VSAUCE: Venus Strategic Atmosphere/ Upper Clouds Explorer

Venus Atmospheric Strategic Science Investigation

L'SPACE Mission Concept Academy - Spring 2021

Team 35

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Special thanks to

the amazing Sheri Klug Boonstra and Dann Garcia
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and Ian Ho-Sing-Loy and Natalia Castillo
for being part of Team 35, regardless of how short their tenure.
The team wishes them all the best in their future endeavors.

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1. Introduction and Summary

1.1. Team Introduction

Dequan Jones is a sophomore student at Chabot College in Hayward, California who will soon transfer to San Jose State University to study computer engineering in Fall 2021. Dequan has experience with the programming languages C++, MATLAB, and Python. In 2020 he participated in the NCAS program where he learned a lot about NASA and improved his communication and teamwork skills. Currently, Dequan is the Project Manager and Safety Officer of L'space MCA Team 35.

James Tseng is a sophomore at University of California, Los Angeles who is studying Aerospace Engineering. He is also involved in another team project with an aerial robotics student organization through the NASA ARMD Undergraduate Student Research Challenge where he has gained experience with the proposal and prototyping process. His area of interest include guidance, navigation, and controls, and autonomous systems; his proficiencies include C++, MATLAB, and CAD (SolidWorks). Currently, James is the Deputy Project Manager and Financial Planning of this team and is involved with the engineering team, and looks forward to designing the aircraft to fly in Venus.

Aurelia Moriyama-Gurish is a freshman at Yale University currently studying Mechanical Engineering and Astrophysics. She is currently involved in the Yale Undergraduate Aerospace Association and is working on robotics sensor designs. Aurelia is proficient in C, C++, MATLAB, and Python programming languages. Currently, Aurelia is the Science team manager and specifically focusing on astrophysical applications.

Mike Huetter is a junior at UC Berkeley originally studying Mechanical Engineering, but added on an Electrical Engineering/Computer Science major. Mike is incredibly interested in robotics as well as most systems mechanical and/or electrical. His skills include AutoCad, Solidworks, Fusion, Eagle, Altium, Java, C, Assembly language, Python, and Matlab. Mike is currently the Engineering team manager and is utilizing his wide breadth of knowledge on the engineering of the project.

Meroujan Mike Bagdadian is a junior at California State University Northridge who originally transferred from Los Angeles Pierce College to study computer science. After successfully completing NCAS during the summer of 2020, a spark ignited which motivated him to continue his participation in the various NASA programs available to college students. His areas of interest include database systems, web development, mobile development, and software engineering. He is most familiar with C/C++, Java, Python, Swift and Go. Mike is excited to contribute his knowledge and problem solving skills to the project.

Juana Arratia is a junior at University of California, Riverside studying Bioengineering. Juana originally transferred from San Diego City College. She has done research summer programs in the past, and has experience with C++, Matlab, COMSOL. She loves research and is excited to explore different ways bioengineering can be applied.

Stephen Seager originally transferred from California State - Fullerton's Mechanical Engineering department and is now currently a senior at California State University - Long Beach studying Aerospace Engineering His areas of interests include rocketry and aviation, with experiences as President of Fullerton's rocket team, and now Vice-President of Long Beach's AIAA chapter. He is proficient with engineering software including matlab, autocad, and solidworks. He has completed the NPWEE Academy and is excited to be a part of MCA.

Aastha Ghimirey is a freshman at University of California Santa Cruz. She is currently studying Computer Science and is looking into majoring in Technology and Information Management. She is proficient in programming languages including Java, Python, and JavaScript. And is currently part of the Society of Women in Engineering in University of California Santa Cruz.

1.2. Mission Overview

1.2.1. Mission Statement

The primary goal of Venus Strategic Atmosphere/ Upper Clouds Explorer (VSAUCE) will be to further the characterization of the atmospheric composition of the Venusian Cloud Tops (at an altitude of ~50 km to 70 km). To accomplish this VSAUCE will employ a high-altitude aerial platform in the Venusian Cloud Tops to collect relevant data. VSAUCE will use the objective measurements within each of the larger goals in order to ensure that each field will be able to benefit from the high-altitude data collected by the instruments. The main scientific goals of the VSAUCE mission are divided into three major sectors:

(a) Habitability: To understand Venus' early history and understand it's habitability potential (or past habitability) and give insight into planet formation within habitability zone

(b) Atmosphere and Energy Exchange: To understand Venus' current atmospheric dynamics and composition (tracking energy deposition and transfer throughout system)

(c) Geological Evolution: To understand the geological history of Venus and present-day interactions between the crustal surface and atmosphere

VSAUCE will use four scientific instruments to collect data of atmospheric composition, atmospheric conditions, and magnetic fields. Within each of the above scientific goals VSAUCE will address the following scientific objectives through the use of the on-board scientific instruments:

(a) Habitability: To determine the history of water on Venus and whether life is or ever has been present on Venus through characterization of atmospheric composition using the two spectrometers (**TLS** and **AMS-N**)

(b) Atmosphere and Energy Exchange: To understand the current composition of Venus' atmospheric composition and energy exchange using data collected by the two spectrometers (**TLS** and **AMS-N**) and the radiation dosimeter and radiometer on the **MET Suite**.

(c) Geological Evolution: To understand the current tectonic or volcanic activity present on Venus through the data collected by the on-board **MAG** and **MET Suite**

A more detailed description of the methods in which each of these instruments will achieve each of these objectives and their respective functions is detailed in *1.4 Payload and Science Instrumentation*.

This mission will aid in furthering all of the major science goals of the Flagship Mission to Venus through data collection within the upper atmosphere. The data collected on this mission may provide further insight into the history and habitability of Venus and revolutionize the search for life.

1.2.2. Mission Requirements

The mission must fulfill the following mass, volume, and cost mission constraints:

(a) The balloon shall have a mass no greater than 175 kgs (385.81 lbs)

(b) The balloon shall have a volume no greater than 60cm x 70cm x 90cm (23.62in x 27.56in x 35.43in) while being stored as a secondary payload

(c) The cost of the mission shall not exceed the $250 million budget

The design constraints of the mission will also need to meet the following expected requirements:

(a) The balloon must have an appropriate entry and descent angle

(b) The balloon must operate within the thermal atmospheric conditions of the Venusian Cloud Tops

(c) The balloon must be able to stabilize in high-g environment and protect instruments during entry

Each of these constraints will be used to guide mission design of the engineering and scientific instrumentation of this mission while maximizing data acquisition to support the mission objectives and main scientific goals.

1.2.3. Mission Success Criteria

The mission success criteria will be guided primarily by the success of the scientific instrumentation data collection. The success of the mission will thus be characterized by the successful completion of the experimental phases.

Phase 1: This stage of the mission is characterized by the first circumnavigation of the VSAUCE balloon. During this phase, the instruments will collect data from a constant altitude within the middle cloud deck -56 km. Completion of the phase will be marked by the successful downlinking of data from each of the instruments to the orbiter.

Phase 2: This stage of the mission will consist of two following circumnavigations of the balloon as it begins to collect data at variable altitudes. The instruments will continue to collect data at these varied altitudes throughout the lower, middle, and upper cloud deck. Completion of this phase will also be marked by the successful downlinking of data from each of the instruments to the orbiter.

Phase 3: This stage of the mission will encompass the remaining circumnavigations the balloon is able to perform preceding its end of life (EOL). During this phase, the instruments will continue to collect data as it varies it's altitude, descending each incrementing altitude by 1 km each circumnavigation. This will allow a great characterization of the vertical atmospheric composition of the cloud deck as well as below the cloud deck. Completion of this phase will be determined by the number of successful data linking circumnavigations the balloon will be able to complete before its EOL.

Each of these experimental phases is further expanded upon in *4.2.4. Experimental Logic, Approach, and Method of Investigation.* Completion of the first two phases will provide a successful mission as the data from these two phases will significantly improve current understanding of the habitability, atmospheric composition, and geological evolution of Venus. Data collected during phase three will also aid in the continued understanding of these characteristics of Venus, but are not considered a requisite to the success of VSAUCE's mission.

1.2.4. Concept of Operations (COO)

The concept operations for this mission are shown in the diagram below.

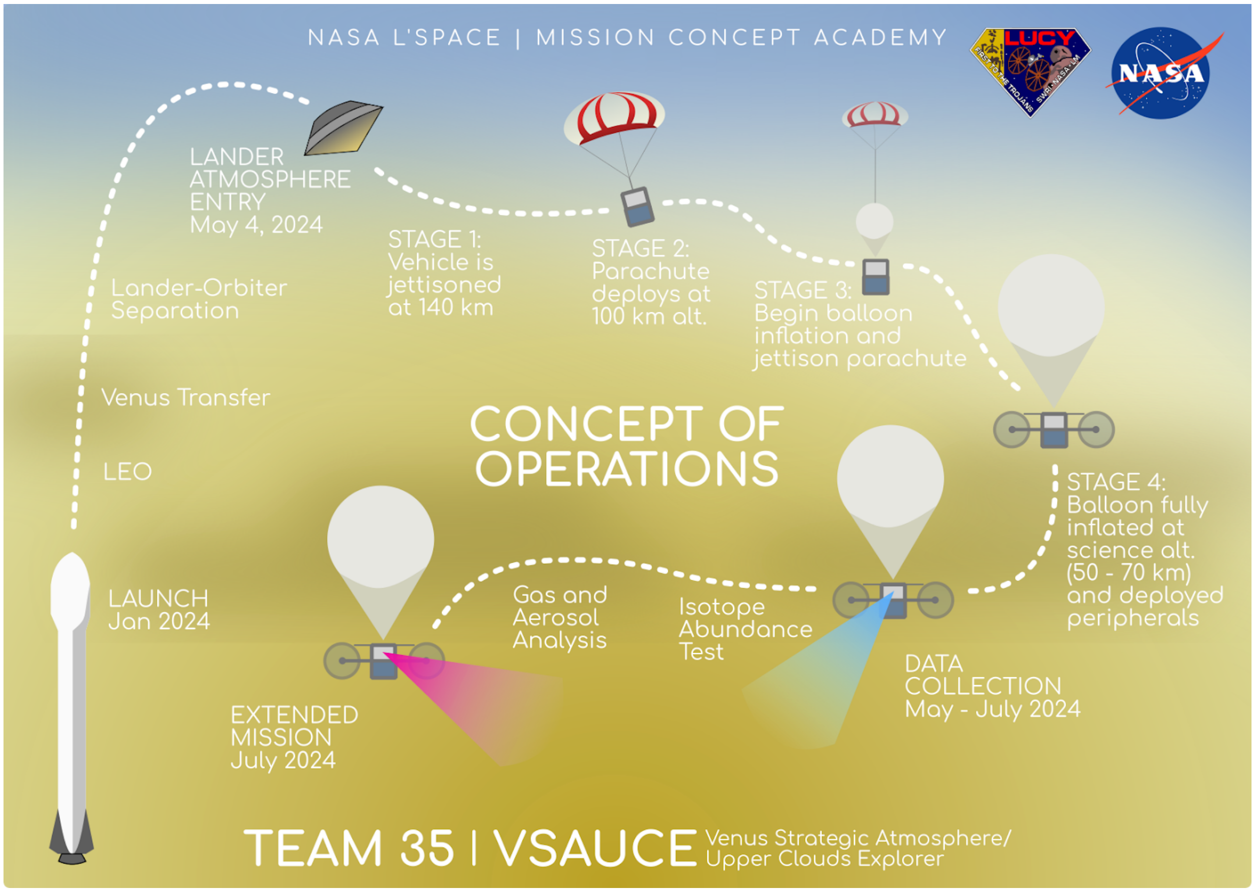

Figure 1. Concept of operations graphic.

