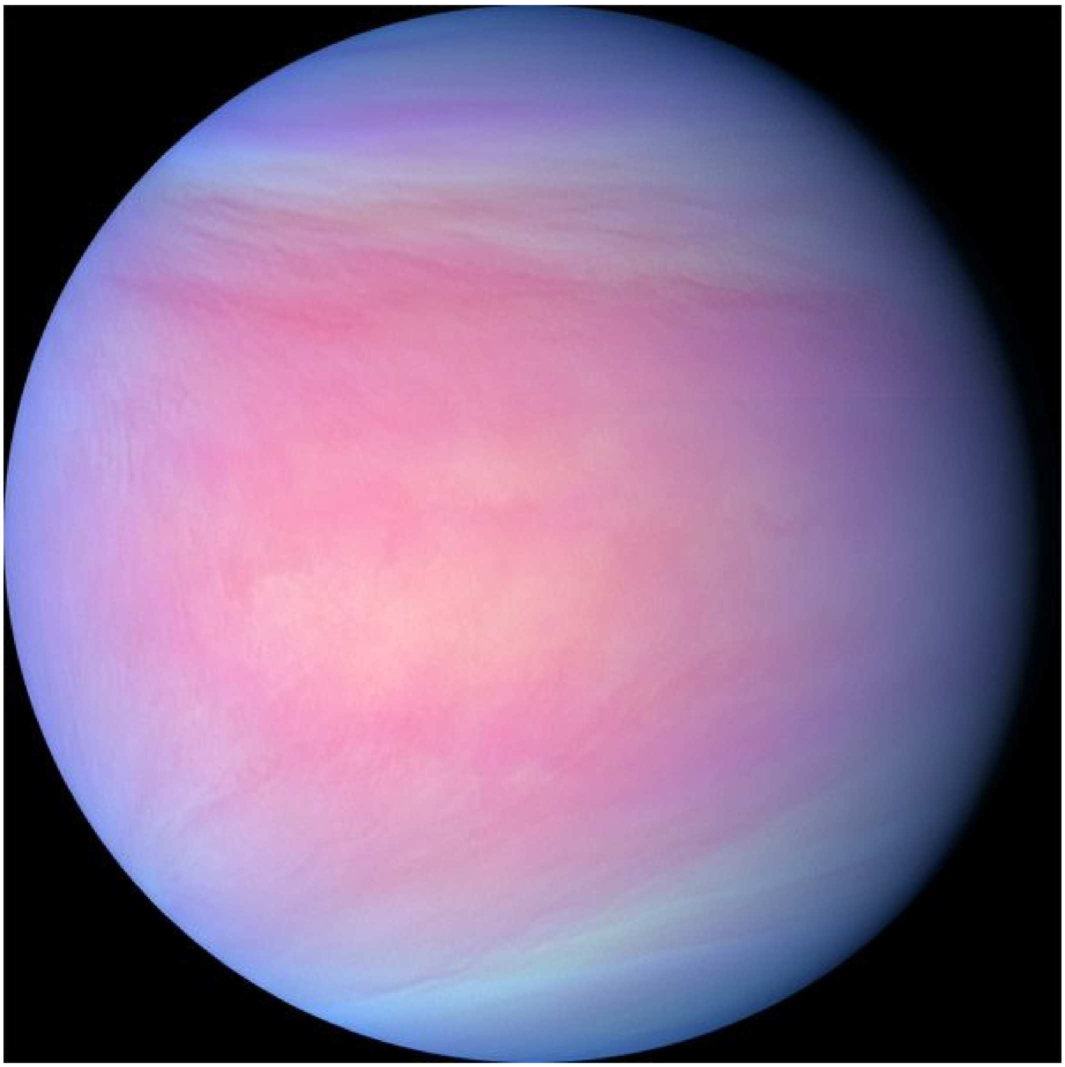
V.E.G.A.N.

Venusian Experimental Ground & Atmosphere Network



Team 6

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Class of 2020

AERSP 401B: Detailed Spacecraft Design

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Executive Summary

The goal of the VEGAN mission is to further the knowledge gained by the Vega and Venera missions that took place throughout the 20th century. Building on them, the reference for proposal[I.1] (RFP) states that the mission design requires the return of samples from Venus to Earth for further study. This proposal was expanded on by creating a mission that will not only land on the surface to complete analysis with advanced equipment, but capture and return samples from the atmosphere to Earth. Basic requirements for the mission consist of the lander surviving on the surface for at least 3 hours, longer than any previous mission, and the successful return of atmospheric gas and particle samples to Earth. The RFP suggests a mission timeline with launch in 2029 so this is set as the year for the launch window. With this launch window the mission will take approximately 16 months to complete.

The mission must depart Earth for Venus on October 29, 2029 for an optimal transfer. Once reaching Venus, the orbiter will use aerobraking to put itself into a 400 km parking orbit around the planet to await the completion of the lander and Venusian Air Vehicle (VAV) missions. Once the circular parking orbit has been achieved, the orbiter will wait until the correct trajectory to reach the landing site is achieved and then deploy the descent vehicle containing the VAV and the lander. At 80 km the descent vehicle shell will break up, and the lander and VAV will separate. The lander will continue to the surface where it will begin in-situ measurements. The VAV will slowly descend to 50 km, taking 3 atmospheric samples and deploying an aerogel capture system for particulate matter. At 50 km, the main engines will fire, boosting the VAV back up to a stable circular orbit at 400 km. Once in this orbit, the orbiter will maneuver to rendezvous with the payload of the VAV. The payload will be transferred to the orbiter for transfer back to Earth. At this point, the orbiter will wait in the parking orbit to transmit data gathered from the lander or until the lander ceases operation. A burn will be performed by putting the orbiter on a transfer orbit to the Earth. Once it arrives at Earth, the orbiter will rendezvous with the ISS to deliver the samples for analysis.

Launch Vehicle

The team has finalized their selection of the Falcon Heavy as their launch vehicle, whose payload fairing of 13 m long and 5.2 m in diameter will be sufficient in size to fit our payload, and is capable of taking our mass of about 24,000 kg of payload outside of Earth orbit.

Structures

The structures involved in the mission will include an Earth return vehicle (ERV), a Venusian air vehicle (VAV), and a ground vehicle. The air and ground vehicle will be enclosed within a descent vehicle attached to the ERV, which will be sent into the Venusian atmosphere once in Venusian orbit. The descent vehicle will include a drogue-chute to help slow the craft down. The descent vehicle shell will break up and the lander and VAV will separate and their main parachutes will be deployed.

The structures will use a new and developing form of carbon called "carbon nanotube", as it has 600 times the strength of steel by weight. Titanium pressure vessels, surrounded by a silicon– containing material, will be used as they were in previous heritage missions. Around the pressure vessels, multi-layer insulation (MLI) coated on one or both sides with thin films of aluminum, silver or gold will be used. To evaluate the strength of structures throughout the entire mission, materials that make up critical systems in the structures will be embedded with nanometer-scale sensors that constantly monitor the materials' condition.

Guidance, Navigation, and Control

The spacecraft will utilize multiple attitude determination systems for guidance, navigation, and control. Each part of the mission has an additional attitude determination and control system that can be engaged in the event the primary system fails. Before interplanetary travel, the Microcosm Autonomous Navigation System (MANS), an Earth-referenced attitude sensor, will provide accurate real time orbit determination and will allow the spacecraft to perform any necessary maneuvers before entering its interplanetary trajectory. Additional GPS and Kalman filtering support will place the spacecraft within 15-100 m of it's desired path.

During interplanetary travel, the LN-200S will be the primary system used, with the Deep Space Network as the secondary system. LN-200S uses three fiber-optics gyros and three microelectrical-mechanical systems (MEMS) accelerometers that measure velocity and angle changes while producing very little white noise. LN-200S can be used on the descent vehicle since it is hermetically sealed.

For rendezvous and docking on Venus, stronger sensors are required to battle the thick atmosphere. Kurs-NA broadcasts radar pulses from multiple antennas which analyzes the variation in strength to compute position, attitude, and approach rate between two spacecraft. The Next Generation Advanced Video Guidance Sensor (NGAVGS), the secondary system, uses a laser sensor that illuminates a target made of retroreflectors, images the reflected light, and performs pattern-matching on the reflected images to determine attitude and orientation. Each system has the capability to run fully autonomously, however, in the event of an emergency, commands from ground control can be sent to either system to reorientate the spacecraft.

Propulsion

Once the launch vehicle has boosted the mission to LEO, the main engine on board the orbiter will take over. The Vinci engine will be the main engine for the mission, see appendix B for engine information. The fuel will be stored in Carbon Composite Fuel tanks as this will significantly decrease the mass. In order to prevent boil-off, the tanks will be insulted using at least 60 layers of MLI blankets. This will be enough to keep the boil off to a minimum. In order to capture at Venus, aerobraking will be employed.

After gathering its samples and data, the VAV will ascend to the orbiter. The VAV uses a two stage design with the lower stage consisting of a solid rocket motor modeled after the STAR 48. The upper stage consists of a Rutherford engine. The Rutherford engine is a 3D printed, electrically turbo-pumped engine created to be lightweight, efficient and reliable. This engine will propel the upper stage to the 400 km altitude orbit to rendezvous with the orbiter and perform the circularization burn. The RCS system onboard will be used to provide corrections and alignment to the orbiter when docking.

Power

A multitude of subsystems heavily rely on the electrical power system of the ERV to perform their functions. The power subsystem has four basic functions that must be considered. These basic functions include power source, energy storage, power regulation & control, and power distribution.

For transfer from Earth to Venus, solar power will be the most applicable source of power due to the increased Solar Energy Flux received travelling to an inner-planet. We are using Gallium Arsenide (GaAs) as the material for the solar panels. GaAs has a high efficiency, converting 27% to 28% of sunlight into electrical power. GaAs is flexible, lightweight, and provides more radiation resistance as opposed to others such as silicon. The solar panels will have a total surface area of about 11 m^2 .

The batteries must be reliable, lightweight, able to operate in space, and have a long life. Li+ batteries were chosen as backup power source due to their high energy density of 265 Wh/kg, operating temperatures of -40°C to 50C, and life of 30000 cycles. Li+ has been chosen for the batteries on the Lander, as well.

Thermal

Thermal control during interplanetary travel, as well as within Venus will utilize a combination of passive thermal control systems (PTCS) and active thermal control systems (ATCS) to maintain suitable temperature ranges within the structures in order to operate properly. PCTS systems will include MLI, thermal fillers, thermal washers, thermal doublers, and mirror radioisotope heater units (RHU). ACTS will include thermostatically controlled resistive electric heaters, fluid loops, single and two-phase loops, and thermoelectric coolers. Thermal control within the Venusian atmosphere and on the surface will primarily include liquid cooling systems and phase-change change material, as well as heat exchangers, heat accumulators, internal thermal insulators, external thermal insulation, circulation fans, and honeycomb composite material for insulation.

Hybrid thermal control systems will also be utilized. This, in combination with new and advancing technologies in high-heat resistant motors and sensors will ensure that the VEGAN mission will explore Venus more than it has ever been before.

Communications & Ground Control

Once the spacecraft is in a suitable orbit around Venus, the ground control team (Mission Control Center, Spacecraft Operations Control Center, Payload Operations Control Center) will operate intensively for 24 hours in shifts during the critical phase of the mission. All aspects of VEGAN will be transmitted from the orbiter, allowing the team to make compartmentalized adjustments to each of the three vehicles by communicating with the orbiter. It is critical that the communication links on the orbiter are adequately prepared for this. The VEGAN communication system will be composed of six links between the Deep Space Network, orbiter, lander, and VAV (see Appendix D for details). It is effective with adequate margins given the power and size allotments for each vehicle.

Command & Data Handling

The mission will utilize three primary computers for command and data handling. The RAD 5545 will be used on the orbiter since it has high radiation tolerance. The lander will require a computer suited to extreme environments. NASA is currently developing a Silicon Carbide Junction Field Effect Transistor (SiCJFET) which has been successfully tested in the Glenn Extreme Environments Rig (GEER). If developed within the next decade, a functional computer using this technology would secure the data storage and transmission capacity of the lander. The VAV will use a specialized computer based on the D-17B used on the Minuteman ICBM. It will be supplemented with modern computing technology suited to VAV GNC requirements.

Payload & Science

Once the VAV is deployed, the Aerogel capture system will be deployed to gather particulate samples and the gas capture system will inject the atmospheric sample at 70 km, 65 km, and 60 km. When the lander touches down, the equipment will be deployed and start transmitting the data. Approximately 0.5 Gb of data in total will need to be transmitted from the lander. See Payload subsystem for a detailed list of the equipment onboard the mission. After the VAV Rendezvous, the orbiter will return to Earth. When it arrives at Earth, aerobraking will be used to capture, using small burns from the main engine and cold gas thrusters to correct the orientation.

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I. Introduction

As one of the brightest objects in the sky, it comes as no surprise that the first observations of Venus date back to 1610 with Galileo Galilei. Interplanetary exploration of Venus began in the early 1960's with the introduction of the Venera and Mariner programs. On December 14th, 1962, the National Air and Space Administration (NASA) completed the very first successful Venus flyby with Mariner 2[I.2]. Since then, several other missions including flyby, atmospheric, and lander missions have successfully furthered our understanding of Venus and its atmosphere. It is believed that the surface and climate of Venus exhibit similar geological processes to that of Earth in its early life. Between 50 and 70 km, the atmosphere of Venus is similar to Earth's surface at 1 atm, and a temperature between -10°C and 20°C provides an adequate environment for bacteria to thrive for perhaps billions of years[I.3]. However, there has yet to be a mission where samples of the planet have been brought back to Earth for study.

In 2017, a Venus atmospheric sample return mission concept was proposed at the Planetary Science Vision 2050 Workshop[I.1]. The objective of the mission is to revisit and improve on previous Venusian missions, and to explore modern and near-term technologies in order to plan a mission to return atmospheric samples from Venus before the year 2030. However, Venus's harsh climate has proven to be the biggest challenge in acquiring both atmospheric and ground data. Its sulphuric acid clouds, atmospheric pressure of 90 times that of Earth, and temperatures reaching more than 500°C have challenged scientists and engineers since the inception of Venusian exploration[I.4]. Many of the initial spacecraft were failures as they quickly lost communication with Earth due to electrical shortages and other equipment failure. While many of the later missions from programs like Venera, Vega, and Mariner were successful, the issue of withstanding Venus' atmosphere limited the data collected. The longest amount of time spent on the surface was 110 minutes (Venera 12)[I.5].

The VEGAN have taken these constraints and heritage missions into consideration in order to design a mission for a Venus sample return. The primary objective for this mission is to obtain an atmospheric sample on Venus at an altitude between 50 and 70 km, and to complete remote measurements on ground samples of the Venusian surface. Secondary objectives include analyzing ground samples for seismic activity and composition and evaluating it for possible past forms of life. Team VEGAN hopes to spend the most amount of time on the Venusian surface to date.

II. Mission Requirements & Constraints

A. Functional Requirements

The functional requirements of VEGAN are based on a design that will achieve the top level requirements and constraints set forth by the Venusian environment. The orbiter, air vehicle and ground vehicle must be able to:

1. Withstand the entry descent and landing procedures.
2. The ground vehicle must be able to withstand the pressure and temperature on the surface for a minimum of three hours and complete in-situ measurements.
3. The air vehicle must be able to survive in the Venusian atmosphere long enough to be able to complete in-situ measurements as well as collect various atmospheric samples.
4. The air vehicle must return atmospheric samples to the orbiter.

In order to meet requirements outlined above VEGAN will need to have a very robust structural design, as the temperature on the surface is around 500°C at a pressure around 90 atm. As for the air vehicle, it will need to withstand Earth-like temperature and pressure as well as sulfuric acid rain. The air vehicle will need to have sufficient Guidance, Navigation, and Control (GNC) systems to be able to ascend to orbit from the atmosphere and rendezvous with the orbiter.

B. Top Level Requirements

Top level requirements are requirements of the mission that have the absolute highest priority. These requirements were developed after the briefing of the project idea.

1. The mission capabilities must exceed those of the Russian Venera and Vega missions in order to advance our understanding of the evolution of Venus.
2. Return an atmospheric sample from an altitude between 50 and 70 km.
3. Complete in-situ measurements of atmospheric samples.

Achieving these top level requirements will ensure mission success. With these top level requirements achieved the Venusian atmosphere will be able to be studied in greater depth.

C. Constraints

The mission will have several necessary constraints to provide a scope within which the mission will be completed.

1. The proposed mission should be completed before the year 2030.
2. The lander must survive for a minimum of 120 minutes
3. The air vehicle must collect a sample between 50 and 70 km above the surface for most accurate Earth-like temperature and pressure

III. Mission Architecture

A. Main Mission Phase Plan

Launch to LEO

31 October 2029 — 1 Nov 2029

This stage will be achieved through the use of the Falcon Heavy launch platform. Shown in Fig. 1, the rocket will launch from Kennedy Space Center at 20:00 EST, for approximately 10 minutes before entering a low Earth orbit (LEO) of 400 km and inclination of 28.5°. The spacecraft will complete one full orbit at this inclination to allow trajectory corrections. The Falcon Heavy has a successful launch record and can put satellites into correct orbits, enabling the correct placement of VEGAN for an efficient transfer to Venus.

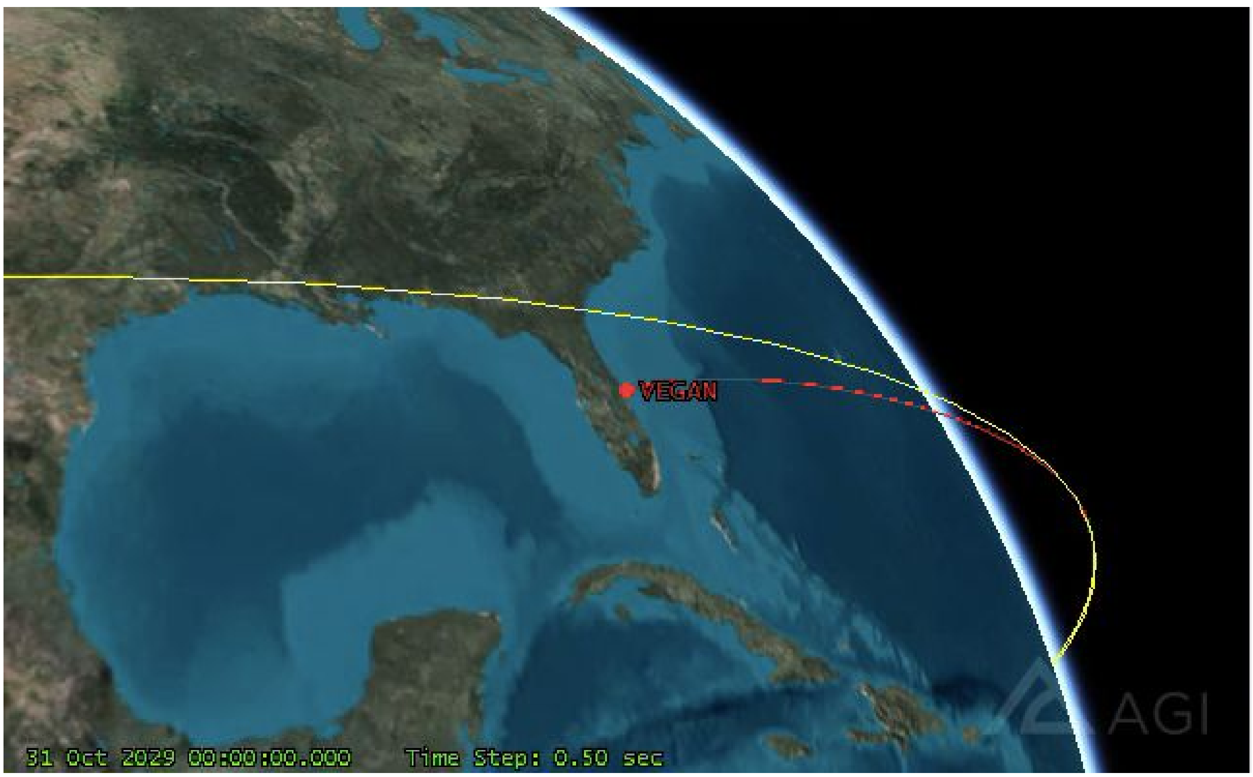


Figure 1. Departure from Cape Canaveral, Florida (red), and entering LEO (yellow).[MA.1]

At approximately 22:01 EST, the spacecraft will cross the descending node and implement a pure inclination change from 28.5° to 7°, requiring $\Delta v = 2.862$ km/s. After the spacecraft arrives at position parallel to the Sun vector, at approximately 00:24 EST, the spacecraft will implement a maneuver of $\Delta v = 3.89$ km/s to depart Earth on a heliocentric trajectory to Venus.

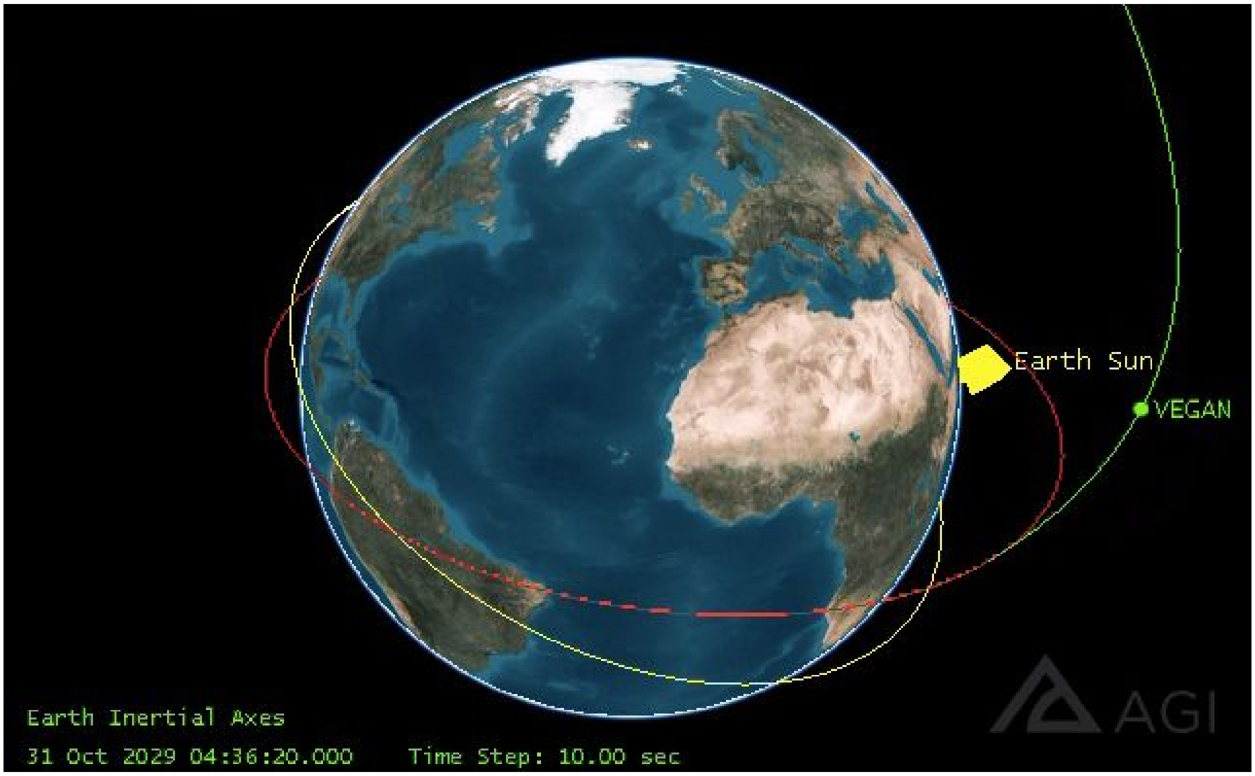


Figure 2. Original orbit (yellow), new inclination orbit (red), escape trajectory (green), and Earth-Sun vector (yellow, middle right)[MA.1].

Transfer from Earth to Venus

1 Nov 2029 — 20 February 2030

The spacecraft will travel for 112 days (approximately 3.68 months) on a heliocentric elliptical orbit to Venus. Venus has an inclination of 3.4° with respect to the ecliptic, and the transfer orbit has an inclination of 7° with respect to the ecliptic.

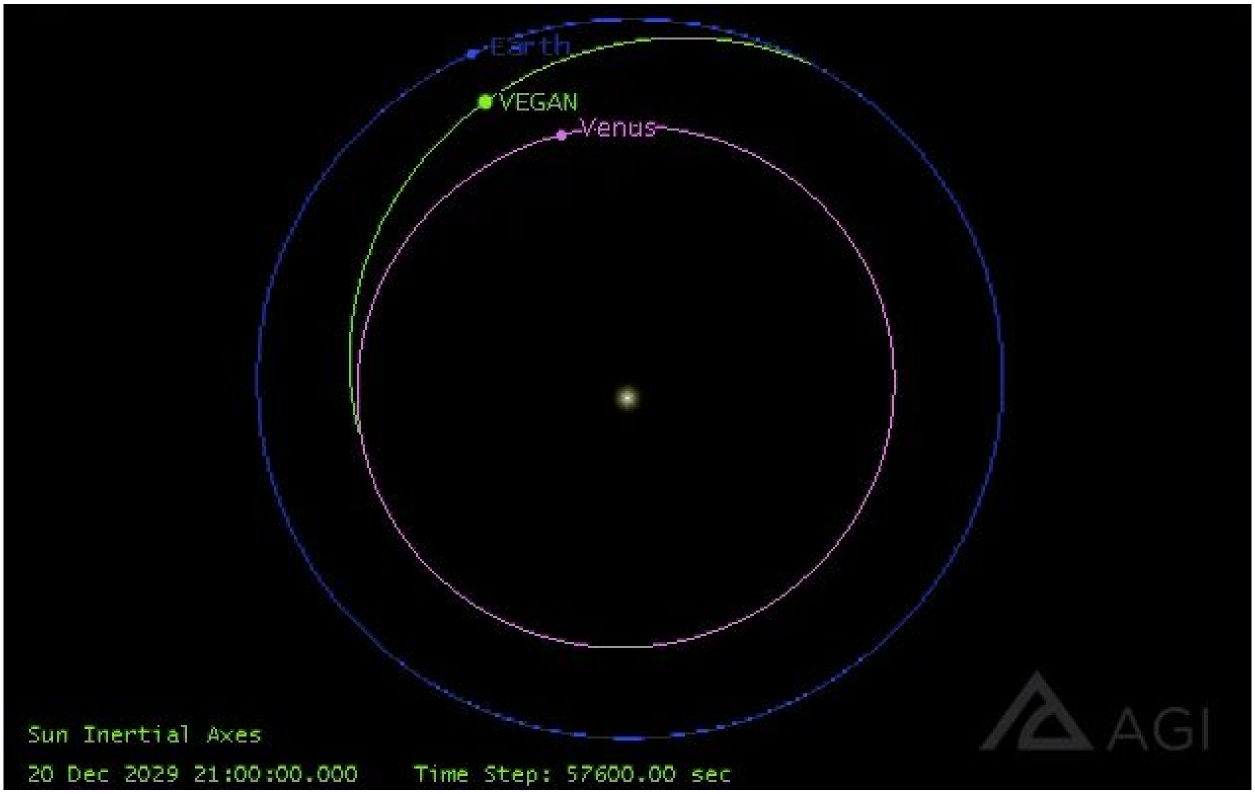


Figure 3. Heliocentric orbit of spacecraft (green) from Earth (blue) to Venus (pink)[MA.1].

Transfer windows to Venus come every 2 years so it is mission critical that this deadline is met as to minimize the fuel that must be carried onboard the craft. Once reaching Venus, the orbiter will use aerobraking to put itself into a 400 km parking orbit around the planet to await the completion of the lander and VAV missions. The spacecraft requires $\Delta v = 4.57$ km/s to be captured by Venus.

Start orbiting Venus and Deploy VAV

20 February 2030

Once captured, the spacecraft will have an inclination of approximately 2.3° with respect to the Venusian equator. The descent vehicle will be deployed at the southern tip of Guinevere Planitia, at approximately 10°N, 40°W. The spacecraft will complete at least one full orbit, depending on the weather, before implementing an inclination change from 2.3° to 10°, requiring $\Delta v = 5.21$ km/s and deploying the descent vehicle. At 250 km, drogue-chute will be deployed to help slow the craft down. At 80 km the descent vehicle shell will break up, the VAV will separate and their main parachutes will be deployed. The VAV will slowly descend to 50 km, taking 3 atmospheric samples and deploying an aerogel capture system for particulate matter.

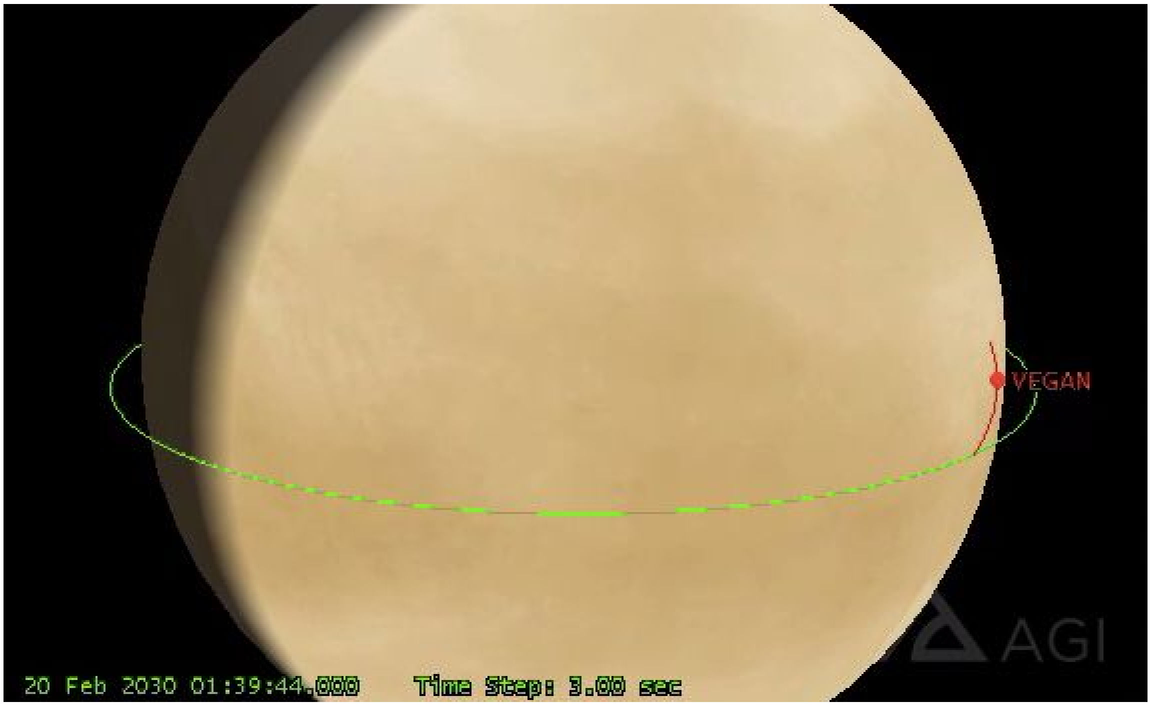


Figure 4. Injection inclination (green) and new inclination plus deployment of descent vehicle (red) to Guinevere Planitia[MA.1].