Since this mission is to serve as the secondary payload, the mission begins at 200 km in altitude when the lander deploys this mission's vehicle. The team estimates that the initial launch will commence in a window around January 2024, tentatively Jan 11, 2024, and take approximately four months to arrive at Venus.

The Entry and Descent procedure, which ultimately does not conclude with a landing since this is an airborne mission, is conducted in four stages and is described in detail below in Section 1.3. (Descent Maneuver and Vehicle Design Summary). At the end of the descent procedure, the vehicle reaches the science altitude where it can begin its autonomous mission to collect data. The mission timeline expects at least 45 days of deployment to be considered successful. The mission, however, is expected to last much longer than that duration and has an extended duration planned for the remainder of its operational life.

1.2.5. Major Milestones Schedule

1. **Pre-Phase A: Conceptual Study** - Jan 12, 2021

2. **Phase A: Preliminary Analysis** - Jan 19, 2021

3. **Phase B: Preliminary Design and Technology Completion** - February 8, 2021
    a. **Preliminary Design Review (PDR)** - April 19, 2021
    b. **Tech Completion** : April 19, 2021 - October 25, 2021

4. **Phase C: Final Design and Fabrication** - October 25, 2021
    a. **Critical Design Review (CDR) -** October 25, 2021
    b. **Fabricate and Code Products** - Oct 25, 2021 - April 26, 2023
    c. **System Integration Review (SIR) -** April 26, 2023

5. **Phase D: System Assembly, Integration and Testing, Launch** - May 3, 2023
    a. **Assembly and Integration** - May 3, 2023
    b. **Test Readiness Review** - July 5, 2023
    c. **Formal Testing Stage -** July 5 2023 - September 6, 2023
    d. **Flight Readiness Review** - September 6, 2023
    e. **Flight Tests and Operations -** September 13, 2023 - December 14, 2023
    f. **Launch** - Jan 11, 2024
6. **Phase E: Operations**
    a. **Primary Mission** - 60 days duration, May 11, 2024 - July 10, 2024
    b. **Extended Mission** - July 10, 2024 - TBD

1.3. Descent Maneuver and Vehicle Design Summary

The vehicle is designed as a balloon and gondola system to reduce complexity and further the Aerobot design as proposed in the Venus Flagship Mission with an added system to provide attitude control, propulsion, and as a secondary power generator turbine. The vehicle in its stowed configuration has a dimension of 60 cm by 66 cm by 81.8 cm which conforms to the mission volume constraints. The vehicle's expected mass is 139.74 kg, which conforms to the mission mass constraints. The team also expects the maximum mass to be 188 kg, which is just slightly outside the constraints. This is a good indicator that the vehicle will be able to comply with the constraints by launch. The Entry and Descent Maneuver is outlined in the graphic below.

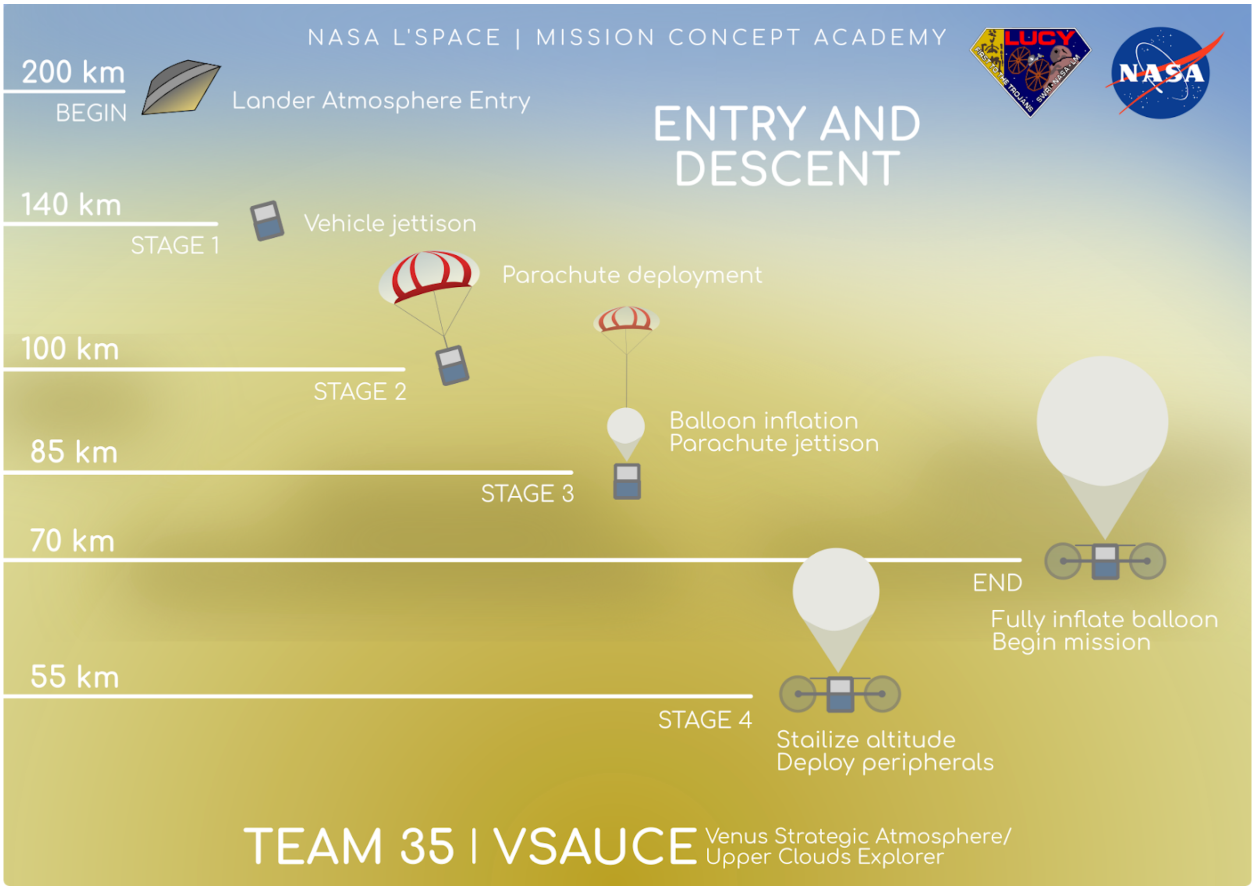

Figure 2. Entry and descent graphic.

The vehicle will enter the atmosphere at an altitude of 200 km as a secondary payload to a Venus lander for the primary mission. At 140 km when the lander detaches the main payload and the vehicle, stage 1 is commenced when the vehicle is jettisoned to freefall so that it will fall away and clear itself from the other components also fallin in the vicinity.

Stage 2 commences when the vehicle senses it's barometric pressure is equivalent to the predicted Venusian altitude of 100 km, which the freefall time is kept track of on a timer, and is factored into the subsonic parachute deployment time.

Stage 3 commences at roughly 85 km in altitude where the balloon begins inflation. The Balloon System will activate in order to ensure the vehicle can maintain stability and float at the desired altitude range of 70-50 km (TBR). The balloon will inflate for 60 seconds, at which the subsonic parachute, with the vehicle now being slowed to 10 m/s 85km above the venusian surface. After 385 seconds of inflation, the subsonic parachute will be jettisoned, and the vertical movement of the balloon shall be controlled using the balloon apparatus.

Stage 4 occurs roughly after 615 seconds the vehicle will be 55km above the surface and float. At this juncture, the balloon system (internal and external) shall be completely inflated. Upon being fully inflated, the vehicle will rise to the height of 70km, the top of the science altitude, and begin circumnavigation and charging the solar panels.

1.4. Payload and Science Instrumentation Summary

To accomplish each of the above mission-specific objectives, the team will be using the following instrumentation, each of which will contribute to either (a), (b), or (c) science objectives listed above in 1.2.1 Mission Statement:

- **Aerosol mass spectrometer with installed nephelometer (AMS-N)** will measure the light scattering from particles to characterize them (a) (b) (c)
- **Tunable Laser Spectrometer Instrument (TLS)** will perform aerosol detection and analysis, including organic material (a) (b)
- **3-D Fluxgate Magnetometer (MAG)** will measure and characterize the magnetic fields or magnetic field remnants present as well as capture any magnetic signals emitted from lightning sources (c)
- **Meteorological Suite (MET Suite)** will measure the barometric pressure, air temperature, the up and downwelling fluxes, the ionizing radiation levels, and the vertical winds. Each of these will be measured by individual sensors which will report to a single data handling unit (b) (c)

2. Evolution of Project

2.1. Evolution of Mission Experiment Plan

Iteration 1:
Scientific Goals:

1. Investigate signs of current or past life
2. Determine composition of the atmosphere in the cloud layer
3. Investigate seismic activity

Experiment Plan:

Deploy an aerial platform to the middle cloud deck at a constant altitude ~56 km and determine the composition of the atmosphere with a gas chromatograph mass spectrometer, investigate the presence of seismic activity using an infrasound sensing microphone, and investigate the possibility of current or past life using the flourometric microscope.

Summary:

While the goals listed in this iteration are a good start, the team felt that it would be better to make the mission's goals more broad and include specific objectives that should be accomplished to contribute to such goals.

Iteration 2:
Scientific Goals:

1. Habitability: Determine the history of water on Venus and whether life is or has ever been present on Venus
2. Atmosphere and Energy Exchange: Understand the current composition of Venus' atmosphere and energy exchange
3. Geological Evolution: To understand the current tectonic or volcanic activity present on Venus

Objectives:

1. To collect spectrometric data of the the atmospheric particles and test for evidence of and other particles indicative of past life
2. To accurately determine the percent composition of the Venusian atmosphere and understand the radiation distribution
3. To understand the presence of volcanic activity through detection of sulfuric particulate matter in the air and to measure the magnetic field of Venus in order to understand its geologic evolution

Experiment Plan:

Deploy a variable altitude balloon within the Venusian cloud layer to accomplish objectives using an aerosol mass spectrometer with a nephelometer combo (AMS-N), a tunable laser spectrometer (TLS), a meteorological suite of instruments, and a magnetometer. The balloon would ascend/descend within the cloud layer from ~51 km altitude to ~62 km to determine any vertical variation in isotopic ratios.

Summary:

Including specific objectives for each goal helped the team figure out exactly which instruments are most significant for the mission. The Vega missions of the past did include balloons however these balloons remained at a constant altitude for the duration of their missions. Team 35 chose to measure at various altitudes within the cloud layer because it has never been done before. Varying the altitude would allow the team to gain a wealth of information about the history of Venus and its atmosphere that has not yet been revealed.

Iteration 3:

Scientific Goals:

4. Habitability: Determine the history of water on Venus and whether life is or has ever been present on Venus through characterization of the composition of the atmosphere
5. Atmosphere and Energy Exchange: Understand the current composition of Venus' atmosphere and energy exchange
6. Geological Evolution: To understand the current tectonic or volcanic activity present on Venus

Objectives:

4. To collect spectrometric data of the the atmospheric particles and test for evidence of and other particles indicative of past life
5. To accurately determine the percent composition of the Venusian atmosphere and understand the radiation distribution
6. To understand the presence of volcanic activity through detection of sulfuric particulate matter in the air and to measure the magnetic field of Venus in order to understand its geologic evolution

Experiment Plan:

The science team decided that the mission should be carried out in experimental phases. Although the balloon would be designed to last 60 days on Venus, that is not a guarantee. To ensure that the balloon could at least accomplish the minimum success criteria for this mission, the first phase would be to allow instruments to take measurements at a constant altitude during the first circumnavigation.This provides time to ensure the instruments are calibrated and the measurements taken in this phase will provide a baseline for measurements in the next phase.

Phase two experiments will occur for three circumnavigations. In this phase, the balloon will vary it's altitude, ascending/descending between a 51 km altitude to a 62 km altitude. The balloon will do this once during the day and once during the night so that not only vertical variation in measurements can be considered, but also diurnal variation.