VAV rejoings ERV and Orbit Rendezvous

22 February 2030 — 25 February 2030

At 50 km the VAV parachutes will detach and the main engines fired, boosting the VAV back up to a stable circular orbit at 400 km. Once in this orbit, the orbiter will maneuver to rendezvous with the payload of the VAV. The payload will be transferred to the orbiter for transfer back to Earth. At this point, the orbiter will wait in the parking orbit to gather and transmit all the data gathered from the lander or until the lander ceases operation due to the conditions on the surface of Venus.

Return to Earth

12 August 2030 — 9 February 2031

The orbiter will implement a maneuver requiring $\Delta v = 6.70$ km/s to change the inclination to 7.68° before implementing another maneuver requiring $\Delta v = 7.82$ km/s perpendicular to the Sun vector that will put the orbiter on a heliocentric orbit back to Earth. The orbiter will travel for approximately 181 days. Once the orbiter arrives at Earth, another maneuver requiring $\Delta v = 6.36$ km/s will allow the orbiter to rendezvous with the ISS to deliver the samples for analysis.

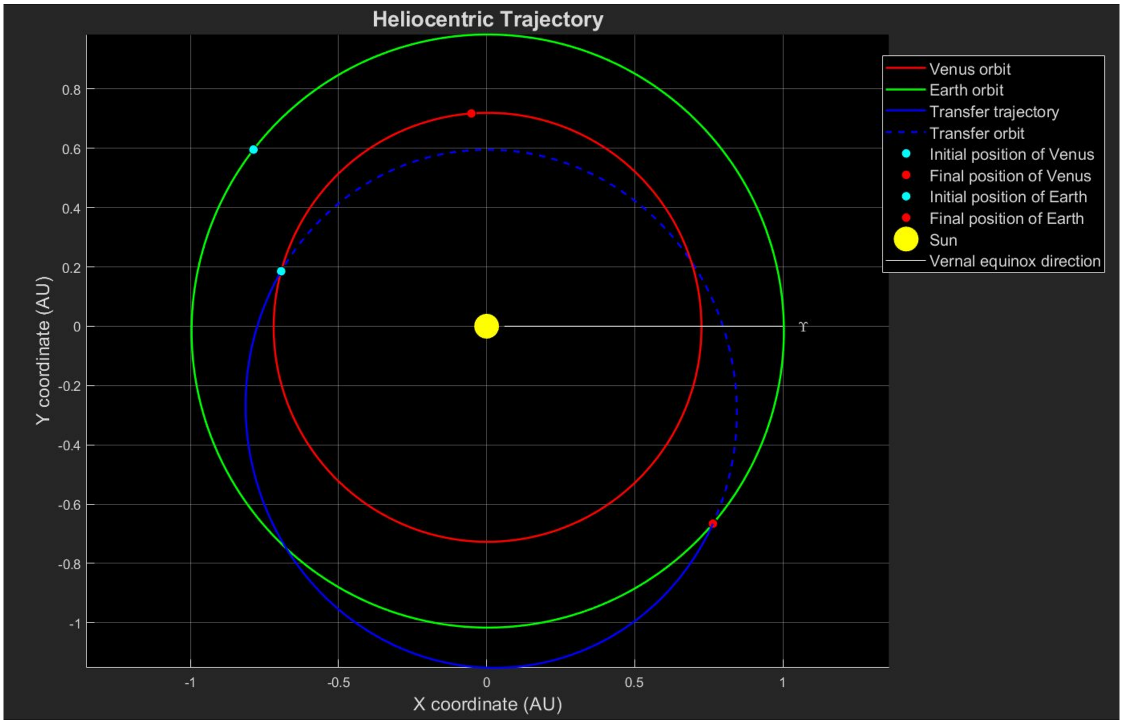


Figure 5. Return trajectory (blue) of spacecraft[MA.2].

B. Concept of Operations

VEGAN is a Venusian exploration mission designed to gather data on various parts of the makeup of Venus. There are two science gathering vehicles to be deployed on the mission, the Orbiter, and the Venus Air Vehicle (VAV). Each of these parts will work together to bring vast amounts of data on the atmosphere and surface of Venus. The main goal of the mission is for the VAV to gather and return atmospheric samples back to Earth. This has not yet been done before in a mission to any planet. The prospect of bringing back samples from the Venusian atmosphere is especially exciting due to the fact between 50-70 km in altitude, the atmospheric conditions are very similar to the surface conditions of Earth. Signs of past biological life may be present. The graphic below outlines the mission plan.

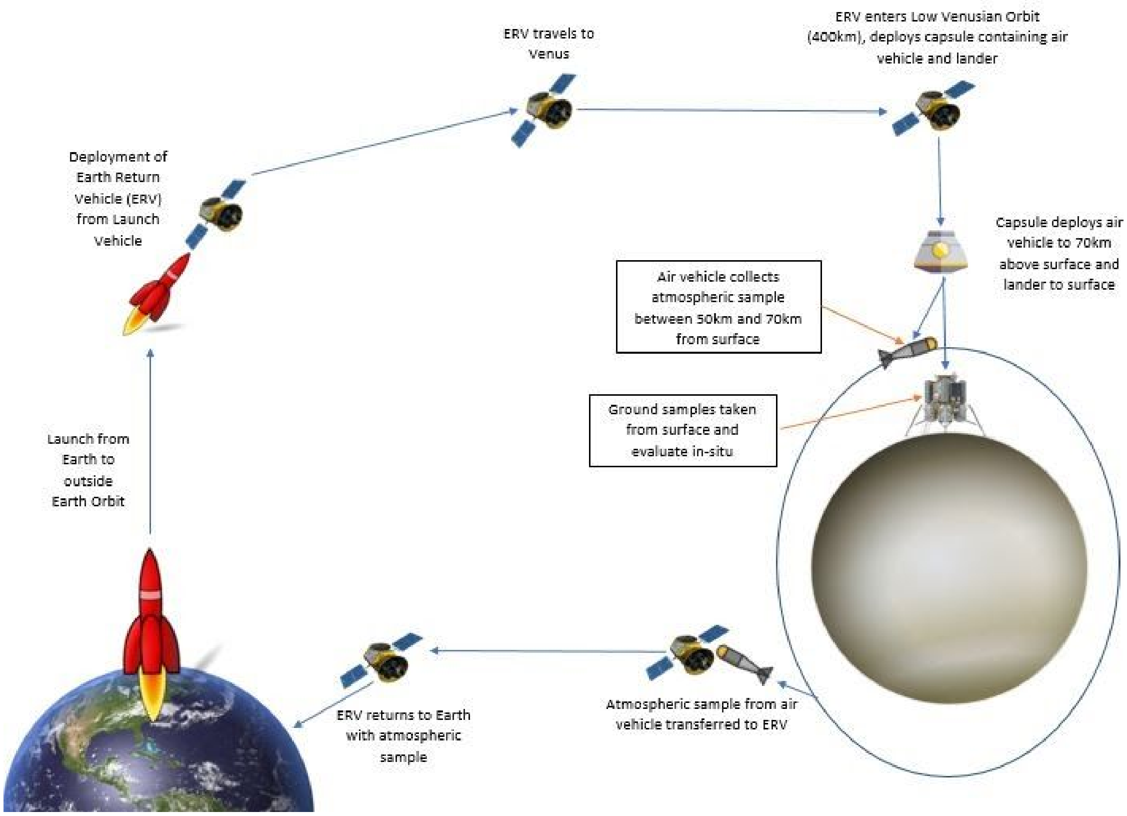


Figure 6. Venusian Atmospheric and Ground Sample Collection Graphic

The VEGAN mission will consist of 5 stages outlined in mission architecture. Each stage contains its own challenges that must be overcome outlined in the mission requirements. Through the efficient integration of the mission subsystems, new knowledge of the Venusian environment can be gained. System requirements were discovered for each mission section and solved independently, then reviewed in total for each subsystem. Breaking up the mission in this way made it easier to visualize the connections between each subsystem and create the most optimal solution to achieve the goals of each mission phase effectively.

C. Vehicle Configurations

As seen in the mission architecture, there will be three separate structures acting separately but remaining in communication with one another. Before launch, all three vehicles will be in contact as part of one large space vehicle. Below is an illustration visualizing this vehicle within the launch vehicle payload fairing. This image was borrowed from the proposed Venera-D mission, which will also deploy an orbiter, lander, and air vehicle[S.6].

Figure 7. Visualization of Space Vehicle Within Payload Fairing

Simplified images of the VAV and lander below show estimated dimensions for the vehicles separately, as well as together.

Dimensions for the air vehicle were predicted after selection of the engines that will be used and the amount of fuel needed to carry the VAV back to orbit after capturing the air sample and can be seen below. The size of the payload section was evaluated after considering the necessary sensors and capsules needed to retrieve the sample. These selections were described in detail in the Payload and Propulsion sections.

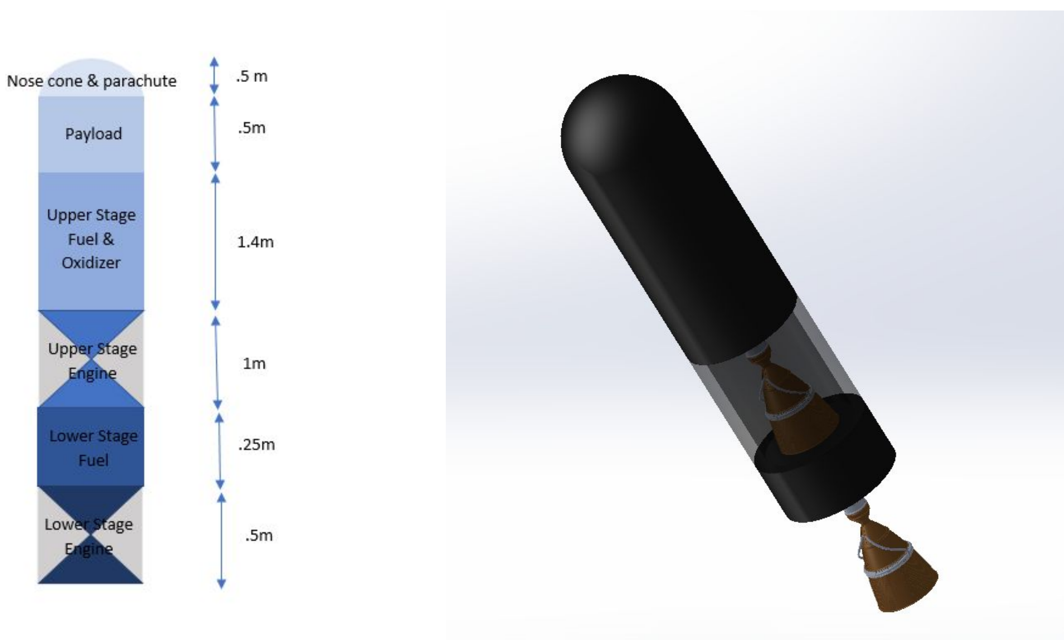
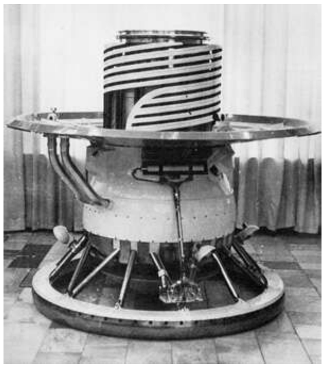


Figure 8. Venusian Air Vehicle Dimensions

The design for the lander resembles that of heritage missions that proved successful in the past. The image below, also borrowed from the Venera-D proposed mission, shows dimensions similar to those of the Venera 9 lander[S.6].



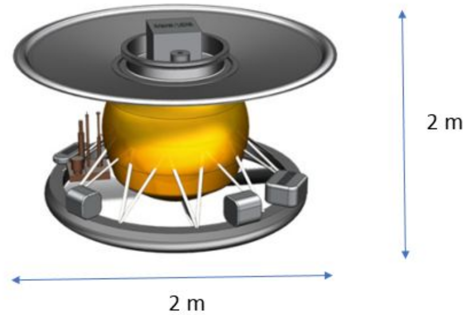


Figure 9. Lander Dimensions

During entry into the Venusian atmosphere, the VAV and lander will be contained within a shared capsule before the VAV is released into the atmosphere. These capsule dimensions are shown in the image below. This configuration of the VAV and lander within the capsule allows for the most efficient use of space and allows to minimize the size of the capsule. The height of the capsule allows for the structurally sound configuration of the vehicles as well as the space needed for whatever parachutes and instruments are needed throughout entry.

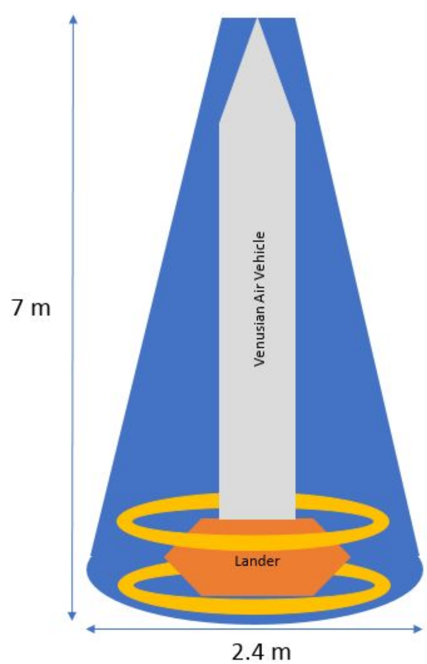


Figure 10. Descent Vehicle Dimensions

Finally, the image below shows a simplified view of the dimensions of all structures together as they have left the launch vehicle and travel towards Venus. Dimensions were predicted using the chosen engine and required fuel (explained in propulsion subsystem) and the size of solar panels needed (explained in power subsystem).