In phase three the balloon will carry out bonus experiments. These experiments are not required for mission success but if the balloon has survived beyond the first two phases, it will have the opportunity to gather as much information as possible below the cloud layer

Summary:

While the goals stayed the same, the science team had to consider the possibility of the balloon not surviving as long as expected. This is why the team developed experimental phases. The first phase would accomplish the minimum success criteria but the completion of phase two would reveal a lot more significant information about Venus. Organizing the experiments this way felt like the best way to accomplish this mission's goals.

2.2. Evolution of Descent Maneuver and Vehicle Design

The vehicle design underwent significant changes as the science team decided on the mission experiment plan. Three iterations are shown below.

Iteration 1:

The first vehicle design proposed very early on in the development for this mission was a multi-vehicle deployable fixed wing swarm of aircraft. This design was largely inspired by the Aerovironment Switchblade 600 tactical missile system. The Aerovironment Switchblade 600 drone is designed with outwards folding wings and control surfaces (elevator and tail), so that they are cylindrical in shape when stowed in and launched from a tube (*Tactical Missile Systems*, 2021).

Figure 3: Rendering of deployed Aerovironment Switchblade 600.

This design would have been implemented as four rectangularly shaped drones that would deploy in a similar manner but together from the rectangular volume constraint of the Venus lander. Each individual vehicle would hold certain scientific instruments necessary for the scientific mission, and fly independently rather than in formation so the mission as a whole sees a greater sample area.

The decentralized aspect of this vehicle design may overall increase the redundancy in the event one vehicle fails to deploy, but the decentralized approach is rather limited in scope and poses significant challenges to the budget since each drone must carry it's own flight computer, active propulsion, power generating sources, and communication systems. The redundancy that can be built into such small aerial vehicles is quite hard to achieve in budget. The risk of failure is also significantly higher for each vehicle since the vehicle must be constantly propelled to remain afloat, and power generation is much harder for a vehicle of this size, which is possibly catastrophic should it fly into the dark side of Venus.

These combined risks would have rendered the mission with a very short timeline, possibly with a mission lifespan of less than 10 days. Since the science team had decided on an experimental mission with a timeline of at least 60 days, it became abundantly clear that this multi-vehicle deployable drone system is not sufficient to carry out the mission requirements.

Iteration 2:

The team decided on a balloon airframe based on the Venus Flagship. Another balloon design iteration for the vehicle was shaped similar to a hollow dumpling. This design is efficient because it is very aerodynamic as well as the large bottom keeps the mass distribution close to the bottom of the vehicle. This design also gives a large enclosed space to help shield the internals from any jerk caused by the descent maneuver (which is still about the same as the current iteration) and the strong winds.

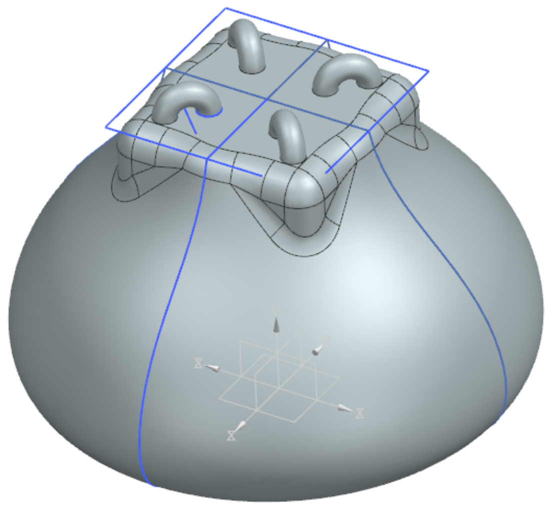

Figure 4: Dumpling CAD model render.

As the team conducted more research on past Venus missions, it became clear that the vehicle does not have to be aerodynamically efficient, since it is directly carried by the wind, and that the inclusion of turbines meant that higher drag was actually desired. Further, the aerodynamics of the vehicle is trivial compared to the high drag form factor of the balloon itself.

Most of the components are also individually shield from corrosive elements, and therefore the structure would not have to shield the component, particularly since many of the components need open access to the atmosphere for measurement or for cooling purposes. In addition, this design added a lot of complexity in internal structure and possible manufacturing complexities. This design is also not the ideal shape for the volume dimension constraints.

Iteration 3:

In deciding on the inclusion of attitude control and turbine, an idea proposed was to achieve a longitudinal form factor of the balloon to induce form drag so that the balloon faces a particular direction in the strong Venus winds, similar to an airship. This design featured a cylindrical shaped balloon that was also variable altitude, with a spherical superpressure interior balloon.

The vehicle initially in the stowed state would be rectangular to fit in the required volume. The deployment process was mechanical, actuated by the tethers attached to the initial parachute, which would pull the balloon out as well as rotating the top two quarters of the structure to it’s deployed position in front and behind. Also using the mechanical force of the tethers, the magnetometer as well as the two propellers mounted on booms will be extended. A rough deployment diagram is shown below (without the turbines).

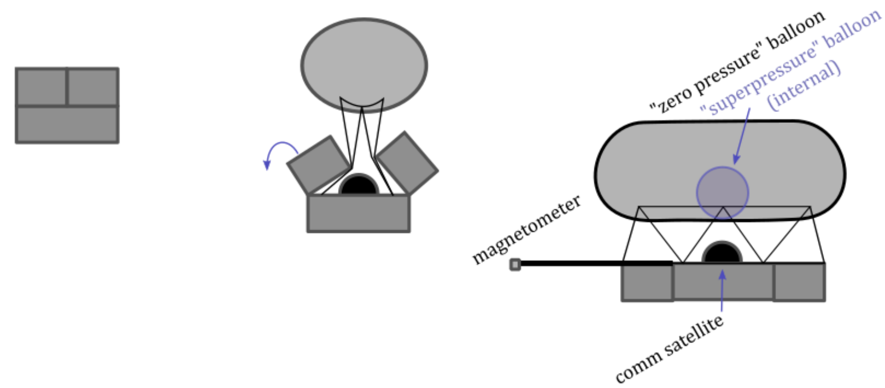

Figure 5: Drawing of longitudinal structure and balloon deployment.

This design was ultimately not chosen due to the complexity and risks involved with a deployable structure, such as the possible deployment failure or even possibility of structural failure. The cylindrical balloon would pose a significant design challenge due to the changing volume and as to how to engineer the shape to produce an optimal form in both high altitude and low altitude configurations. This design would also expose more surfaces (and interior) to the Venusian atmosphere, and thus require more shielding which would carry more weight against the mass constraint.

2.3. Evolution of Payload and Science Instrumentation

Iteration 1:

1. **Gas Chromatograph Mass Spectrometer:**
   A GCMS is the combination of two useful and very powerful tools, a gas chromatograph and a mass spectrometer. The gas chromatograph essential takes in a gas sample and separates different molecules in the mixture. At different times, the molecules are released by the gas chromatograph to be analyzed by the mass spectrometer.

2. **Atmospheric Structure Instrument:**
   A package of very useful tools including wind, air temperature, and pressure sensors and a nephelometer to determine size of aerosol particles.

3. **Fluorometric Microscope:**
   Measures the cloud droplets for small traces of constituents associated with past or present life.

4. **Infrasound Sensing Microphone:**
   Microphone that detects infrasound waves caused by seismic events.

Summary:

Initially, the team was not entirely certain on which goals to accomplish. This uncertainty was reflected in the team's first iteration of instrumentation. While a spectrometer is always useful, the science team was still deciding on exactly what type of spectrometer to use. The GCMS is a good choice but the team felt there may be a better option.

The Atmospheric structure instrument package would be very useful in characterizing the atmosphere in the cloud layer so this instrument package was considered by the science team to be a great option. The only reason this package is not included in the following iterations is because it evolved into the meteorological suite (MET Suite) which includes similar instruments along with a few others.

Although the detection of phosphine in the Venusian clouds is now believed to be a false alarm, this team considered a confirmation on the presence of current or past life would be a great goal to The infrasound sensor was replaced in following iterations because the MET suite includes a barometric pressure sensor that can detect seismic activity.

Iteration 2:

1. **Tunable Laser Spectrometer:**
   Useful for identifying isotopes in gas samples and determining isotopic ratios which provide insight into physical and chemical processes occurring in the atmosphere.

2. **Aerosol Mass Spectrometer with nephelometer:**
   A mass spectrometer and nephelometer combo with two sample inlets. One inlet is for gas samples that are ionized, sorted, then detected by a mass spectrometer. The other inlet is for sampling aerosol particles to be analyzed by the nephelometer which will determine size, shape, and refractive index of particles. Useful for distinguishing between different particles.

3. **Meteorological Suite:**
   Includes a barometric pressure sensor to read ambient atmospheric pressure and detect infrasound waves caused by seismic activity. Wind and air temperature sensors are also included. Radiation dosimeter measures radiation levels in the cloud layer.

4. **Fluorometric Microscope:**
   Measures the cloud droplets for small traces of constituents associated with past or present life.

5. **Magnetometer:**
   The magnetometer will search for remnant crustal magnetic fluxes as well as determine any magnetic signals emitted from lightning.

Summary:

After confirming the main scientific goals for this mission, instrumentation changed drastically between iterations 1 and 2. The Tunable Laser Spectrometer was considered to be a very significant instrument for its ability to measure isotopic ratios that can provide insight into the evolution of Venus' atmosphere.

Mass spectrometers are capable of measuring a wide range of species in the atmosphere so having one will make it easier to fully characterize the cloud layer. The mass spectrometer decided on by the science team would be the Aerosol Mass Spectrometer that includes a nephelometer. It replaced the GCMS because it is capable of measuring both gas composition and properties of aerosol particles and more found in the Venusian clouds. Mass spectrometers can sometimes confuse some isotopic species and that is what the TLS specializes in. These two spectrometers compensate for each other's weaknesses and will provide a wealth of information that not only contributes to the first mission goal but even the second and third as well.

The fluorometric microscope would be a significant instrument in determining current or past habitability on Venus however the cost to include such an instrument and the fact that it only contributes to one of the three mission goals made it a lot harder to keep around. The magnetometer was inexpensive compared to other instruments so it was considered a necessary instrument.

Iteration 3:

1. **Tunable Laser Spectrometer**

2. **Aerosol Mass Spectrometer with Nephelometer**

3. **Meteorological Suite**

4. **Magnetometer**

Summary:

The team decided to stick with four of the five instruments from the previous iteration because each one was capable of significantly contributing to the mission goals stated in the third iteration of the mission experiment plan. The issue with the fluorometric microscope is that it has a high cost, it is at low TRL, and requires complex mitigation methods to avoid risks that may cause it to fail. The science team decided that too much would be at risk if this instrument was implemented. Also, compared to the other instruments, its contributions would be minimal despite its high cost to manufacture.

3. Descent Maneuver and Vehicle Design

3.1. Selection, Design, and Verification

3.1.1. System Overview

The overall vehicle design has the main design intent of supporting the science equipment but the design is constrained by the 60 cm by 70 cm by 90 cm volume allotted as the secondary mission cargo. Thus a major design factor space optimization and minimal complexity to reduce the risk of component failures.

The team decided to pursue a balloon design due to the lack of complexity and relatively simple descent maneuver and design. The main capsule has a cylindrical cavity in the center and an octagonal outer shape where most of the scientific instruments and circuitry are attached. The cylindrical cavity holds the helium pump and folded balloon while it is being delivered to Venus. The balloon is a variable altitude balloon like Aerobot as proposed in the Venus Flagship Mission, which has a balloon-in-a-balloon connected via a pump to be able to achieve different balloon volumes and thus different buoyancy for varying altitudes. The inner balloon is filled with very dense helium and will be used to inflate the other balloon for altitude control.

The vehicle utilizes the upwards tension on the tethers caused by the parachute and balloon to deploy the extendable appendages found on the vehicle, which are the propulsion motor turbines, the antennas, and magnetometer. These components are connected to the cables that attach the balloon to the payload so this mechanism will lock into place once the cables go taunt. With this design the vehicle is able to utilize long poles needed for the antenna and wind turbines in the limited space confinements. There is also a compartment on the bottom of the vehicle sealed from the atmosphere that contains the batteries and circuit boards to protect these components from the sulfuric acid in the atmosphere.

The vehicle structure with the motors stowed, antennas and magnetometer deployed, CAD render tertile views are shown below.

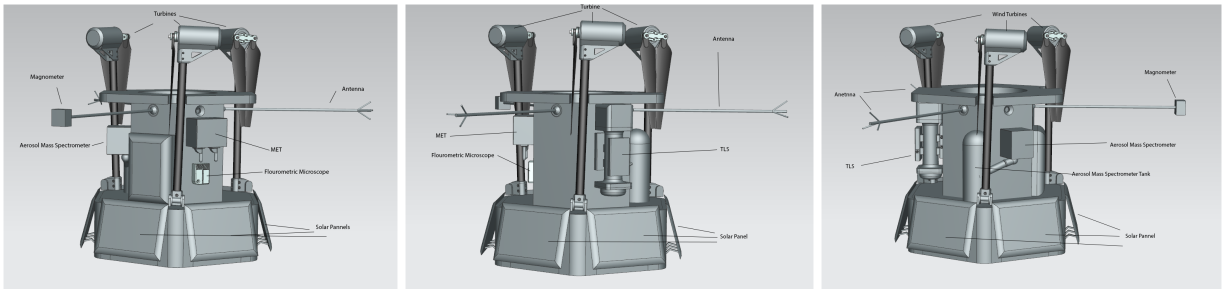

Figure 6. CAD render tertile views of vehicle and scientific payload

The vehicle with the expanded balloon CAD render is shown below.

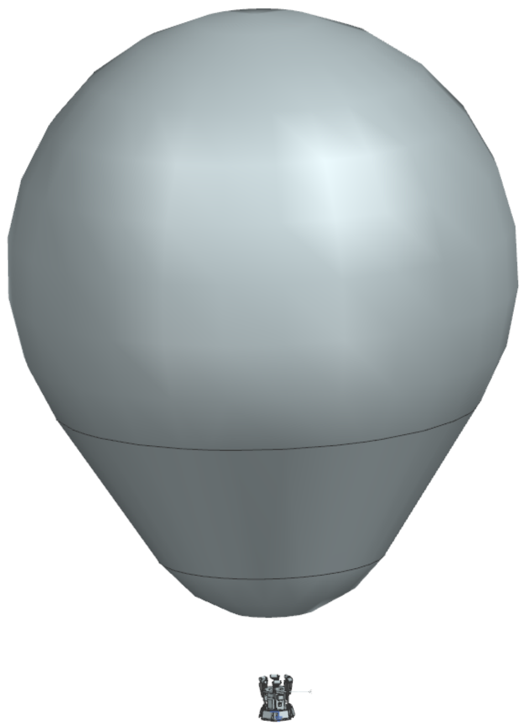

Figure 7. CAD render of vehicle with inflated balloon/

The overall mission entry, descent, and float maneuver will utilize a single-parachute system under subsonic conditions since the vehicle is dropped at 140 km altitude at a vertical speed of 35 m/s downwards, as per the main mission's requirement. The Entry and Descent procedure is outlined again in the graphic below.

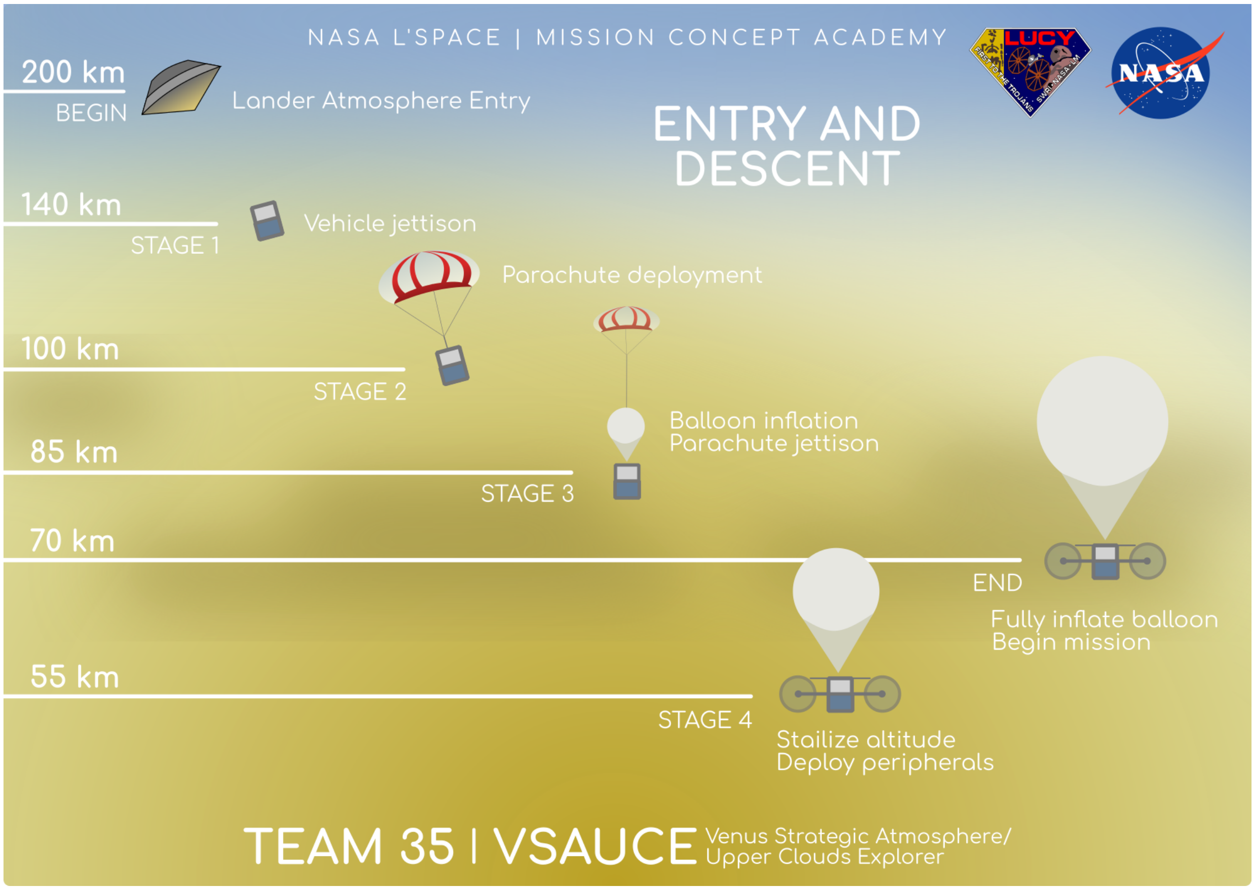

Figure 8. Entry and descent graphic.

The parachute shall be housed and layered in the vehicle's stowed state, and the first parachute deployment will occur once the vehicle structure opens. Upon initial opening, the vehicle will remain in it's open position so that the balloon deployment will be simplified, with the parachute pulling the balloon material out of the stowed compartment.

The subsonic parachute (DGB) shall deploy at 100 km (TBR) while the vehicle is in a state of free-fall to ensure that the vehicle is clear of other components from separation of the primary mission. With the deployment of the subsonic chute, the vehicle will begin balloon inflation and will be slowed to 10 m/s and at an altitude of 85 km (TBR) above the surface and the subsonic chute will be jettisoned. At 55 km above the surface, the vehicle will be slowed to maintain altitude via the balloon. The Balloon System shall be in full control of the ascent/descent of the vehicle for the remainder of the mission, in which the first step will be to fully inflate the balloon to reach the top of the science altitude at 70 km, to both test the balloon capability as well as to charge via the solar panels. The weight of the subsonic parachute is expected to be 7 kg (TBR). A trade study shall be conducted to determine the material for the parachute strings, however the main candidates are nylon and kevlar.

The Balloon System will be housed within the center storage area of the vehicle, with the tethering and cable systems of the parachutes and the balloon underneath the Balloon System. The tether system will consist of a 3 point mount tether configuration to a single union buckle along in order to provide tangle-proof deployment and release during the parachute and ballooning sequences.

The vehicle is designed to be electrically powered, as this setup is the simplest to integrate all power dependent systems and instruments, and with power generation. Six batteries will store the energy produced by both solar panels and power turbines, and feature MPPT charging to maximize the amount of charge stored in the batteries. The batteries should hold sufficient charge to allow for the science payload to continue operations in the dark side of Venus. The turbines benefit from having wind gusts ubiquitous throughout Venus, and thus would be able to operate ideally continuously and generate additional power in the dark side of Venus.

The vehicle, unlike the Aerobot proposed in the Venus Flagship Mission (Gilmore et al., 2020), differs in design with the inclusion of active attitude control through the use of two motors and propellers mounted on the ends of deployable booms. This serves two purposes, for attitude control and propulsion, and as a secondary power generator by allowing wind gusts to turn the propellers and backdrive the motor as a generator. The attitude control and turbine subsystem are controlled by the flight computer utilizing the peripheral sensors and position tracking through the orbiter.

In order to communicate with the orbiter, antennas are required to deliver and receive information for both the science payload measurements and the flight controls. Two antennas are utilized on the vehicle for redundancy. Due to the thick atmosphere and possibility of clouds interference, L band frequency radios (1-2 GHz) are a good candidate for the medium of transmission. Due to the balloon structure, the antennas must be placed far away from the vehicle in order to minimize blocking by the balloon. The antennas will be mounted on booms and stowed during transit to Venus, and deployed through tethers connected to the balloon, and extend out away from the balloon.

3.1.2. Subsystem Overview

The vehicle subsystem is divided among the functional operations of the vehicle, which are the vehicle structure, deployment and balloon, power generation, power storage, propulsion and turbine, system control, and communication. The vehicle's expected mass is 121.44 kg without the scientific payload, and the expected maximum mass to be 164.9 kg. The breakdown of the components by subsystem of mass taulation is shown below. The total mass discussed in context with the scientific payload is included in Section 7 Conclusion.

Sub-system	Component	Quantity	Expected Mass (kg)	Maximum Mass (kg)
Structure	Vehicle Structure	1	25	30
Structure	Shielding and Insulation	1	0.5	1
Balloon	Parachute	1	7	10
Balloon	Zero-Pressure (ZP) balloon	1	14	16
Balloon	Super-Pressure (SP) balloon	1	7	8
Balloon	Helium Pump and Stored Gas	1	18	22
Balloon	Tethers	6	0.1	0.3
Power	Solar Panels	6	1	1.5
Power	300 Ah Battery with BMS	6	6	9
Power	MPPT Charger Module	3	0.3	0.8
Propulsion	BLDC Motor	3	0.3	0.5
Propulsion	Folding Propellers	3	0.18	0.2
Propulsion	Electric speed controller (ESC)	3	0.07	0.1
Propulsion-Structure	Carbon Fiber booms	3	0.08	0.2
Propulsion-Structure	Motor housing and structure	3	0.2	0.4
Propulsion	Thermometer	3	0.07	0.1

Control	Flight computer	2	0.05	0.1
Control	IMU/Inertial Navigation System	2	0.32	0.5
Communication	Data transmitter	2	0.75	1
Communication	Antennas	2	0.5	1
Structure	Wiring	1	0.5	1
	Total Mass (kg)		**121.44**	**164.9**

Table #: Vehicle component subsystem breakdown

The vehicle's specific (without scientific payload) power consumption and generation is tabulated in section 3.1.7 Performance Characteristics and Prediction

Vehicle Structure

The overall structure of the vehicle is designed to keep the vehicle as vertical as possible in the turbulent environment as well as protecting its cargo from the atmosphere. To maintain the vehicle's upright position, the overall weight should be evenly spread across the vehicle with a higher distribution near the bottom, keeping the center of gravity in the center near the bottom. This will allow gravity to help keep the gondola portion vertical as the torques should resist pitch and roll rotation. This is incorporated into the vehicle through symmetry around the yaw axis. The vehicle is designed as a hexagonal prism shape with large plates on the top and bottom so it looks like a I when viewed from the side. This increases the moment of rotational inertial to help stabilize the craft. Each scientific instrument is also spread out on each side of the hexagonal prism to balance out their weight. The batteries are positioned on the bottom of the vessel to keep the center of mass near the bottom. Most of the features that can pattern are patterned, such as the solar panels, turbines, batteries, and antennas.