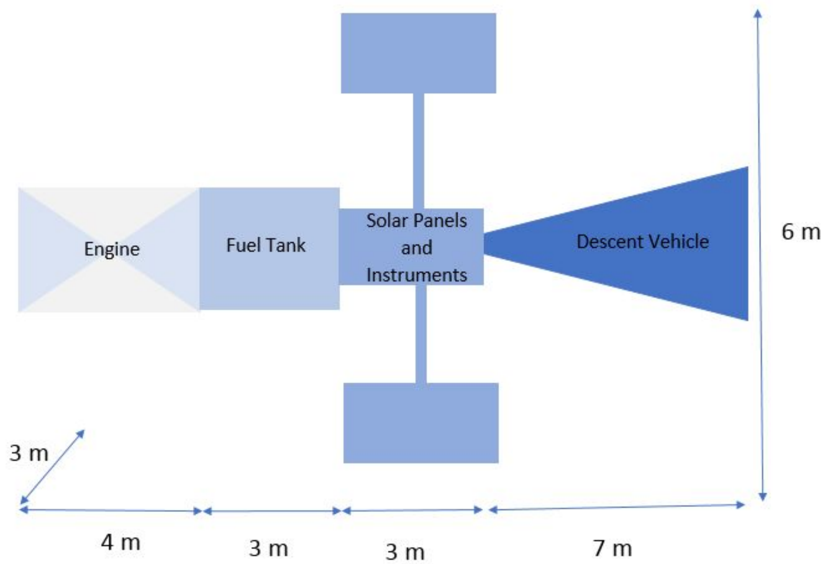


Figure 11. Attached and Extended Space Vehicle Dimensions

IV. Subsystems

A. Structures

Venus' harsh climate has proven to be the biggest challenge in acquiring both atmospheric and ground data. Its sulphuric acid clouds, atmospheric pressure of 90 times that of Earth, and temperatures reaching more than 500°C have challenged scientists and engineers since the inception of Venusian exploration[S.1]. Many of the initial spacecraft were failures as they quickly lost communication with Earth due to electrical shortages and other equipment failure. While many of the later missions from programs like Venera, Vega, and Mariner were successful, the issue of withstanding Venus' atmosphere limited the data collected.

In order to ensure that data will be acquired, the team decided to split the mission into three different structures. They chose to make ground sample collection completely independent from atmospheric sample collection. This made it so that if one of the structures fails, it will not necessarily prevent data from being acquired from the other structure. The whole mission will consist of an Earth Return Vehicle (ERV) that will eject a descent vehicle containing the Venusian Air Vehicle (VAV) and the lander. The descent vehicle will include a drogue-chute to help slow the craft down. The descent vehicle shell will break up and the lander and VAV will separate and their main parachutes will be deployed. While the lander will be left on the Venusian surface, the air vehicle will meet back with the ERV to pass on the atmospheric sample and then the ERV will return to Earth with said samples.

The ERV in itself is a revolutionary concept in space travel. Data collected from other planets is often taken in flyby, orbit, or on the surface and then transmitted to Earth. The first time a space mission will travel to another planet and return to Earth will be a Mars sample-return mission (MRV) that is scheduled to begin in 2020[S.2]. This mission will consist of a Mars rover that will collect ground samples in 2020 and leave them on the surface of Mars. A lander with an ascent vehicle will be launched in 2026 and pick up the samples in 2028. A European Space Agency (ESA) built Earth return orbiter launched in 2026 will then meet the ascent vehicle and collect the ground samples, before taking advantage of the Earth-Mars return window in 2031. Since this is the first vehicle of its kind, the VEGAN team plans to closely study the ESA ERV in designing an ERV that will travel to Venus and back. Figure 6 shows the makeup of this earth return vehicle[S.3]. It contains "a basketball-sized container with samples from Mars, the Orbit Insertion Module – a chemical propulsive stage for inserting the spacecraft into Mars orbit that is ejected to save mass on the return to Earth – and the Earth entry capsule that will splash down on Earth." The ERV used for the VEGAN mission will also include all the instruments necessary to conduct in-situ data evaluation in communication with the lander.

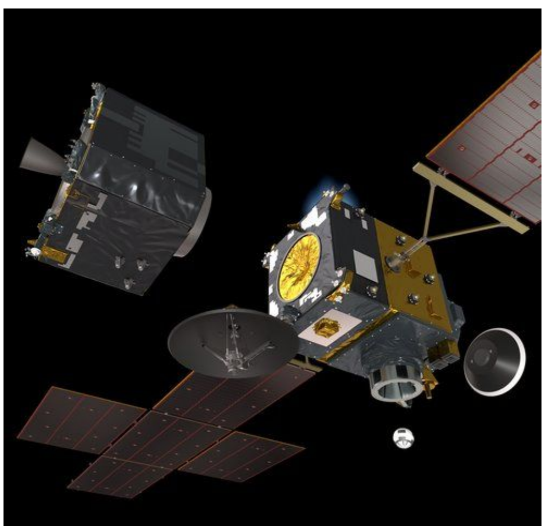


Figure 12. Visualization of the Orbiter

As for the VAV, there have been several different structures used to explore the atmosphere of Venus and other planets. The goal of the VEGAN mission is to obtain an atmospheric sample from a specific range of the Venusian atmosphere and resembles that of Earth (around 50 to 65 km from the surface). In the past, the atmosphere of Venus has been studied via orbiters and balloons. However, an actual sample of the atmosphere has yet to be returned. Several designs to accomplish this have been considered. Figure 13 shows some of the air vehicle structures that have been considered by the VEGAN team[S.4]. Figure 13.1 shows an atmospheric skimmer using a flyby spacecraft. While this design avoids the dangerous portion of the Venusian atmosphere, it does not reach the Earth-like part of the atmosphere where our samples the mission requirements state that samples must be collected from. Figure 13.2 represents a low altitude probe that would collect samples at low velocities and meet with the orbiter once they have been collected. Figures 13.3 and 13.4 represent a VAV that would deploy a balloon around the desired altitude, and then bring it up to an altitude where an ascent vehicle would ascend to the orbiter. Figure 13.5 shows a high-altitude spacecraft collecting samples at high velocity.

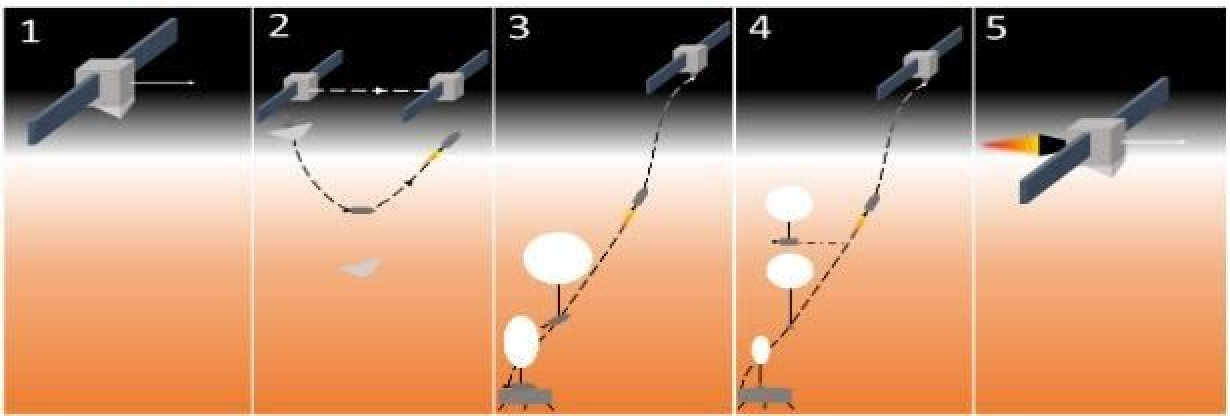


Figure 13. Potential Orbiter, VAV, and Lander Architectures

The team's decision to use a sounding rocket with an air-capture system was the result of cost efficiency and technology readiness level. Due to the significant amount of thrust needed to return the VAV to orbit, a structure able to contain a large amount of fuel while also remaining aerodynamic is needed. This excludes the possibility of a weather balloon, as it cannot return to orbit. The skimmer would require too large an amount of fuel in order to fly to the desired altitude and then return to orbit and rendezvous with the orbiter. Also, there have already been sounding rockets created that have been able to reach Earth orbit from its surface. In 2018, the Japanese Aerospace Exploration Agency (JAXA), successfully launched a sounding rocket, the SS-520-5, that carried a three-unit cubesat into lower Earth orbit[S.5]. The efficiency and high TRL ensured that this was the best choice for the VAV.

The final structure involved in the mission is the lander, which will perform in-situ measurements with scientific instruments on the surface of Venus. Lander designs will be similar but altered versions of those that have performed successfully on Venus, mainly the later Venera missions. This is due to their absence of high-temperature avionics. However, there will be more consideration for instruments that have been developed since that can better withstand the high heats and pressures. A titanium structure along with temperature-resistant covers must be used in order to protect onboard electronics and allow measurements to be taken for significantly more time than previous missions. It must be designed so that its center of mass is at the lower end to maintain its vertical position on descent.

The lander and VAV will both be contained within a descent vehicle on transit and on entry to Venus's atmosphere. This structure is crucial in protecting the lander and VAV from the forces and temperatures applied on entry. The descent vehicle must rely on aerobraking and dampeners before a drogue parachute is deployed to slow the structure before part of it separates in order to release the air vehicle at the desired altitude with its own parachute. It later separates completely to release the lander, also with its own parachute. The image below shows the Venera-D descent vehicle as it releases the lander[S.6]. The VEGAN mission will differ where a drogue-chute will be deployed at 250 km to help slow the craft down. The descent vehicle shell will first break up at 80 km and the lander and VAV will separate and their main parachutes will be deployed. While the lander continues to the surface, the VAV will descend to 50 km to take atmospheric samples.

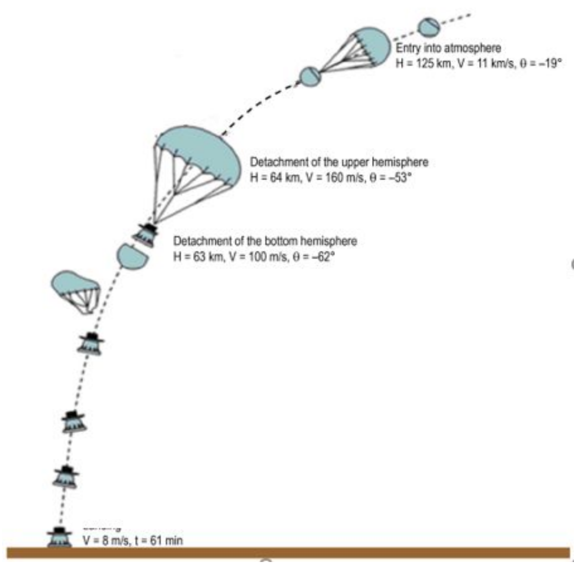


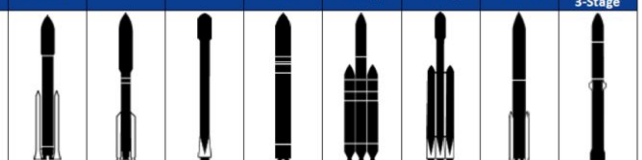
Figure 14. Venera D Descent Vehicle Concept

All structures involved in the mission must maintain suitable conditions for on-board sensors and technology to work. The materials used to make the structures should be designed to satisfy performance criteria, such as buckling, yielding, creep at a temperature of 500°C, and to tolerate a pressure range of 100–150 atm. In previous heritage missions, Soviet Venera and VEGA missions used titanium pressure vessels surrounded by a silicon– containing material. Around the pressure vessel, MLI's typically consisting of shields of Mylar (polyester) or Kapton (polyimide), coated on one or both sides with thin films of aluminum, silver or gold were used. There have also been significant advancements in the understanding of a form of carbon, called "carbon nanotube", which has 600 times the strength of steel by weight. A lattice of carbon nanotubes can store hydrogen at high densities, and without the need for extreme cold[S.7] to ensure the strength of structures throughout the entire mission. Materials that make up critical systems in a spaceship will also be embedded with nanometer-scale sensors that constantly monitor the materials' condition

B. Launch Vehicles

The last decades have seen breakthroughs in launch vehicle technology. The invention of reusable, commercial vehicles allow space exploration to be conducted frequently and at a fraction of the price. The figure below shows launch vehicles that are currently active for deployment of payloads[LV.1].

Table 1 . Comparison of Available Launch Vehicles

	NASA	Commercial Currently in Service				Commercial Currently in Development		
	SLS Block 2	Atlas V	Falcon 9	Antares 230	Delta IV Heavy	Falcon Heavy	Vulcan ACES	New Glenn 3-Stage
								
Scheduled completion date	No earlier than 2028	Currently in service	Currently in service	Currently in service	Currently in service	2017	2023	
Cargo payload fairing size (meters)	10	5	5.4	3.9	5.2	5.2	5	
Upmass to low Earth orbit (metric tons)	130	7.4–17.9	11.2–15	4.4	25.5	–	–	Not reported
Upmass to cislunar orbit (metric tons)	52	2.1–6.3	1.9–3.5	1.5[a]	10.5	6.1–12.9	14	
Upmass to Mars (metric tons)	41	1.4–4.8	Not applicable	1[a]	8.1	3.9–9.3	10.5	

The team based their selection on payload fairing size and ability to carry the payload outside of Earth orbit. Falcon Heavy, whose payload fairing of 13 m long and 5.2 m in diameter will be sufficient in size to fit our payload, whose post-deployment volume can be seen in the vehicle configurations[LV.2]. It is also capable of carrying 26,700 kg of payload mass to geostationary transfer orbit, which is sufficient for the VEGAN mission's payload mass of 24,000 kg, while also factoring percent error for the mass estimate.

C. Propulsion

Once the launch vehicle has delivered the spacecraft to LEO the main propulsion system on the orbiter will take over for the remainder of the mission. The propulsion system on the orbiter will be responsible for getting the mission to Venus and back to earth. Due to the time constraints of the mission and the high mass of the vehicle, a large single chemical engine will be used. Using one engine will reduce the complexity of the mission The engine that was chosen is the Vinci Engine, depicted in Figure 15**,** under development by the Ariane Group for use by the European Space Agency. This engine combusts liquid oxygen (LOX) and liquid hydrogen (LH2) producing 180 kN of thrust in a vacuum at an Isp of 465 seconds. This engine, once in operation, will be one of the lightest, most powerful, and most efficient engines in its class. The first flight of the Vinci engine is planned for the upper stage on the Ariane Rocket in 2020.[P.4] Estimated burn times are 330 seconds for the outbound to Venus burn and 104 seconds for the return to earth burn. Since this engine is the main mode of propulsion for the mission, it needs the ability to be relit many times. This performance metric was of special consideration for the Vinci program and this engine will be able to be relit many more times than its competitor the RL-10.