Most of the equipment is safe to be exposed to the Venusian upper atmosphere due to sealant and shielding. However, the design mitigates risks with the electronics such as the batteries by isolating them inside the structure to protect it from the sulfuric acid and high winds. Additionally, it helps shield the other components of the vehicle if a catastrophic failure occurs with any of these parts (e.g. a battery explosion).

Deployment and Balloon

The Balloon System consists of a balloon-in-balloon apparatus and the balloon inflation system, which will continuously pump helium into the balloon-in-balloon apparatus and will eventually be jettisoned. The Balloon System is placed in the center of the vehicle on top of the tether system during flight and entry. Upon deployment of the subsonic parachute at 100 km, the balloon shall begin inflation. The Balloon System will activate in order to ensure the vehicle can maintain stability and float at the desired altitude range of 70-50 km (TBR). The balloon will inflate for 60 seconds, at which the subsonic parachute, with the vehicle now being slowed to 10 m/s 85km above the venusian surface. After 385 seconds of inflation, the subsonic parachute will be jettisoned, and the vertical movement of the balloon shall be controlled using the balloon apparatus. After 615 seconds the vehicle will be 55km above the surface and float. At this juncture, the balloon system (internal and external) shall be completely inflated, and the vehicle shall jettison the balloon inflation system. Upon being full[y inflated, the vehicle will rise to the height of 70km and begin circumnavigation.

As stated, the Balloon System consists of two sections: an upper/outer balloon chamber and a lower/internal housing chamber. The outer balloon chamber pressure will match the atmospheric pressure of the current altitude, with a max altitude being 70km above the surface **(value of pressure 70km above the surface)** and a minimum of 50km above the surface **(value of pressure 50km above the surface)**. In order to decrease in altitude, the outer balloon will transfer helium to the internal chamber, or external exert helium to match the appropriate pressure of the desired altitude. The internal chamber will be at a higher pressure, thus will be able to conduct appropriate pressure changes for the outer chamber as altitude decreases.

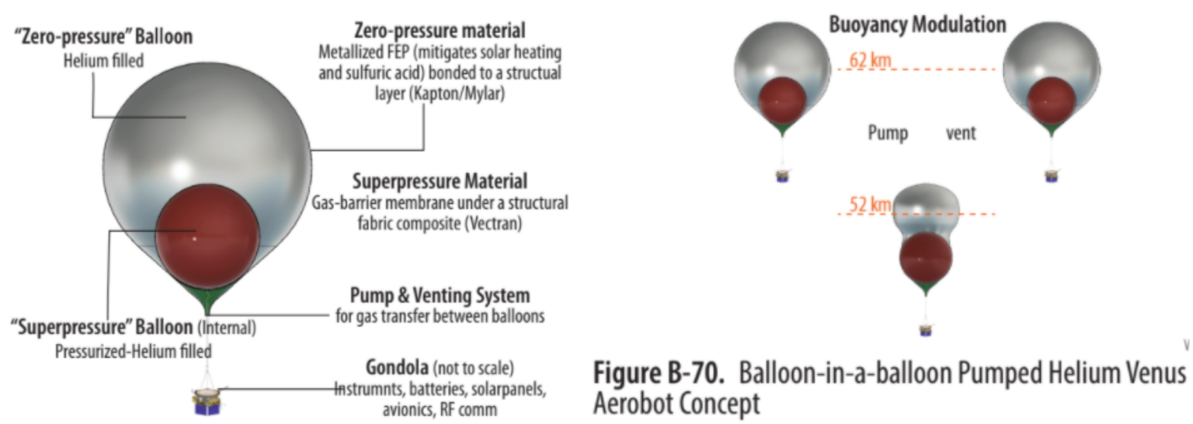

Figure 9. Aerobot balloon-in-a-balloon system. (Gilmore et al., 2020).

The balloon will begin circumnavigation at upon full inflation and rising to 70km, with the fully inflating balloon reflecting a spherical shape. As altitude decreases to 50km throughout the timeline of the mission, the balloon will resemble a top-heavy figure 8 shape due to the outer balloon tightening around the internal chamber at the base. The balloon system, upon inflation, will be 17m tall, with an outer chamber diameter of 16m and an internal chamber of 8m. The balloon material will consist of Mylar-Kapton as it acts well under solar heat.

Primary Power Generation

Using solar as the main form of power generation is ideal due to the increased solar intensity in the Venusian atmosphere. This is particularly the case at higher altitudes, as shown below, where above 65 kilometers, the atmosphere is almost clear, and provides very capable power generation with solar panels.

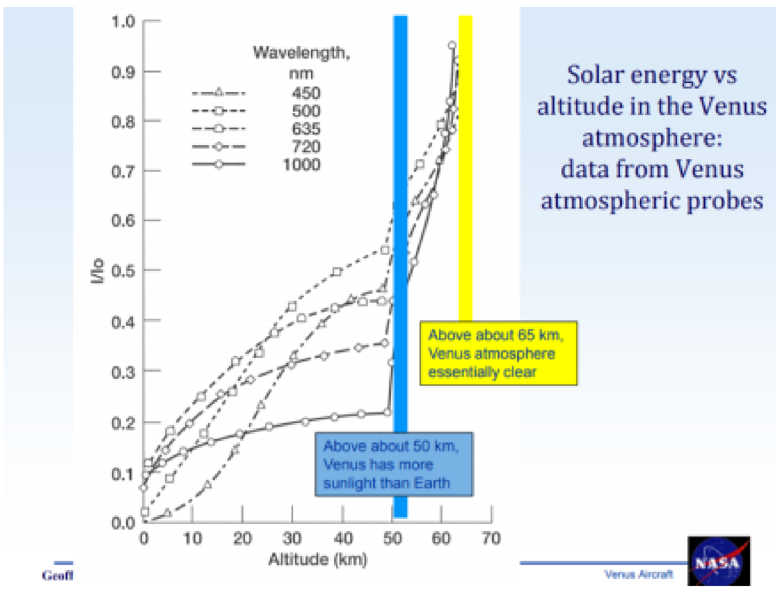

Figure 10: Solar energy vs altitude in the Venus atmosphere. Slide 6 (Landis, 2013).

This energy is harnessed through solar panels. The panels will be placed on each facet of the hexagonal body of the vehicle. Since the vehicle will spend the majority of its time in the upper atmosphere on the cloud tops, the albedo factor due to the clouds will be quite large, and thus the radially facing solar panels take advantage of the reflected sunlight from all directions.

A good commercial off the shelf (COTS) candidate for solar panels are the PHOTON solar arrays that utilize the AzurSpace 4G32C solar cells, in which the cells have a peak efficiency of 32.2% (*32% Quadruple Junction GaAs Solar Cell*, 2019). These solar panels have a proven flight heritage in satellites and SmallSats missions and deemed a technology readiness level of 9 (Dunbar, 2020). However, this technology has not been proven in environments such as the corrosive environment of the Venus atmosphere. Therefore, further trade studies and verification will need to be conducted in order to render the COTS solar panels to be mission ready.

From the provided data sheet of the AzurSpace 4G32C solar cells, which are a Quadruple Junction GaAs solar cell, the average power produced in nominal conditions is roughly 1.3 watt. This is approximated with the fact of Venus' higher solar irradiance; the beginning of life (BOL) power produced is roughly 1.5 watts, while decaying to about 1 watt after 1E16 MeV absorbed. With a surface area about 1 square meter allocated to solar panels, and the area of each cell is 30.18 square centimeters, rounded up to 31 square centimeters to account for other power electronics, the vehicle can accommodate a maximum of 333 solar cells. Design wise, this indicates 55 cells per side of the hexagonal structure, which can be constructed in strings of 11. This indicates that the vehicle would be capable of producing 495 watts of power at optimal conditions, and on the lower bound roughly 300 watts of power. The overall vehicle power consumption and generation is tabulated in Section 3.1.7 Performance Characteristics and Prediction.

Power Storage

The power generated by the solar panels and turbines are stored through batteries. First, the power generated is passed through a Maximum Power Point Tracking (MPPT) and hardware voltage and over-current protection unit, which is critical to maximize power efficiency and to protect the battery to maintain battery overloading protection. The designed 6 300 Ah battery packs will be capable of delivering 1.8 kAh power if wired in parallel. However, this configuration decision can be changed if certain instruments require higher voltage power. This requirement will need to be further revised on the basis of the battery cell chosen and volume constraint of the battery packs the vehicle is capable of holding.

No specific candidate for battery cells have been chosen at this time, although a trade study is to be conducted. Based on flight heritage and studies conducted by past NASA research, COTS cells made by Samsung, Sony, Panasonic, and LG are good candidates (Bugga et al., 2019). The Samsung 35E has the highest specific energy density, but verification testing will determine which cells can sustain corrosion the longest in the Venusian atmosphere (Dunbar, 2020).

One candidate for the MPPT and battery protection system is the NanoAvionics EPS Maximum Power Point Tracking (MPPT) power conditioning and distribution unit (*CubeSat Electrical Power System EPS*). The unit has a 96% conversion efficiency which is optimal.

Propulsion and Turbine

The propulsion and secondary power generation is mounted on booms that extend outwards from the vehicle to utilize a larger flow volume and allow greater yaw actuation. Due to the volume constraint requirement, the booms must be stowed and the propellers folded prior to the descent. This adds complexity to the deployment of this system. The design accounts for this through redundant deployment mechanisms. The primary method of deployment will be through a cable and pulley system that is actuated from the tension of the balloon tethers deploying. The pin joints of the booms are designed to mechanically lock into the deployed position once the position is reached, and remain locked in position until the end of the mission.

The propeller blade design will be determined iteratively through simulation and analysis for the optimal balance of thrust, torque, and revolutions per minute (RPM) of the motor in both propulsive and generative states of operation. The propellers will be fabricated out of non-corrosive materials such as nylon or carbon fiber, which have good light-weight properties and high rigidity. Trade studies will determine the optimal material.

The brushless direct current (BLDC) motors are chosen for it's high RPM capability and reliability without electrical contacts of brushes wearing down over time, compared to a brushed DC motor. The motors and electronic speed controllers (ESC), as well as the temperature sensors in the motor housing, will be sealed airtight and the motor shaft lubricated with anti-corrosive lubricants. Testing in Venus atmospheric-like conditions will characterize the operating conditions, such as temperature, duration before overheating, and possible lifespan predictions.

Utilizing turbines as a power generation is feasible due to the high winds and periodic oscillations and gusts. Due to the horizontal and vertical shears, the turbine is able to be powered during these transient changes in wind speeds. Other studies and white papers following the Decadal Survey explored the use of these shears to power gliders, as shown below. Black Swift technologies has developed a high-fidelity simulation of the wind patterns by modeling the "convective plumes (3 m/s) measured by the Vega balloons," (Elston et al., 2020).

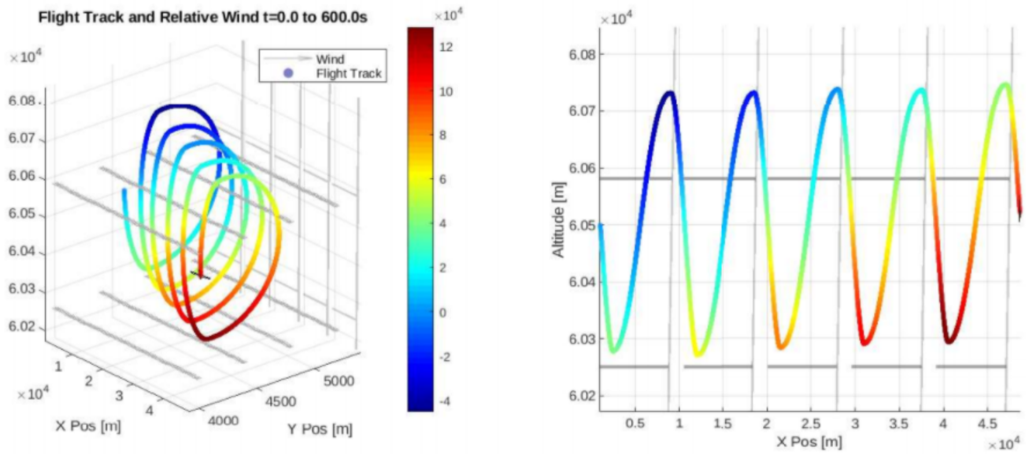

Figure 11: Oscillations in flight path due to periodic wind gusts. (Elston et al., 2020).

Since the vehicle has significant mass (>150 kg) and a high drag factor, the high level of oscillation in wind gusts would not instantaneously carry the vehicle at the same speed, thus sufficient for the turbines to spin.

For the motors to supply power as a secondary power source, the motors are also connected to full bridge rectifier modules with six diodes, since the BLDC motors are three phase, to convert the AC power generated to DC. The power is directed to the MPPT charger to maximize the generator efficiency. Since the propeller blades are optimized for both thrust and power generation, the power generated will not be as much as a purpose-built generator, such as a Ram Air Turbine (RAT) seen on aircraft. Using an estimate of a nominal 5 watts of power generated by each turbine, which is based off of measurements from a RAT mounted on an unmanned aerial vehicle (UAV) (Valencia et al., 2020). This charge power is considerably small compared to the power generated by the solar panels, and thus is mainly supplemental charge that will be useful in the dark side of Venus, and most of the charging to be conducted in the sunlit side of Venus. The overall vehicle power consumption and generation is tabulated in Section 3.1.7 Performance Characteristics and Prediction.

Attitude Control

The motivation for attitude control is to enhance achieving objective (c) of the stated mission goals to understand volcanic activities on Venus. It would be ideal for the vehicle to maneuver close to known or suspected volcanic sites. Since the vehicle will be carried by the high speed wind currents, it is ideal for the vehicle to be capable of maneuvering into a wind current that carries the vehicle over volcano(s) for the science payload to study the difference in atmospheric composition.

In the Venus Flagship Mission study, the Aerobot balloon in the mission would be tracked as it is carried by the atmospheric winds around the planet.

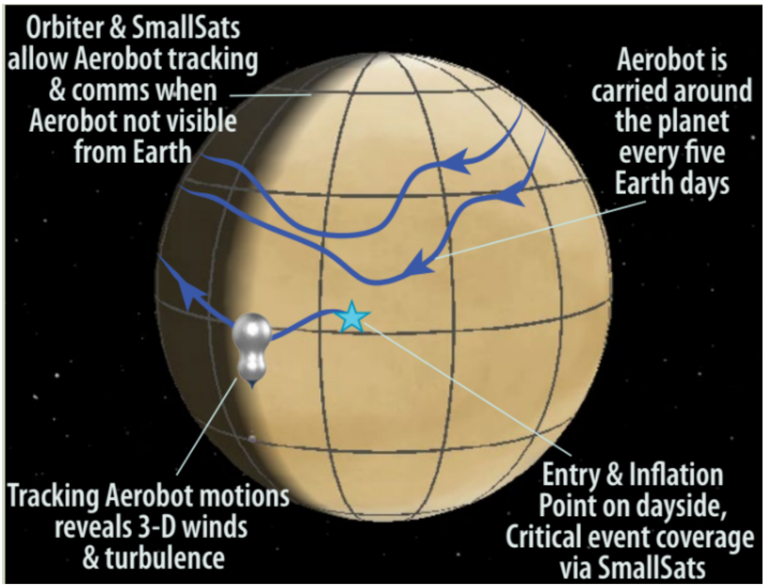

Figure 12: Visual graphic of possible traversal path of Aerobot in the Venus Flagship Mission. Mission Architecture section of the Fact Sheet (Gilmore et al., 2020).

However, due to the scope of this mission, there is only one orbiter. Thus, acquiring the location of the vehicle through standard global positioning systems (GPS) will be a significant challenge, and thus planning autonomous flight paths will also be a complicated endeavor. Further, since there is no magnetic field on Venus, a compass is useless for determining vehicle orientation.

However the location and speed of the vehicle can be approximated by determining the distance from the data travel time from vehicle to orbiter when both are in range, resulting in a circle of possible locations of the vehicle from the orbiter--essentially the triangulation method but with only one receiving station. This distance can be tracked and integrated to determine the location of the vehicle relative to the orbiter, which has a known location in its orbit. This has very low accuracy, especially as the distance between the orbiter and vehicle is large. More mathematical analysis and simulation will be required to determine the statistical accuracy of this method, or other more precise methods with other technologies on the orbiter or vehicle, such as having directional receivers oriented in different directions on the orbiter.

Should the orbiter be able to determine and track the location of the vehicle, the trajectory of the vehicle in the wind can be tracked sporadically as the orbiter orbits Venus roughly ever 24 hours (Khatuntsev et al., 2013), while the vehicle would circle Venus every 5 days. Thus, the vehicle can be commanded to attempt to navigate onto other wind currents and thus roughly characterize the wind currents in the Venusian Cloud Tops.

System Control and Data Collection

The vehicle is monitored and controlled via a central flight computer. The computer performs all logical tasks onboard the vehicle, including vehicle controls, power management, data collection, and communication. None of the computation tasks on the vehicle will not be computationally intensive. Therefore, it is likely that a Single Board Computer (SBC) is sufficient for the operations of the vehicle and payload.

To actuate vehicle controls, which are the variable altitude balloon for vertical adjustment and propellers for directional adjustment, the flight controller tracks various measurements taken from the vehicle, in addition to the position estimation from the orbiter. Since the vehicle nominally stays at an altitude of 50 to 70 km, the altitude is difficult to track, since this is well outside the range of precise radar altimeter capabilities. To determine altitude, the vehicle will use the barometric pressure sensor in the Meteorological Suite (MET). This is useful for comparing the estimated position to known GIS Venus data, and to estimate the altitude of the vehicle and adjust the variable altitude balloon. The vehicle also includes multiple Inertial Measurement Units (IMU) that can track the vehicle orientation, and determine the direction of navigation.

The flight computer will also monitor and allocate power resources according to demand from the instrument payload and flight controls, and the power supply. The flight controller is required to maintain a sufficient amount of power on the vehicle, and pause all power-consuming operations for the solar panels and turbines to recharge the batteries to a threshold level.

The SC-SPARC8 Spacecraft Controller built by the Southwest Research Institute is a good SBC candidate for the vehicle and its data management needs (*Single Board Computers*, 2021). The board internally contains 1.25 Gb SDRAM, which can sufficiently store the data collected from the science payload (250 MB, elaborated in section 4.1.2) for roughly 5 days (approximately 1 circumnavigation). This storage size is ideal for safety and risk mitigation in the event that the orbiter was not able to establish communication with the vehicle on a certain pass, or that the data uplink was interrupted.

The scientific payload will need to be controlled in timed increments to obtain the readings in separate intervals to not overload the batteries. The operations will be conducted on a scripted schedule, and can be updated via commands sent from the ground station on Earth, through the orbiter, and updated in the vehicle when the orbiter and vehicle are in radio contact.

Communication

Because there is no plan to retrieve the payload at the end of its mission, communication must be relayed throughout the mission. This is challenging since there is only one orbiter that has a different trajectory and orbit period with the vehicle, and will not be able to communicate unless both are within proximity in passing. Because of this the data obtained from the instruments must be stored until connection with the orbiter is achieved. The vehicle is equipped with 2 different antennas each with 4 prongs separated by 30 degrees. This is to enable a wide coverage since antennas send out signals orthogonal to the tip so that the orbiter will be able to acquire the signal with minimal losses.

In integrating the antenna into the payload, the antenna should be placed far from the balloon to prevent the balloon from blocking the signal sent upwards. The antenna boom also must have high strength to withstand the high winds. To accomplish this within the volume constraints, the antenna will not be rigidly attached to the vehicle while it is stowed in transit. The antennas are attached to the tethers of the balloon so that once the balloon is deployed, the antenna will extend and be held perpendicular to the main structure.

3.1.3. Dimensioned CAD Drawing of Entire Assembly

The CAD render of the vehicle structure assembly in the stowed motors, deployed antennas and magnetometer configuration and Engineering Drawings of vehicle components are shown below. The vehicle when completely stowed has a volume dimension of 60 cm x 66 cm x 81.8 cm.

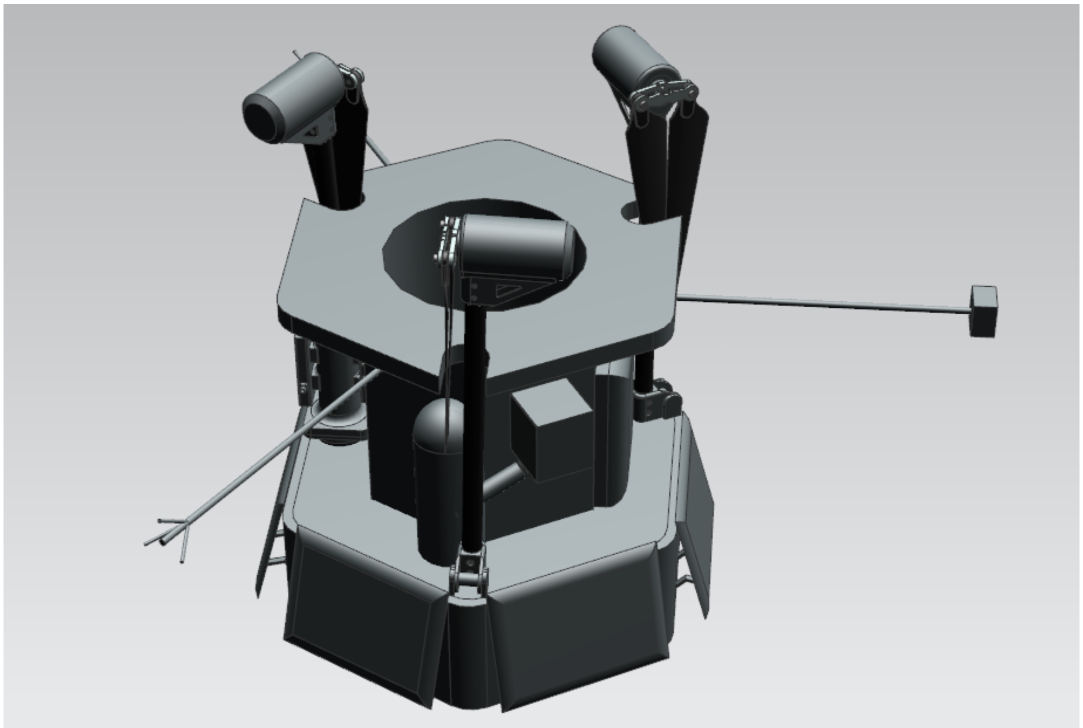

Figure 13. CAD render of vehicle structure with half deployed configuration.