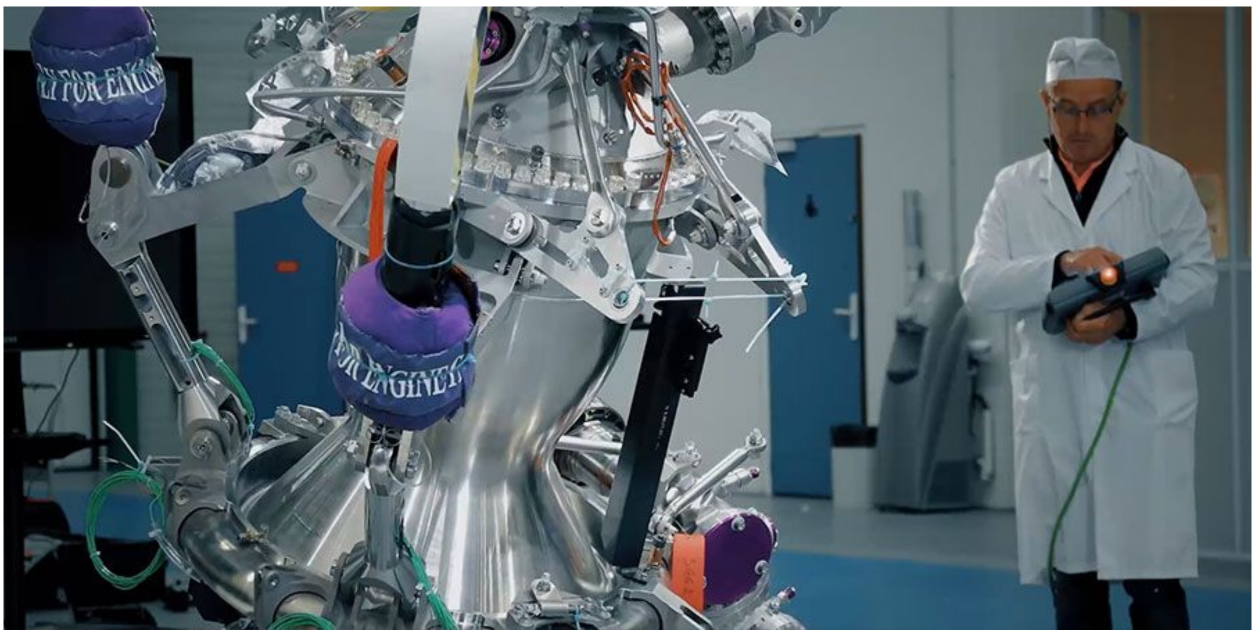


Figure 15. Vinci Engine[P.1]

Various other engines were considered with different fuel types such as the RL-10A-4-2 engine developed by the United states and the RD-0410 developed by Russia. The RL-10 engine is going to be used on the upper stage of the space launch system and combusts LOX and LH2. It is very similar to the Vinci engine but of an older design resulting in less efficiency and thrust. The RD-0410 was considered as it does not use cryogenic fuel, it combusts Unsymmetrical Dimethyl Hydrazine (UDMH) and N2H4. This fuel type can be stored for long periods of time without degradation but with a very large loss in efficiency. All the engines considered with their statistics and performance metrics in the mission can be found in the table in the appendix B. In order to conserve mass, the fuel tanks being used are of an advanced carbon composite design. These tanks will have the same volume of aluminum tanks with only 40% of the mass[P.7]. This is a very significant reduction in the dry mass of the craft resulting in an appreciable performance increase. For this mission, preliminary calculations show a required LH2 volume of 16,576 L and a LOX requirement of 47703 L. To increase space efficiency, these will be stored in one large multi chamber tank. In order to help with the issue of long-term storage of the cryogenic fuel, multi-layer insulation (MLI) blankets will be used to insulate the tanks and prevent significant fuel boil-off[P.6]. Studies have been done that with 60-70 layers of insulation on the tanks will be able to reduce the boiloff to approximately 0.05% per day[P.5]. This means that no active cooling system will be required which would increase the mass, power requirements, and complexity of the mission.

Table 2. Mission Analysis of Prospective Orbiter Engines

Engine	Mission Mass (kg ±10%)	Outbound Fuel (kg ±10%)	Return Fuel (kg ±10%)	Outbound burn time (sec ±10%)	Return Burn Time (sec ±10%)
RL10A-4-2	19127.00	9806.40	2452.00	507.67	109.37
RD-0146	18916.00	9522.70	2454.90	730.08	161.84
HM-7B	19480.00	10047.00	2541.00	787.10	171.04
Vinci	18802.00	9416.50	2437.50	278.68	62.04
RD-843	33980.00	19210.00	6941.50	31.11	8.76
RD-0410	14501.00	4570.40	1708.30	1324.40	432.05
X3	7748.00	1386.00	214.00	5600000.00	840000.00

The VAV propulsion system will be responsible for getting the vehicle back into orbit around Venus and rendezvous with the orbiter for the return trip. It was found that at least a 2-stage ascent vehicle will be required in order to achieve a stable orbit at 400 km altitude. Several different engine types were considered, and they are tabulated in the appendix. Different fuel types were considered, and various combinations of upper and lower stages were analyzed in a custom MATLAB Script to find the combination that produced the lowest mass of the vehicle. With these parameters in mind, the results of the analysis showed that the optimal combination would be a lower stage consisting of a solid rocket motor similar in performance to the star 48 motor and an upper stage consisting of the Rutherford engine produced by Rocketlabs.

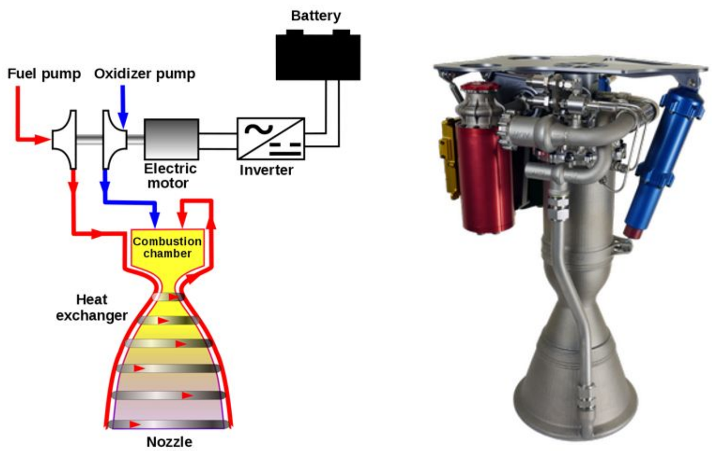


Figure 16. Rutherford Engine

The solid rocket motor will have an Isp of 290 seconds which is a high efficiency for solid propellant. Using the solid rocket motor will simplify the ascent vehicle and reduce the chance of failure[P.3]. Simplicity of operation is a very important criteria for the selection of the propulsion system because of the harsh conditions on Venus. The upper stage engine, the Rutherford depicted in Figure 16, is a 3D-printed, electrically turbopump engine developed and flown by rocket labs. Instead of the combustion of the engine being used to power the turbo pumps, electric motors and an onboard battery pack is used to power the turbopumps allowing the engines to have better throttle control and reliability on startup. This engine combusted LOX and RP-1 and has an Isp of 343 seconds in vacuum. It is an extremely light engine due to its 3D printed construction while also being able to produce thrust levels of 24 kN. This engine is currently flown onboard the electron rocket in a pack of 9 as the first stage and a single as the second stage so it has seen extensive use[P.2] .

Config (Upper / Lower)	Total Mass (kg ±10%)	Upper Stage. Fuel Mass (kg ±10%)	Lower Stage Fule Mass (kg ±10%)
RL10A-4-2 / STAR 48A-1	2093.6	1220	560
RL10A-4-2 / GEM Series	2165	1500	340
RL10A-4-2 / Rutherford	2139.8	1180	580
HM-7B / Star 48A-1	2177.6	1220	640
HM-7B / GEM Series	2279.3	1460	490
HM-7B / Rutherford	2149.9	970	810
Rutherford / Star 48A-1	1614.4	930	530
Rutherford / Gem Series	1697.5	1500	50
Rutherford / Rutherford	1663.2	780	660

Table 3. Mission Analysis of Prospective VAV Propulsion

D. Communications & Ground Control

In order to achieve synergy in all components of the mission, a communications framework must be set up between the different vehicles and the Deep Space Network (DSN). Once the spacecraft is in a suitable circular orbit around Venus, the ground control team located at the Mission Control Center (MCC), Spacecraft Operations Control Center (SOCC), and Payload Operations Control Center (POCC) will operate intensively for 24 hours in shifts during the critical phase of the mission. All aspects of VEGAN will be transmitted to and from the orbiter, allowing the team to make compartmentalized adjustments to each of the three vehicles by communicating with the orbiter. It is critical that the communication links on the orbiter are adequately prepared for this. The VEGAN communication system will be composed of six links between the DSN, orbiter, lander, and VAV (see Appendix D). It is effective with adequate margins given the power and size allotments for each vehicle. The required link margins are 20dB for commands and 5dB for data transmission[COMM.10]. Descriptions for the six links of the network are given below:

(1) The orbiter needs a 220 kb/s maximum data rate[COMM.3] for the aerobraking phase of the mission, however the mode data rate for this link will be much lower as the orbiter sends scientific data during the return to Earth. The orbiter's high-gain antenna (HGA) will not transmit in the Ka-band due to power constraints (see Table 6). The link will not need to use Ka-band as the X-band link will be suitable for the command and data transmission over the long mission duration.

(2) The biggest constraint for the lander link is the time in which the lander will be able to transmit to the orbiter. The lander will gather a total of 65 GB of scientific data which will be transmitted over the course of 15 orbital periods (1 Earth day). With a data rate of 200 Mb/s and a 2m gimballed antenna, all high-priority science data can be returned to the orbiter by completion of the first period of 95 minutes, well within the expected lifetime of the lander.

(3) The VAV will need to send navigational and avionic data to the orbiter so that the orbiter can send the necessary corrections to the VAV trajectory. Once in orbit, the VAV will rendezvous with the orbiter. The VAV requires larger margins of error for the communication link due to the vibrations and constant change of attitude during its ascent to orbit, therefore a lower antenna gain and high pointing error is anticipated.

(4) The link between the DSN and orbiter has an adequately high link margin for command transmission[COMM.10], and the DSN will be at liberty to decide when to allocate extra power toward the orbiter uplink.

(5, 6) The forward links from the orbiter to the VAV and lander (Figure 17) have very low power requirements, so they can afford to use high-order phase-shift keying for their modulation. Their link margins can be buffered significantly by increasing the power if necessary.

The center of communication for the network will be the orbiter, which will communicate with the DSN, VAV, and lander. The orbiter will be outfitted with the Small Deep Space Transponder (SDST) and Electra transceiver[COMM.4], allowing it to receive data from the DSN via microwave signals[COMM.1]. The SDST is a very reliable option for the mission, having been used on a variety of missions with over one million operational hours in total[COMM.2]. The SDST utilizes the X-band (8-12 GHz) and Ka-band (26.5-40 GHz) frequency range, a precise and powerful range commonly used in military and space applications. The SDST is ideal due to its flexibility; it can receive and transmit X-band signals and receive Ka-band signals when needed. The orbiter will use one HGA communicating in the X-band[COMM.3] and three low gain antennas (LGA) in the Ka-band. Only one LGA will be needed at a time for the lander, however an extra antenna will be added for redundancy to supplement the VAV or lander. This configuration has been used in other missions and is being used for planned missions as well[COMM.9]. The X-band HGA will have three purposes; it will be necessary for transmitting scientific data to Earth, receiving commands from ground control, and for the high-bandwidth activity of the aerobraking phase necessitating a real-time data rate of at least 220 kbps[COMM.3]. To communicate with the atmospheric vehicle a Ka-band HGA will be used to send navigational and avionic commands sent from ground control or by an automatic trigger.

The VAV will need to receive continuous feedback from the orbiter in order to navigate properly. To do this, the Electra transceiver will be used[COMM.4]. This small, cheap, and effective transceiver will be suitable for the purposes of the VAV, as it has been used extensively on other missions with similar structure[COMM.5]. It is able to relay data across a broad range of ultra-high frequencies (390-450 MHz) as well as Ka- and X-band frequencies, and will be used to navigate as the VAV ascends. The VAV will transmit in the Ka-band since there will be a suitable amount of extra power and little atmospheric attenuation at its altitude of operation. Once the vehicle comes within 500m of the orbiter, the process of docking will begin. To establish the best connection, the rendezvous laser radar (RVR) will be used along with proximity camera sensor (PXS)[COMM.6] as discussed in the GNC subsection.

The purpose of the lander antenna is to transmit scientific data to the orbiter as quickly as possible before the hardware fails. All components of the lander's antenna must be able to withstand the harsh conditions. At the Venusian surface, the lander will perform in-situ analysis on the ground sample it collects. A Ka-band HGA and Electra transceiver will be used to transmit data from the lander as previous Venus missions have done. However, because the analysis will be done in-situ it is necessary to maximize the speed of data transmission. Therefore the antenna will be fixed to a gimbal on top of the lander, allowing it to point to the orbiter during transmission. The high gain signal is most effective on an accurate and precise trajectory, therefore it will be important to keep the gimbal mechanism shielded from the ambient conditions to minimize pointing error. The gimbal rotation is critical for transmitting the analysis results to the orbiter[COMM.7]. In order to reduce the complexity of the antenna system, it is advantageous to use only two antennas, one for uplink and one for downlink. The orbiter will only be able to access transmissions from the lander for an ideal time of 10 minutes and 43 seconds out of an orbital period of 95 minutes, assuming an ideal gimbal rotation of 180°. With a beamwidth of 0.3°[COMM.8], along with the rotation of the gimbal, the lander antenna is able to transmit data smoothly at a high rate for approximately 5 minutes per orbital period. This access window will be adequate for the transmission of all high-priority science data within the first orbital period (see Appendix D). Therefore it is critical for the lander to gather scientific data in a timely manner, rotate the gimbal precisely, and to survive until completion of the first period.