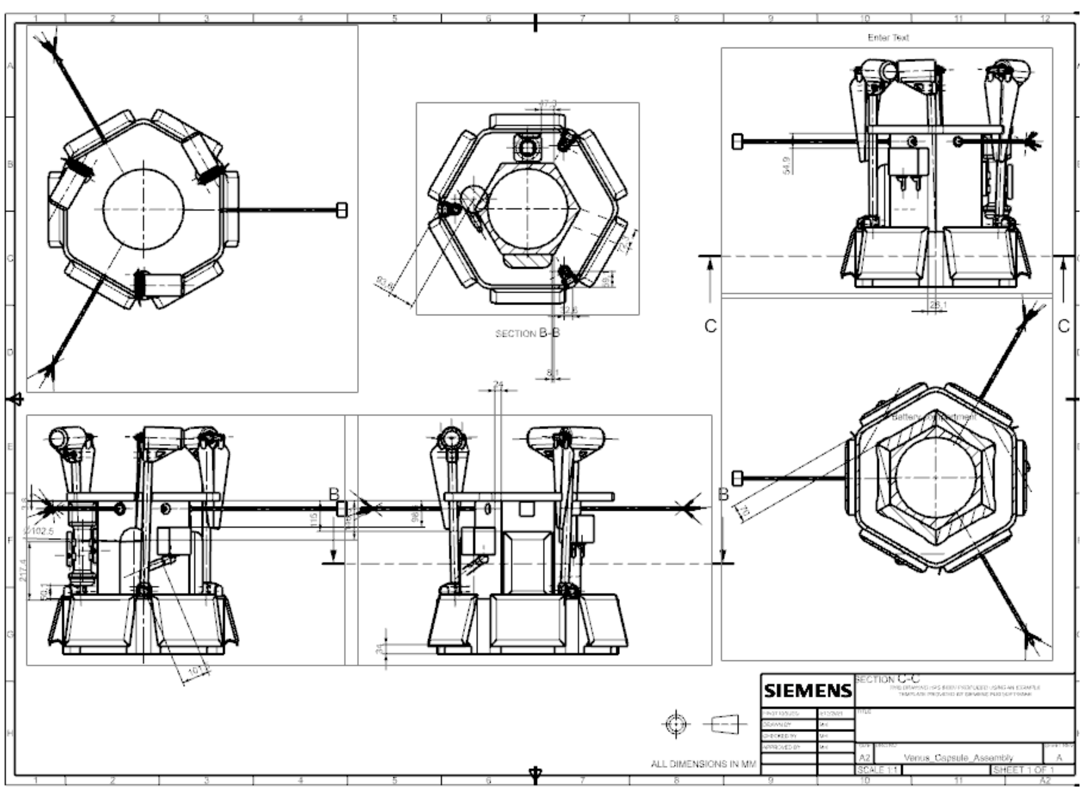

Figure 14. Engineering drawing of entire assembly

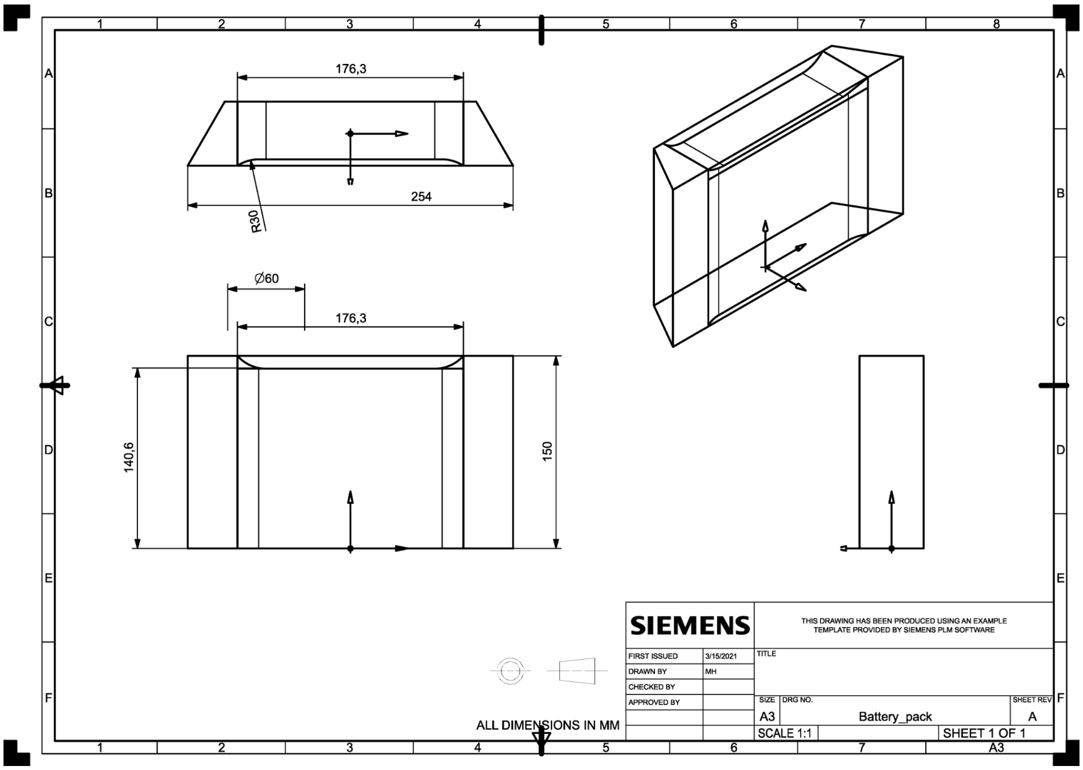

Figure 15. Engineering drawing of battery packs

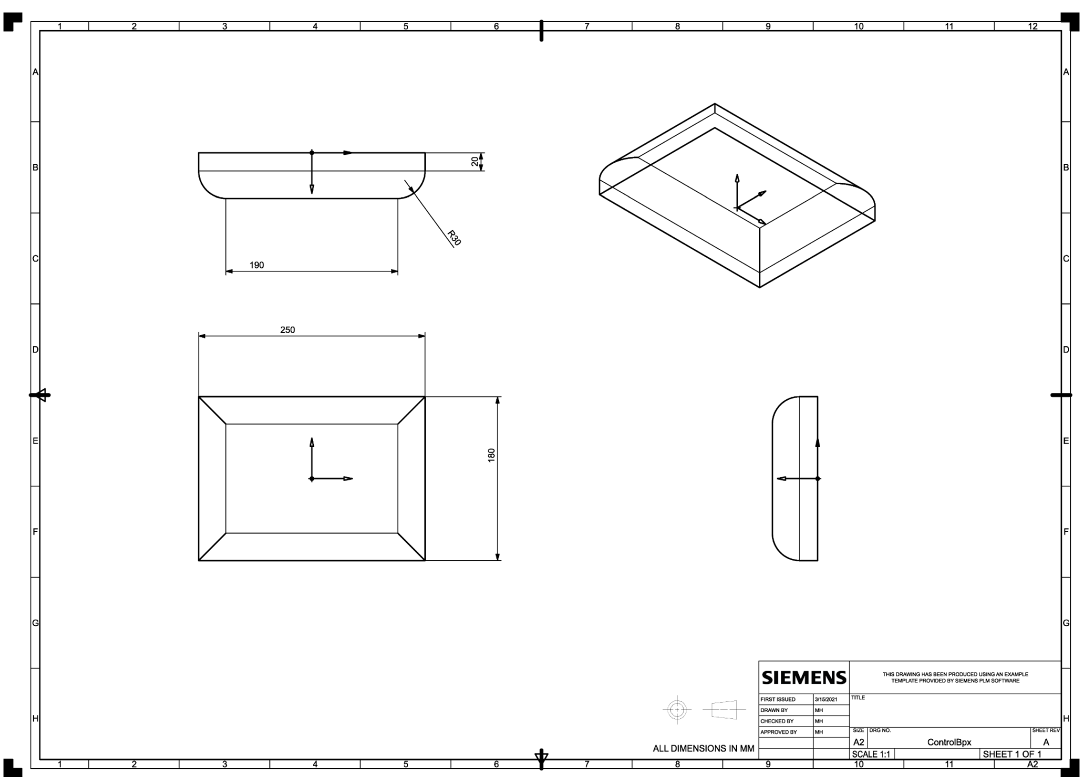

Figure 16. Engineering drawing of control center

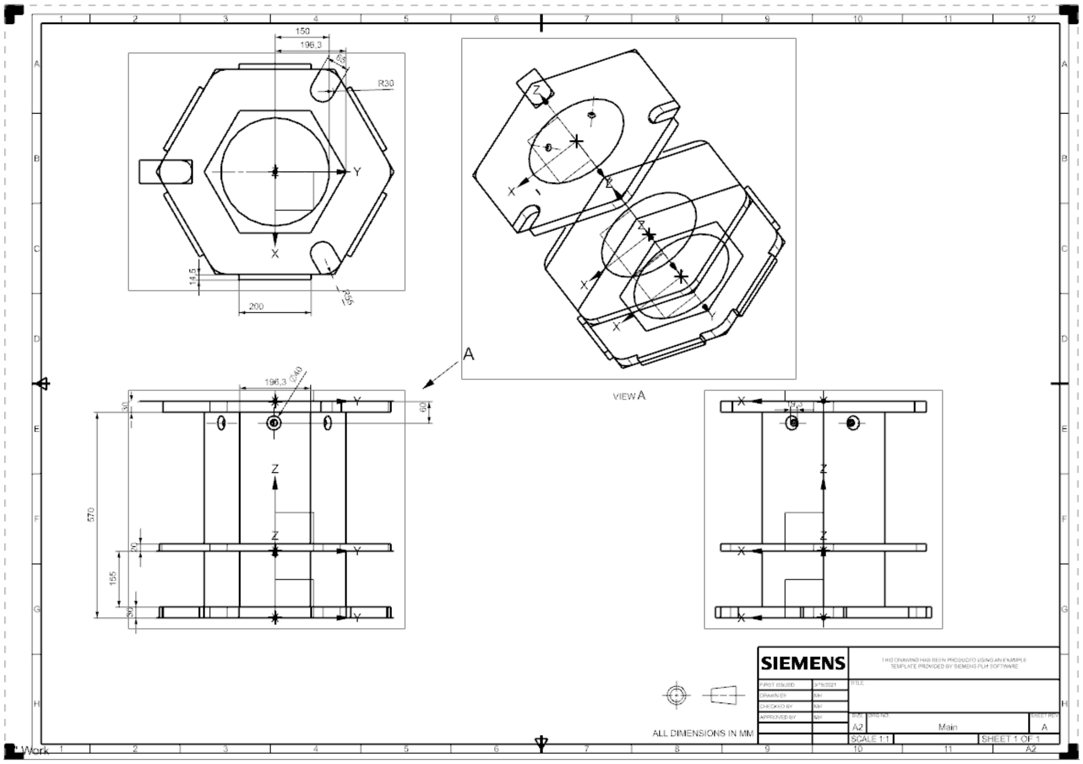

Figure 17. Engineering drawing of main section

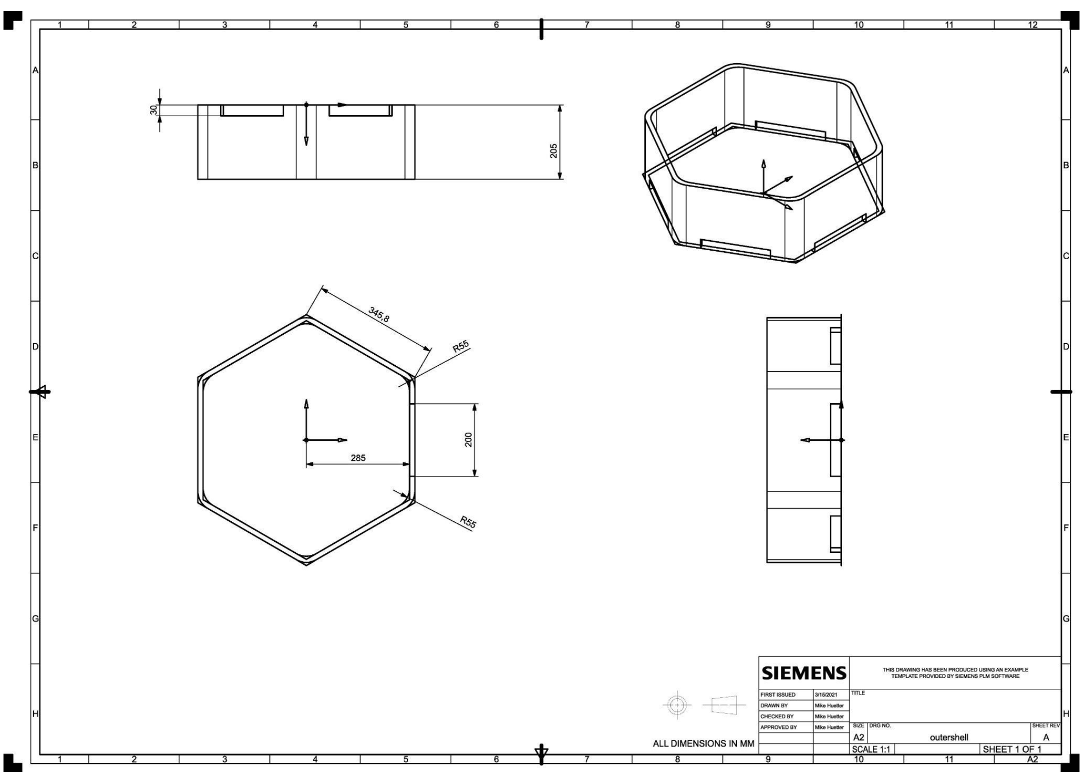

Figure 18. Engineering drawing of outer shell

3.1.4. Manufacturing and Integration Plans

For the vehicle and instruments, NASA will be handling the manufacturing along with outsourcing to private companies like Lockheed Martin. JPL will be the main source for assembly. Manufacturing is heavily reliant on the number of workers employed for such a mission. NASA has recently been in the market for using commercial parts rather than MIL-SPEC, or military defense standard parts, in order to reduce costs, obtain state of the art technology, and reduce production time (Perry, 1994).

According to Precision Castparts Corp Project Manager Lanel Wolff, the amount of time that it took to create backshells for airplane cast parts were typically around 2-3 months for their customers such as Boeing and General Atomics (Wolff). Other parts that would be needed for the creation for the mission would be actuators, manifolds, reservoirs, and solenoid values. An aerospace company like Pneudraulics can typically make such products to customer specifications within 3-9 months depending on sizes (Salazar, 2021).

As for the electronic components that are required for the Entry and Descent, a company called HiRel Connectors is specialized in sending out numerous components and wirings in less than a month. HiRel Connectors has shown to be reliable as they have worked on NASA's Orion space program in creating high density connectors (*About HiRelCo*, 2021). To create the electronic components needed for the mission, the machinery department in HiRel uses a lapping room to create rubber inserts. Over 500 parts can be done in an hour. After inspection through scoping, the parts are sent to the Environment Assembly department for plasma treatment. The entire process for the plasma treatment for over 500 parts at HiRel can take about 1-2 hours. Cartilage clips can be produced in high quantities in a short amount of time. 3500 pieces can take about one hour to create into a roll and then another hour for removal. The assembly for 300 connectors can take about a month to complete.

This machine is additive manufacturing, essentially an industrial 3D printer. In order to reduce production time on large parts, using the EOS M 400 would be a good way to reduce time into production. The EOS M 400's volume constraints are 400mm x 400mm x 400mm (*EOS M 400-4*, 2021). No tooling is needed while using this machine. It can reach up to four times more productivity than regular manned machinery. It can cut the time off of creating and manufacturing products. There is not much public information to how manufacturing companies produce their products. As such, the government may have limited insight into how these parts are designed and does not control changes a manufacturer may make to a part's design or manufacturing process. Generally, information about commercial-grade parts is limited to published material and any other information the manufacturer is willing to release (*NASA's Parts Quality Control Process*, 2017).

The SOA in subsonic trailing decelerator technology are ribbon and ringsail parachutes, used individually or in clusters, such as those employed on Pioneer Venus Large Probe, Galileo, Apollo and being tested for Orion.The amount of heritage in subsonic parachutes for other planetary applications is much larger than with supersonic parachutes, though not always in a relevant environment (e.g., temperature and density), and reflects the larger application base of subsonic parachutes at Earth. Entries to Venus and the giant planets can use traditional subsonic parachutes with good efficacy, although development of higher-temperature-capability textiles is warranted for those applications. The craft's parachute will be designed and fabricated by Airborne Systems in Santa Ana, California where Orion's parachute system was designed and tested.This process is estimated to not take more than three months using COTS components (*NASA Technology Roadmaps*, 2015).

NASA’s Balloon Program Office uses multiple types of balloons to lift scientific payloads into the atmosphere. The Balloon Program Office supports numerous space and Earth science research missions, and different balloons may be more beneficial to different payloads. The two types of balloons currently used by the NASA Balloon Flight program are zero-pressure and super-pressure. Though either balloon can be used for any flight type, zero-pressure balloons typically are used for short flights, whereas a super pressure balloon is required for an extended flight. Both types of balloons are made of thin plastic film, called polyethylene. The thickness is similar to that of plastic sandwich wrap. The most common size of NASA’s balloons is 40 million cubic feet. The vehicle’s zero-pressure balloon shell will be made of 0.8 mil single layer co-extruded LLDPE film while the super pressure balloon shell will be made of 1.5 mil co-extruded LLDPE film (Fairbrother). Columbia Scientific Balloon Facility and NASA’s Balloon Program Office should be able to provide the necessary balloons for this mission. Another option considered is to purchase Voss Controlled Meteorological (CMET) helium pumped balloons (Hall et al., 2019).

A good commercial off the shelf (COTS) candidate for solar panels are the PHOTON solar arrays that utilize the AzurSpace 4G32C solar cells, in which the cells have a peak efficiency of 32.2% (*32% Quadruple Junction GaAs Solar Cell*, 2019). These solar panels have a proven flight heritage in satellites and SmallSats missions and deemed a technology readiness level of 9 (Dunbar, 2020). However, this technology has not been proven in environments such as the corrosive environment of the Venus atmosphere. Therefore, it is necessary to conduct further testing with the unit while utilizing the NASA Glenn Extreme Environments Rig to render the COTS solar panels as mission ready. Ordering these solar panels from AzurSpace should not be a problem and should not take more than a month to get the components to assembly.