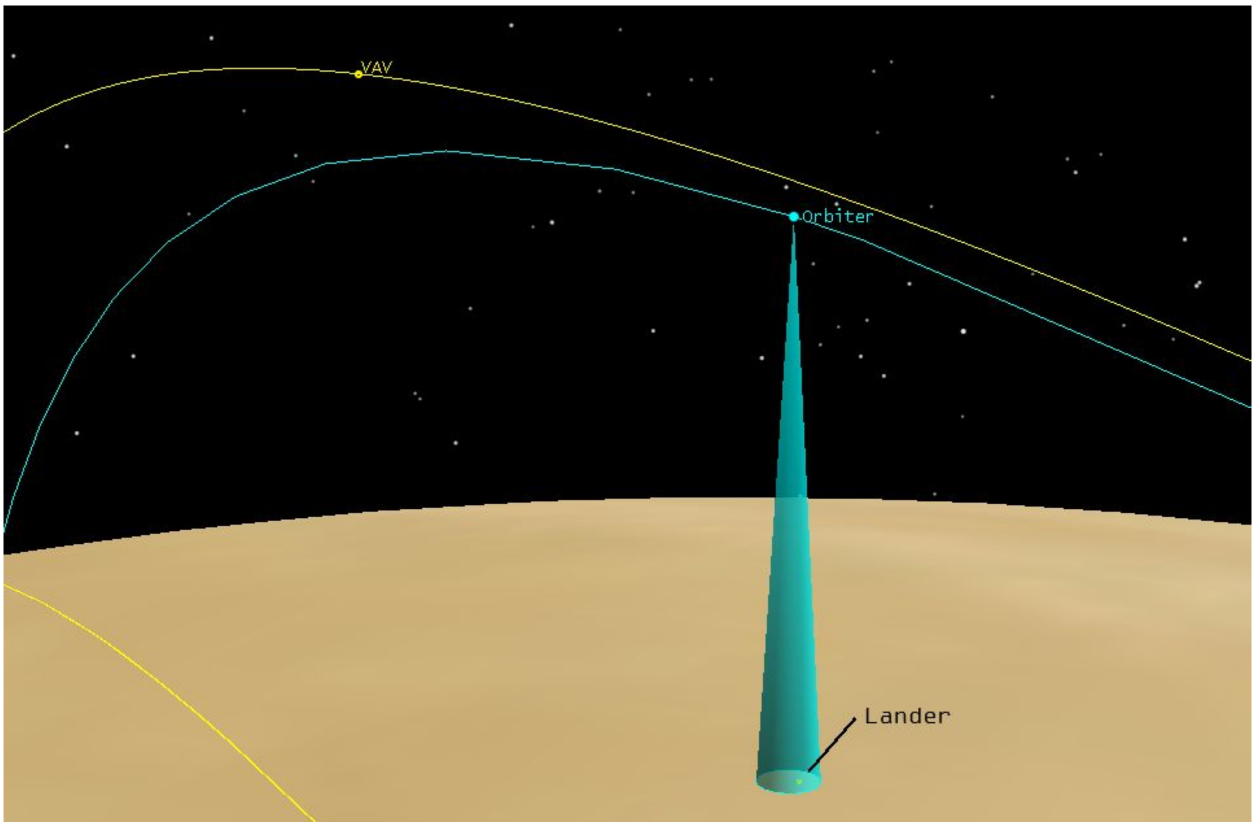


Figure 17. Simulation of orbiter-lander downlink with 6.56° beamwidth[COMM.11]

E. Command & Data Handling

The mission will utilize three primary computers for command and data handling. They will be necessary to fulfill the requirements for data storage and transmission. If all components work as intended, they will be able to withstand the harsh physical effects of Venus and interplanetary space. Obstacles introduced by the environment include radiation, high temperature, high pressure, and high vibration. Each computer has been selected to overcome these issues.

Large amounts of data will need to be processed onboard to not only correctly control the attitude of the spacecraft but also process the results from the scientific equipment onboard. On many other space missions, the RAD 750 guidance computer has been used on spacecraft due to its high radiation resistance. This design has been used since its creation in 2001. The RAD 5545 is the successor of the RAD 750, claiming to have a tenfold processing power increase from the RAD 750 while retaining its proven radiation tolerance. Due to the high data processing needs of the mission, the RAD 5545 will be used in the orbiter. The RAD 5545 processor will be capable of 3.9 GFLOPS of processing power while consuming 20 Watts of power[CDH.1]. The lander's science equipment will require a powerful processor resistant to the extreme conditions that exist on the surface of Venus. There has been recent development into extreme environment resistant computer hardware resulting in the development of the Silicon Carbide Junction Field Effect Transistor (SiCJFET). It has been proven to operate correctly for weeks in the NASA Glenn Extreme Environments Rig (GEER)[CDH.2]. However, it has a low technology readiness level and will need significant development and testing before a mission. If developed within the next decade, a functional computer using this technology would secure the data storage and transmission capacity of the lander. The VAV will need a guidance system to properly control its flight on Venus. The VAV guidance system will use a computer based on the D-17B used in the Minuteman ICBM guidance system. This computer will allow the missile to reach an orbit with adequate accuracy so that the docking system will be able to take control[CDH.3][CDH.4]. It will be developed under heavy security, since it is essentially a missile computer.

F. Guidance, Navigation, & Control

Autonomous spacecraft navigation systems will reduce the manpower and workload required by satellite controllers and trackers to maintain spacecraft positional data. Multiple navigation, attitude and orbit control, and docking systems are used in the case of failure. Manual override is available for all systems. As a result, the Guidance, Navigation, & Control subsystem must meet the following requirements:

- Successful use of autonomous navigation and guidance systems.
- Successful launch and arrival at Venus with spacecraft capable of making multiple trajectory corrections during its flight.
- Successful inclination change at Venus to position spacecraft above Guinevere Planitia.
- Successful reorientation of spacecraft to face solar cells towards the Sun and communication antennae towards the Venusian surface.
- Successful separation and rendezvous/docking of descent vehicle and orbiter.
- Successful launch and arrival at Earth.

Navigation Systems

(1) Near Earth, the primary navigation system is the Microcosm Autonomous Navigation System (MANS) alongside GPS tracking, which will provide orbit, attitude, and Sun direction prior to the interplanetary trajectory. MANS is able to accurately predict the position of the

spacecraft within 100 m, the velocity within 0.4 m/s, the attitude within 0.03°, and the angular rate within 0.005°/s[GNC.1]. MANS uses modified Barnes conical Earth sensors to measure the size of the Earth and determine the relative positions of the Earth, Moon, and Sun[GNC.2]. MANS does not require GPS or ground support, but including GPS receivers improves position accuracy to 15-100 m. Both will be used to monitor correction maneuvers while in LEO before departing on an escape trajectory. GPS tends to be noisy as signals travel through the atmosphere before reaching the receiver. Kalman filtering will be used to reduce sensor noise data on board the spacecraft. Kalman filters require small computational power and are of simple form, but increases accuracy by using the "predict and update" method[GNC.3]. The system's state is estimated using the system's dynamic model, known control inputs, and multiple sequential measurements from sensors, and deals with uncertainty in sensor noise by estimating the state as an average of the predicted state and new measurement using a weighted average. The weighted measurement lies between the predicted and measured states, and the weights provide a means of uncertainty, so measurements with smaller uncertainty are trusted more[GNC.4].

(2) Near Venus, LN-200S is a vehicle-based inertial measurement unit (IMU) that will be paired with the Deep Space Network (DSN), an Earth-based tracking system. Both will be used during the interplanetary trajectory and while at Venus. The LN-200s is a fiber-optic IMU composed of three microelectromechanical systems (MEMS) accelerometers that measure velocity and angle changes. The accelerometer has a bias repeatability of 300 µg and max input acceleration of 40 g. The gyro has a bias repeatability of 1°/hr. It provides attitude and acceleration data for Earth and heliocentric orbits and missions lasting up to 6 years, with a radiation tolerance of 10 Krad and survival temperature of 85°C, and has the lowest gyro and accelerometer white noise in its class at 35 µg/√Hz[GNC.5]. As a result, LN-200S can also be implemented onto the descent vehicle.

Attitude & Orbit Control Systems

Errors in the ephemerides of Venus must be included in calculations as the Sun's sphere of influence was not accounted for in calculations. Midcourse guidance will be required as imperfect boost guidance combined with uncertainties in the astronomical constants can cause error in distance of closest approach on the order of 370.4 km to Venus[GNC.6]. There is also the issue with the Venusian plasma environment and its interaction with the solar wind[GNC.7].

(1) Thrusters will be used for attitude and orbit control systems during interplanetary trajectory maneuvers and at Venus. Reaction wheels may seize due to the extreme cold, the solar radiation pressure may negatively influence plus the lack of magnetic field at Venus make magnetic torquers impractical[GNC.8].

(2) In addition, a coarse Sun sensor, a redundant sensor, delivers information about the position of the sun relative to the spacecraft. The detectors have an accuracy of 1.5° and its detectors are able to withstand the Sun's radiation using shielding[GNC.9].

Docking Systems

(1) Kurs-NA is a fully autonomous rendezvous, final approach, and docking sequence system, that measures the relative range, radial and angular velocity, and orientation angles of the two docking spacecraft. Kurs has a position accuracy of 9 m, radial velocity accuracy of 0.1 cm/s, and orientation angle accuracy of 1.2°[GNC.10]. Kurs-NA uses signals sent from the target vehicle that can be received by several antennas on the chaser vehicle to determine its line-of-sight and pitch angles for the far-rendezvous beginning at 200 km and pitch, heading and line of sight angles as well as range and range rate during the close rendezvous[GNC.11].

(2) The Next Generation Advanced Video Guidance Systems (NGAVGS) uses a laser sensor that illuminates a target made of retroreflectors, images the reflected light, and performs pattern-matching on the reflected images to determine the relative positions of two spacecraft[GNC.12]. Two wavelengths are sent out, 850 nm and 808 nm. The target passes the 850 nm wavelength that produces the foreground image with the bright spots from the retroreflectors and blocks the 808 nm wavelength that produces the background image. Subtracting the two, essentially subtracting the background reflections, leaves an image solely of the retroreflectors. Spots are then created from lit pixel data, and matches these spots to spots based on the geometry of the target. The NGAVGS is able to provide tracking from up to 300 m to within docking range and provided six degrees of freedom for position and attitude[GNC.13]. The sensor head is mounted externally, and the laser and electronics box is mounted internally to eliminate environmental effects.

G. Power

Many subsystems on the mission have a significant interdependence with the power subsystem. These subsystems include Guidance Navigation and Control, communications, and propulsion subsystems. That means that all of those subsystems depend on the electrical power system of the spacecraft to perform their functions. For example, the GNC system is responsible for accurately calculating the location and velocity of the probes through launch into interplanetary trajectory, arrival at Venus, through separation and rendezvous of orbiter and descent vehicle, rendezvous of descent vehicle and VAV, and departure for Earth. Each vehicle will contain a star tracker, accelerometer, ring laser gyroscope, and control moment gyroscope. These instruments require electrical power to perform their vital functions. Therefore, it is evident that GNC success, and overall mission success, is critically dependent on the proper functioning of the electrical power system.

The power subsystem has four basic functions that must be considered. These basic functions include power source, energy storage, power regulation & control, and power distribution. For each function the hardware, software, and interfaces must be determined. Types of primary power systems include photovoltaic solar panels, thermoelectric source, thermionic source, thermodynamic source, fuel cells, primary batteries, and nuclear fission. Secondary power systems include NiCd (Nickel Cadmium), NiH (Nickel Hydrogen), Li+ (Lithium ion), and NaS (Sodium Sulfur) batteries[PWR.1].

Due to Venus' proximity to Earth, solar power will be the most applicable source of power for transit from Earth to Venus. The European Space Agency's (ESA) ExoMars Trace Gas Orbiter orbits Mars at a 400 km altitude. The ExoMars orbiter is powered by solar wings, as well as 2 lithium-ion batteries that have about 5100 Wh of total power capacity. The solar wings on the ExoMars orbiter are taking advantage of the solar energy flux from the sun.

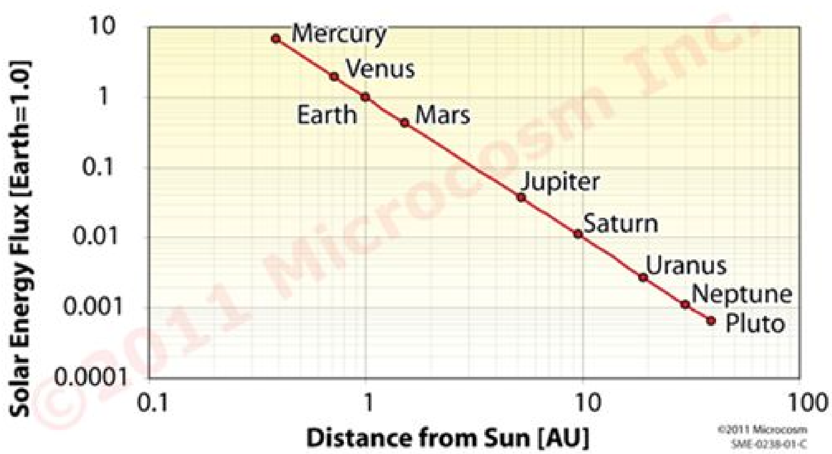


Figure 18. Solar Energy Flux as a Function of Distance from Sun

Figure 18 depicts the relation between the solar energy flux and distance from the sun. It also shows that there is a logarithmic relationship between solar flux and distance from the sun. Venus, being closer to the sun than Mars is, has an even greater solar energy flux. The increase in solar energy flux as the spacecraft moves towards Venus makes solar an extremely effective source of power.

The Soviet Venera, and Vega missions utilized solar power as well. These missions, 18 in total, demonstrate the ability to use solar power to power a spacecraft that is en route to Venus. The Venera 1 mission, which was launched on February 12th, 1961, used two solar panels with a total area of two square meters to power the 2.035 m x 1.050 m spacecraft. The Venera 4 mission, which was launched on June 12th, 1967, was powered by 2.5 square meter solar panel 'wings' with a span of 4 meters. The Venera 4 spacecraft consisted of a bus that was 3.5 meters high that was carrying a 383 kg lander probe which contained instruments crucial to mission success inside of a pressurized vessel[PWR.2]. And similarly, the Vega 1 mission was powered by twin large solar panels. The solar panels powered instruments that included an antenna dish, cameras, spectrometer, infrared sounder, magnetometers, and plasma probes. It is sufficiently evident that solar power is capable of powering the spacecraft as it transits from Earth to Venus.

Material options that were initially considered for solar panels included silicon, GaAs (Gallium Arsenide), and InP (Indium Phosphide). These options were narrowed down to silicon and GaAs. Indium Phosphide solar cells provide superior radiation resistance and their durability has been displayed on the LIPS III satellite[PWR.3]; ; however, the other two options have had wider use for space missions and have performed well. Silicon is commonly used as the material for solar cells on Earth. Silicon is the cheapest option and can be approximately 14-20% efficient[PWR.4]. GaAs solar cells were used on the Venera 3 mission, and serve as the solar arrays for the International Space Station (ISS). GaAs has a few key advantages over silicon. GaAs has a high efficiency, converting around 27% to 28% of sunlight into electrical power[PWR.5]. GaAs is flexible, lightweight, and provides more radiation resistance as opposed to silicon. Silicon does not absorb sunlight as well as GaAs, therefore more silicon is required per watt of energy than GaAs. Silicon solar cells also require a layer of rigid glass which further increases weight[PWR.5]. For these reasons, GaAs has been selected as the material for the solar cells. The solar panels will have a total surface area of about 11 m^2[PWR.4]. GaAs has a technology readiness level (TRL) of 9 based on its previous use on missions.

As in any space mission, redundancy is vital to the success of the mission. The solar cells will require a backup system in the event of damage due to foreign object debris, solar cell failure, or solar blocks such as an eclipse. The backup power system for the spacecraft will be a set of batteries. Initial battery options included NiCd (Nickel Cadmium), NiH (Nickel Hydrogen), Li+ (Lithium ion), and NaS (Sodium Sulfur), as aforementioned. The battery backup power is crucial to the mission. Backup power is utilized in events such as nighttime and eclipse experimentation, during launch and post launch until solar arrays are deployed, and to provide power if the solar arrays are not functioning. The batteries must be reliable, lightweight, able to operate in the extreme conditions of outer space, and have a long life[PWR.6]. The two competing battery options were narrowed down to Li+ and NiCd due to their previous use in space missions. The Explorer missions used NiCd batteries and many space applications today use Li+ batteries, including multiple Mars rovers. Overall, however, Li+ batteries were chosen as a backup power source due to their high energy density of around 265 Wh/kg, wide range of operating temperatures of -40°C to 50°C, and long life of 30000 cycles demonstrated at partial Depth of Discharge (DOD)[PWR.6]. The TRL of Li+ batteries is a 9 due to their previous use in missions. Due to the unavailability of solar energy on the surface of Venus, the lander will be powered by Li+ batteries. The mission will require a maximum of 3900 W of power depending on the launch window. The average power required is 2400 W and is displayed in Table 4.

Table 4. Mission Power Required[PWR.4]

Subsystem	Average Power Reqd. (W)	Maximum Power Reqd. (W)

Spacecraft (transit)	950	1500
Orbiter	650	1200
VAV	160	300
Lander	240	400

While the orbiter flies over the dark side of Venus where it receives no exposure to the sun, and in turn receives zero solar flux, the power system will utilize the Li+ batteries. The orbiter completes a full circular orbit once every 95 minutes, therefore the orbiter will utilize Li+ power for a third of the orbit (the region where no solar flux reaches). Once the orbiter is back to receiving power from the sun the newly depleted batteries will get recharged from the solar panels.

H. Thermal

One of the most crucial structural designs for the mission will be those that will protect the spacecraft from succumbing to heat and pressure. The Venera-D mission determines the following temperature limitations in order to successfully collect data[TH.1].

Orbiter

- -150°C up to +150°C for framework elements
- -50°C up to +50°C for mechanisms
- -20°C up to +40°C for service/scientific equipment.

Inside Lander

- -50°C up to +50°C

Capable heat shields are critical in entry and ascent. The environment will create significant convective and radiative heating levels as well as significant shear forces to the heat shields. Carbon phenolic and Teflon heat shields have proven to be able to withstand these limits. A study conducted by NASA Ames that compared the two showed that Carbon phenolic loses very little mass responding to the entry environment[TH.2]. While Teflon loses significant mass, if backed by a good reflective surface, it can withstand the heating environment with a reduced thickness required for reflection. Although heat shields will aid in maintaining a reasonable temperature within the structures, there are other precautions that must be taken in order to ensure a working environment for the payloads.

Interplanetary travel between the planets and data collection within Venusian atmosphere will utilize a combination of passive thermal control systems (PTCS) and active thermal control systems (ATCS) to maintain suitable temperature ranges within the structures in order to operate properly. PCTS systems will include multi-layer insulation (MLI), thermal fillers, thermal washers, thermal doublers, and radioisotope heater units (RHU). ACTS will include thermostatically controlled resistive electric heaters, fluid loops, single and two-phase loops, and thermoelectric coolers.

The structures that are involved in interplanetary travel and only exposed to the environment of space will mostly make use of structural coatings and multi-layer insulation (MLI). Thermal coatings, characterized by their thermo-optical properties, are most effective for the ERV due to their absorptivity, emissivity, reflectivity, and transparency. However, they are susceptible to degradation caused by the operating environment and the contamination induced by ground handling or space operations and cannot be used for the VAV and lander. MLIs consisting of layers of plastic material and coated on one or both sides with a layer of metallic material to reduce the radiation, will be used to reduce the radiated heat flux between hot and cold boundary surfaces to prevent large heat leaks.

Thermal control within the Venusian atmosphere and on the surface will use hybrid thermal control systems, which require simpler and lighter thermal control, enabling more functionality with less cabling. This will include liquid cooling systems and phase-change material, as well as heat exchangers, heat accumulators, internal thermal insulators, external thermal insulation, circulation fans, and honeycomb composite material for insulation. Thermal control zones will be required for subsystems such as avionics, advanced instruments, and low temperature energy storage, while sub–systems that dissipate most of the heat like telecommunication and power components should be placed outside of the thermal control zone.

Passive or active cooling would be applied only for components that cannot be hardened to tolerate the Venusian environment. High temperature tolerant components would be used where practical. Some temperature–sensitive components would be maintained inside an insulated thermal enclosure, while other more tolerant components would remain outside.

Sample acquisition and handling systems will directly interface with the environment, including in–situ sensors and drills. Venera 11 and 12 were the first missions to attempt at soil analysis with the onboard sampling system but were unsuccessful due to failed pressure seals. However, Venera 13 and 14, as well as Vega 1 and 2 systems, were capable of functioning at 500°C and consisted of a drill–based sampling assembly, a soil feed mechanism, a gas generator assembly for pyrotechnic devices, and a vacuum chamber[TH.3]. Unfortunately, the maximum operating temperature for available high temperature motors is currently limited to 270°C.

However, a switched–reluctance electric motor has been shown at Honeybee Robotics to run indefinitely, drilling into chalks with no gear reduction at Venus temperatures[TH.4].

Honeybee's switched-reluctance motor (SRM) design uses materials and components based on requirements to survive 460°C at Earth atmosphere. Motor performance is mainly driven by requirements of future Venus drilling and sampling systems and robotic arms. It has been operating non-continuously for over 20 hours in Venus-like conditions and is still functioning properly. Their temperature drill conducted three drilling tests in Venus-like conditions, successfully drilling into chalk to 6 inches deep in each test.

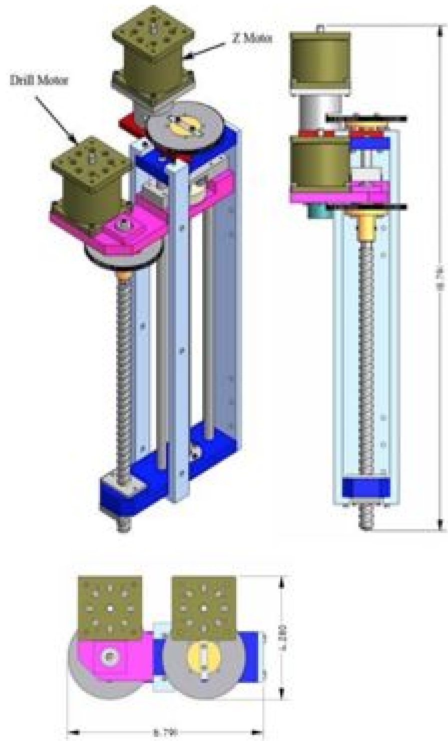


Figure 19. Honeybee High Temperature Drill Prototype

Along with all of this pre-cooling and active thermal control, there have also been large strides in the development of sensors that can continue to collect data under intense conditions. NASA Glenn has tested sensors within their Extreme Environments Rig for jet engines that would operate even in Venusian temperatures of 450° C[TH.5]. The combination of these give confidence in the success and longer lifespan of future Venus missions.

I. Scientific Instruments & Payload

This mission will be the first mission in history tasked with returning samples back from the atmosphere of Venus. Other than the atmospheric samples gathered, much more detailed data will be gathered on the surface using a lander designed to last longer than any other lander previously. Due to the complexity of air deploying the VAV for return to earth, no in-situ analysis of the atmospheric samples will be completed. All analysis will be done once returned to

Earth. This was a crucial decision as any failure would lead to the loss of the samples but simplifying the VAV design to exclude any unnecessary equipment will lead to a greater chance of mission success. Table 6 lists all the equipment that will be used to complete the scientific objectives of the mission. Science priority is decided based on the mission requirements and important that piece of equipment is to achieve the mission requirements . Primary objectives are listed as high (H) while secondary objectives are medium (M) and low (L) depending on the equipment. High priority equipment such as the gas capture system are listed as high since not only are they the primary piece of equipment used for gathering that specific data, but also because it is directly responsible for determining mission success. Equipment may be listed as low priority as it could be backup equipment such as the IR Spectrometer or are not directly tied to mission success.

A variety of seismic equipment and Spectrographs will be used onboard the lander to analyze the interior of the planet as well as the composition of the sediment on and just beneath the surface. A camera system will also be mounted on the lander to take some high-quality pictures on the surface. A variation of the Rock abrasion tool used on the Curiosity rover will be used to gather the sediment samples and they will be fed into a chamber that will contain all the tools from the spectrometers to analyze the sample non-destructively. This chamber will be isolated from the interior from the vehicle so that the equipment is not exposed to the atmosphere.

Table 5. Instrumentation[SIP.1-7]

Instrument	Description	Dimensions	Science Priority	TRL	Comments
Orbiter					
Panoramic Energy-Mass Spectrometer of ions	Spectrometer used for analyzing particle interactions with the upper atmosphere	140x156x156mm ; 2.5 kg; 1.4 W; 4Kb/s	M	9	
Eneregetic Particle spectrometer	Spectrometer used for analyzing highly energetic particles from the solar wind around Venus	180x200x100mm; 3-4 kg; 3-5 W; 1Kb/s	M	9	
UV mapping Spectrometer	Ultra-Violet spectrometer used for mapping of the atmosphere	150x150x200 mm; 3 kg; 4 W; 40Kb/s	H	7	
Visible /NIR light Spectrometer	Used for mapping the Atmosphere in near infarad and visible light spectrum	560x560x230mm; 25 kg; 21 W; 650Mb/h	H	9	
IR Spectrometer	Taking highly detailed measurements of the thermal spectrum of the atmosphere	200x200x100mm; 8 kg; 40 W, 25 Mb/h	L	5	
Magnetometer / plasma instrument	Measures the induced magnetic field and solar wind / upper atmosphere interactinos	150x150x150mm; 3 kg; 7 W; 10Kb/s	M	7	
IR Camera	Takes images of Venus in the IR spectrum	100x100x200 mm; 1 kg; 7 W; 1.6MB per image	M	9	
UV / Visible light camera	Takes images of Venus in the UV/Visible spectrum	220x200x430mmm; 4.1 kg; 19-34 W; 2 MB/image	M	9	
Synthetic Aperature radar instrument	Maps out the structure of the atmosphere	1.5x0.9x0.3 m; 154 kg; 200 W; 800 Kb/s	H	9	

Lander					
XRD / XRF	X-ray diffraction / X-ray Flourecence non-destructive sample analyzer	275x162x190mm; 5 kg; 30W; 100KB/sample	H	8	Requires sample
Mossbauer Spectrometer	Determindes the compsition of iron containing samples	40x40x100mm; 0.5kg; 3W; 5KB/sample	H	8	Requires sample
Camera System	Various lens camera and compression system to take images of the surface and decent	Camera lens' 80x80x60mm, 0.2kg each; Digital camera unit 100x120x80mm, 1.5 kg, 12 W, up to 2.4 MB/image	M	9	
Gas Chomotographer and Mass spectrometer (GC-MS)	Determines the elements and compounds in the atmosphere and soil samples	GC 260x180x130mm; MS 250x150x110mm; 20.5 kg; 60 W: 1 MB/measurement	H	9	Requires sample
Raman Spectrometer	Used to analyze chemical compounds for organic molecules	300x300x250mm; 8 kg; 80W	M	8	
Rock Abrasion tool (RAT)	Grinding system arm mounted to gather surface samples	70(diameter)x100mm; 0.72 kg; 30 W;	H	7	Required access to the exterior of the vehicle
Seismometer	Measures seismic activity on the surface to analyze structure of the planet	310x310x310mm; 5kg; 8.5 W; 38 Mb/day	L	9	Must be placed on the surface away from disurbances
Heat Flow and Physical Properties Package (HFPPP)	Drills into the surface to measure heat flow through the planet to gain information about the inner structure	280x280x280mm; 3 kg; 2 W; 350Mb	M	7	Requires soft enough landing site to drill
VAV					
Atmospheric Sample Collection System (ASCS)	Passive gas collection system	1 L Container Volume; 3 Containers; 2kg/container	H	6	Containers must be resistant to interplanetary enviornmental conditions
Particulate Matter Aerogel Capture System (PMACS)	Passively deployed grid of aerogel tiles	304x304mm Capture Area; 2-4 kg	H	6	Grid container must be resistant to interplanetary enviornmental conditions

The orbiter is tasked with using a power radar instrument to scan the surface as it orbits and creates a detailed topographical map of the surface as well. There will also be an assortment of ultraviolet, Infrared, and visible light cameras on board that will analyze the winds and cloud formation in the atmosphere. Combining the radar and camera data will allow a detailed analysis of how heat is transferred around the planet through the atmosphere. It has been shown that the interaction between the solar wind and the upper atmosphere of Venus creates an induced magnetic field around the planet although the planet has no natural magnetic field of its own, this will be analyzed on this mission through the high energy plasma instruments and mass spectrometers on board.

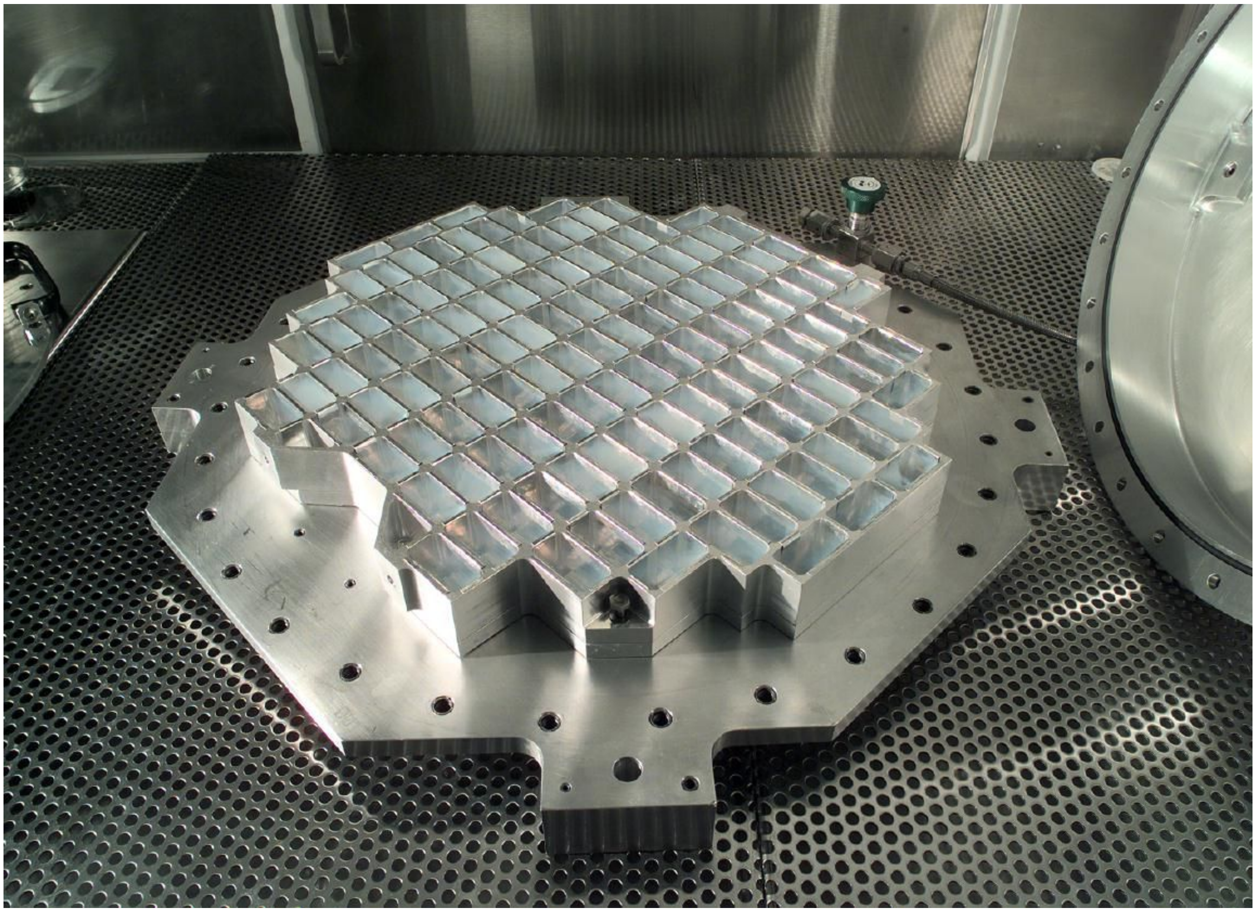


Figure 20. Aerogel collector on stardust mission

The VAV will contain 3 separate gas canisters that can collect atmospheric samples at 3 different altitudes: 70 km, 65 km, & 60 km. These tanks will be very simple in operation only using simple valves to allow the gas in with no active pumping system. Also the VAV will contain an aerogel capture system that will be deployed at the same time the gas capture system is. This will be a 304 mm x 304 mm square block that will be able to catch small particles that can be analyzed back on earth. This aerogel system is based on the design of the capture system used in the StarDust mission that captured dust particles from the tail of a comet and returned them to earth. This system can be seen in Figure 20**.** When retracted the aerogel system will be insulated from the vacuum from space on the return trip so that the sample is not destroyed.

V. Summary Tables

The summary table below portrays estimated mass, power, volume, and costs of the mission broken down by each structure's subsystems.

Estimates of structural masses, power requirements, and volume were based on those of heritage missions as well as newer technologies. The lander will closely resemble previous missions, although it will likely make use of lighter materials that have advanced since these missions. It is on the lower average of previous lander masses that have been used in Venusian exploration. The VAV estimations are based on existing sounding rockets, while the orbiter estimations resemble that of orbiters that have been used to explore other planets, while also considering that it will need to be built more durable to make the round trip. Since these considerations are purely structural, there is no power requirement associated with this subsystem.

The tables listed within the Appendix B show the performance metrics of the engines that were compared. The tables listed in the propulsion subsystem description show how the fuel requirements changed depending on system configuration. The results from analysis are color coded to show their performance level with red being the worst and Green being the option that has been selected for the mission.

The biggest take away for the power subsystem is that the whole mission requires 2.3 kW of power. The solar arrays will be able to meet this requirement with ease due to the solar flux. The majority of cost comes from development and launch of the high-tech gallium arsenide solar arrays.

The scientific equipment onboard the mission has all been chosen according to how effectively that piece of equipment will achieve the goals of the mission. Also overlap in the data collected from each piece accounts for redundancy of data in case of some equipment becoming disabled or inoperable. This redundancy will increase the likelihood of mission success.

The Guidance, Navigation, & Control subsystem uses several instruments to determine the position and orientation of the spacecraft with respect to its surroundings. These values were based on the manufacturer's information provided. The orbiter required the most instruments since it has to be able to arrive at Venus, rendezvous, and return to Earth. The largest instrument was Kurs-NA at 45 kg, and was placed solely on the orbiter. However, no estimate of the Kurs-NA volume was found in literature during research. The lander and VAV required only a fraction of the instruments on the orbiter since they mostly only required short-range navigation and rendezvous.

The mass and power requirements for the communications subsystem were designed to give the links between all components of the mission adequate margins. The power consumption for each link includes a factor of safety which would allow the link margin to be increased if needed. The volume for the subsystem was calculated by taking the rough total volume of the antennas, i.e. parabolic antennas use the volume equation for a disk. The majority of the volume is taken up by the orbiter's high-gain antenna, which has a diameter of 3m.

The power requirements for command and data handling were relatively high considering their low mass and volume, due to their compact size. The RAD 5545 will use large amounts of power since the orbiter will be the center of communication for the mission. Most of the cost of this subsystem comes from research and development of the SiCJFET.

Thermal estimations for mass, power, volume, and cost were determined using information about previous Venus exploration missions, as well as information about technologies that have been developed since that will be utilized during the VEGAN mission. Power requirements resembled proposed levels by Advanced Cooling Technologies for a Venusian mission, as well as those determined for NASA's Mars Earth Return Vehicle. Volume and mass estimates will be lighter than previous missions, as the VEGAN mission will utilize less ATCS like active cooling, which will lessen the plumbing, and therefore decrease the mass and volume. Costs were determined by evaluating current and progressing thermal control systems that will be utilized throughout the mission.

The cost of launching the VEGAN payload on the Falcon Heavy is retrieved directly from SpaceX, who launch payloads into geostationary transfer orbit for $90 million.

Table 6. Mass, Power, Volume and Cost Estimate by Subsystem

Summary Estimates

Subsystem	Mass (kg ±10%)	Power (W ±10%)	Volume (m^3 ±10%)	Cost (Millions USD)
Orbiter				
Structures	2500	0	130	200
Propulsion	14500	0	64.28	75
Power	860	1500	0.55	100
Payload	75	325	2	10
GNC	70	136	0.024	7
Communications	180	700	10	30
C & DH	20	20	1	3.5
Thermal	300	1200		2
VAV				
Structures	280	0	17	1.5
Propulsion*	1580	17000	1.5	10
Power	360	300	0.48	5
Payload	10	0	1	1
GNC	9	42	0.011	2
Communications	20	10	1	0.3
C & DH	20	40	0.1	5
Thermal	100	250		1
Lander				
Structures	1500	0	35	500
Propulsion	0	0	0	0
Power	360	400	0.23	2.5
Payload	50	225.5	1	25
GNC	9	42	0.011	2
Communications	100	10	8	2
C & DH	50	25	0.5	15
Thermal	800	1000		20
Launch				90
Total				
	23753	23225.5	273.686	1109.8

*Note: Power requirement for VAV propulsion unit is for the battery pack powering the main engine. Battery pack only needs to be charged once and used, it is not a continuous power requirement.

VI. Conclusion

The VEGAN mission hopes to honor previous Venus exploration missions, as well as the ever advancing technologies of the modern world in their goal to learn more about Venus than ever before. VEGAN has taken constraints and heritage missions into consideration in order to design one of the first Earth Return missions in history. The goal of this mission is to survive on the surface for at least 3 hours, longer than any previous mission, and the successful return of atmospheric gas and particle samples to Earth.

This revolutionary mission is to launch on the Falcon Heavy rocket into transfer orbit before making its 112 day journey to low Venusian orbit. New, ground-breaking structures will be used to collect and analyze samples of Venus's atmosphere and surface. The Earth Return Vehicle, Venusian Air Vehicle, and lander will be built with the newest technologies and material in order to survive its time on Venus and throughout interplanetary travel.

Advanced attitude determination systems for guidance, navigation, and control will be used, with each part of the mission having additional attitude determination and control systems that can be engaged in the event the primary system fails.

The Vinci engine will be the main engine for the mission, whose fuel will be stored in new Carbon Composite Fuel tanks. A solid rocket motor modeled after the STAR 48 and a Rutherford engine will be incorporated into the innovative design of the VAV that will enter the Venusian atmosphere only to rendezvous with the orbiter once again.

Power sources, energy storage, power regulation, and power distribution have been studied extensively to ensure that each and every part of the mission is supplied with the power necessary to carry out the mission successfully. Flexible and lightweight gallium arsenide solar panels of about $11m^2$ will absorb energy throughout travel and will be stored in lithium ion batteries that will supply the mission structures.

Advanced passive, active, and thermal control systems will ensure that these structures will survive the harsh Venusian conditions as well as the lengthy round trip between Earth and Venus. The latest heat-resistant sensors, motors, and technology will be used to avoid succumbing to these difficult conditions.

Six links between the Deep Space Network, the orbiter, the lander, and the VAV will ensure communication and data feedback throughout the mission. With assistance of the RAD 5545 radiation-tolerant computer used in the orbiter, all components of the mission will have adequate data storage and computing capabilities.

This $1.1 billion, 16 month mission will be one of the most iconic of its time. For decades, Venus has been considered a terrifying, hell-like planet for its 740 K temperatures and 93 bar pressure at the surface. However, it has always piqued the interest of the curious for the possibility of it shedding some light on where we came from and where we are going. The VEGAN team hopes to learn more about Venus, and Earth, than ever before.

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Appendices

A-1:

Solar Power Trade Study

Material	Energy Efficiency (%)	Cost (Million USD)	Volume Required (m^3)	TRL	Score*
Silicon [PWR.7]	17	120	.75	9	2
Gallium Arsenide [PWR.7]	27	100	0.55	9	1
Indium Phosphide [PWR.8]	16	108	0.81	7	3

***Note: scoring is based on a 1 through 3 scale. 1 is the best score, 3 is the worst.**

A-2:

Backup Power Trade Study

Material	Energy Density (Wh/kg)	Life Cycle	Operating Temperature (C)	Score
Li+[PWR.6]	265	30000	-50 to 60	1
NiCd[PWR.9]	150	30000	-40 to 60	2
NiH[PWR.9]	120	30000	-20 to 60	4
NaS[PWR.9]	150	25000	-30 to 60	3

***Note: scoring is based on a 1 through 4 scale. 1 is the best score, 4 is the worst.**

B-1:

Main Engine Specifications

Engine	Maufacturer	Weight(kg ±5%)	Power (kW kg ±5%)	Thrust (kN kg ±5%)	Specific Impulse (seconds kg ±5%)	Fuel	TRL
RL10A-4-2	Aerojet Rocketdyne	168	N/A	99.195	451	LOX/LH2	9
RD-0146	KBKhA	260	N/A	68.9	463	LOX/LH2	9
HM-7B	Snecma	165	N/A	64.8	444.6	LOX/LH2	9
Vinici	Snecma	280	N/A	180	467	LOX/LH2	7-8
RD-843	Pivdenne/Pivdenmash	15.93	N/A	2452	315.5	N2O4 / UDMH	9
RD-0410	KBKhA	2000	N/A	35.3	910	Nuclear / H2	6
X3	NASA (et. Al.)	300	200	0.005	2000	Xenon	6

B-2:

VAV Engine Specifications

Engine	Manufacturer	Dry Mass (kg ±10%)	Fuel tank mass (% ±50%)	Thrust (kN ±10%)	Specific Impulse (sec±5%)	Fuel	Stage	TRL
RL10A-4-2	Aerojet Rocketdyne	168	8%	99.195	451	LOX/LH2	Upper	9
HM-7B	Scnema	165	8%	64.8	444.6	LOX/LH2	Upper	9
Rutherford	Rocket Lab	80kg w/ Power Pack	3%	24	311-343	LOX/RP1	Lower/Upper	9
STAR 48A-1	Northrup Grumman	N/A	5%	Configurable	290	HTPB	Lower	9
GEM series	Northrup Grumman	N/A	5%	Configurable	245	HTPB	Lower	9

C-1:

Guidance, Navigation, & Control trade studies. All systems are on orbiter.

System	Manufacturer	Weight (kg ± 5%)	Power (W ± 5%)	Volume (m^3 ± 10%)	TRL
MANS, Computer[GNC.2]	Microcosm	4.81	30	0.007079	7-8
MANS, Scanner[GNC.2]	Microcosm	3.08	14	0.001768	7-8
MANS, Electronic Unit[GNC.2]	Microcosm	7.98	Passive	0.004025	7-8
*LN-200S[GNC.5]	Northrop Grumman	0.784	12	0.000574	8
Coarse Sun Sensor[GNC.9]	Bradford Space	0.215	Passive	0.000363	9
Kurs-NA[GNC.10][GNC.14]	NIITP	45	50	—	9
*NGAVGS[GNC.12]	Advanced Optical Systems	8	30	0.010324	8

Note: the * references instruments that are included on the lander and VAV.

D-1:

Link Budget

Link Budget - VEGAN								
Parameters			DSN	Orbiter			Lander	VAV
Item	Symbol	Units	FWD -> Orbiter	RET -> DSN	FWD -> Lander	FWD -> VAV	RET -> Orbiter	RET -> Orbiter
Freq.	f	Ghz	7.15	8.42	32.00	32.00	34.50	34.50
Xmtr Pwr	P	W	100000	500	30	150	10	10
Xmtr Pwr	P	dbW	50.00	26.99	14.77	21.76	10.00	10.00
Efficiency	μ		0.67	0.55	0.55	0.55	0.55	0.55
Xmtr line loss	L_l	dB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
Xmtr Ant. Beamwidth	θ_t	deg	0.08	0.83	6.56	6.56	0.30	12.17
Peak Xmt. Ant. Gain	G_{pt}	dB	66.66	45.86	27.92	27.92	54.59	22.55
Xmt. Ant. Diam.	D_t	m	35.00	3.00	0.10	0.10	2.00	0.05
Xmt. Ant. Pointing Offset	e_t	deg	0.02	0.10	0.10	0.10	0.10	0.30
Xmt. Ant. Pointing Loss	L_{pt}	dB	-0.68	-0.17	0.00	0.00	-1.30	-0.01
Xmt Ant. Gain	G_t	dB	65.98	45.69	27.91	27.91	53.30	22.54
EIRP	EIRP	dB	114.98	71.68	41.69	48.67	62.30	31.54
Prop. Path Length	S	km	200000000	200000000	1000	3000	1000	3000
Space Loss	L_s	dB	-275.56	-276.98	-182.55	-192.10	-183.21	-192.75
Prop. & Polariz. Loss	L_a	dB	-1.00	-1.00	-5.00	-2.00	-5.00	-2.00
Rcv. Ant. Diam.	D_r	m	3.00	35.00	0.05	0.05	0.03	0.03
Peak Rcv. Ant. Gain	G_{pr}	dB	45.86	66.66	22.55	22.55	17.46	17.46
Rcv. Ant. Beamwidth	θ_r	deg	0.98	0.07	13.13	13.13	20.29	20.29
Rcv. Ant. Pointing Error	e_r	deg	0.20	0.02	0.10	6.56	0.20	0.20
Rcv. Ant. Pointing Loss	L_{pr}	dB	-0.50	-0.95	0.00	-3.00	0.00	0.00
Rcv. Ant. Gain	G_r	dB	45.36	65.71	22.55	19.55	17.46	17.46
System Noise Temp.	T_s	K	614	135	165	135	54	39
Data Rate	R_i	bps	256000	220000	128000	128000	200000000	256000
Estimated E_b/N_o	E_b/N_o	dB	29.23	12.17	32.03	27.35	18.52	12.85
Bit Error Rate	BER		1.00E-07	1.00E-07	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Required Eb/No	E_b/N_o	dB	4.40	4.40	9.60	4.40	9.60	4.40
Implementation Loss		dB	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00
Link Margin		dB	22.83	5.77	20.43	20.95	6.92	6.45