One candidate for the MPPT and battery protection system is the NanoAvionics EPS Maximum Power Point Tracking (MPPT) power conditioning and distribution unit (*CubeSat Electrical Power System EPS*).The SC-SPARC8 Spacecraft Controller built by the Southwest Research Institute is the top SBC candidate for the vehicle and its data management needs. The engineering team plans to use these units once qualified personnel can confirm that it will be able to withstand rigorous environmental tests. Since these are COTS units getting them on site should be a simple process.

Using prudent and carefully planned methods for specifying tolerances and for designing, manufacturing and mating major elements of aerospace hardware, will result in a cost-effective program with minimal rejects and waivers, and will avoid costly schedule delays due to potential mismatching or misfitting of major components and assemblies.

Elements of large aerospace hardware are often manufactured in disparate locations, manufactured and assembled by different centers, prime contractors, and subcontractors; and manufactured and assembled in varying climates and environments. Several additional factors will be considered in establishing design tolerances and in providing jigs and fixtures to assure that the major elements can be mated successfully prior to launch. A variety of methods of calculating and allowing for tolerance buildup and for ensuring matching components at the assembly site have been developed to meet the specific needs of these large hardware elements of the program (Marshall Space Flight Center, 1999).

The principal effect of nonadherence to proven and verified vehicle hardware integration and tolerance specification practices is the potential delay and attendant costs that would be encountered either in the factory or in the field due to the attempted mating or assembly of parts that do not fit together properly. In such cases, waivers will be obtained, parts will need to be exchanged, or factory/field modification may be required. The effects of specifying tolerances that are too stringent for the application are increased machining, inspection, and shipping protection time and costs. Since tolerances that are either too tight or too loose can create schedule and cost impacts, optimum tolerances and related tooling provisions will be derived for each specific application.

The engineers will be using master gauges, tooling, jigs, and fixtures to transfer precise dimensions to ensure accurate mating of interfacing aerospace hardware. It will be the team's top priority to calculate overall worst-case tolerances using the root sum square method of element tolerances when integrating multiple elements of aerospace hardware.

3.1.5. Verification and Validation Plans

The vehicle and its subassemblies will all be tested for both verification and validation. This is to ensure that the vehicle is capable of meeting the mission requirements and delivering the science objectives.

Verification

The verification process will ensure that the vehicle is able to be built to requirements. Each component will have requirements derived from the subassembly requirements, which themselves are derived from the vehicle requirements in order to satisfy the mission requirements. This process is intended so that each component will be tested to meet the requirements so the vehicle is capable of operating as designed to meet the technical challenges related to material survivability, durability, and overall reliable systems operation.

Since the vehicle is designed with mostly COTS parts, the verification process is critical in choosing the manufacturer and the item to prevent selecting an incompatible or underperforming part which will cause delays and issues later down the testing and integration phase. Beyond trade studies, the COTS components and material must also be individually tested in controlled environments to characterize the operation envelope, and gather important metrics for comparisons between component candidates. While the vehicle is planned to be tested in the Glenn Extreme Environments Rig (GEER) at NASA Glenn Research Center, smaller rigs should be considered that can be set up in a standard laboratory which will be very beneficial to test individual components for verification. The volume of GEER is larger than the volume constraint of the mission, but will not be able to house the vehicle in it’s deployed state with extended turbines and antennas (Reckart & Graham, 2020).

An understanding of material reactions in Venus relevant atmospheric conditions is core to enabling future successful Venus science missions. A few studies have investigated various candidate materials used in fabricating electronics, sensors, and packaging after exposure to simulated Venus surface atmosphere. The GEER is capable of reproducing Venusian temperature, pressure, and atmospheric composition of the Venus surface consisting mostly of CO_2 and N_2 as well as traces of SO_2, H_2O, CO, OCS, HCl, HF, and H_2S. It's common for exposed materials to get examined using Auger electron spectroscopy, X-ray photoelectron spectroscopy, energy dispersive spectroscopy, field emission-scanning electron microscopy, X-ray diffraction, and optical imaging. All of the components will be individually tested in this environment before assembly. The reactivity of the sulfur gas constituents with several of the exposed materials were found to have adverse effects on the materials, particularly those composed of transition metals. Alloys, brasses, and cladded materials all exhibited extensive reactions. For this reason, the vehicle avoids using any of these materials for mission safety. In contrast, compounds of SiC, SiO_2, Al_2O_3, and elemental Au (Gold) and Ir (Iridium) were found to be chemically inert. The vehicle will make use of these compounds where it's necessary while taking full account of the allocated mission budget. The fundamental experimental understanding of material interactions with the simulated Venusian environment gained from previous studies enables improved selection of materials and hardware designs that would increase the success margin of future long duration science missions on Venus (Lukco et al., 2018).

Validation

The validation process will ensure that the vehicle will be able to withstand the environment of the Venus atmosphere. The initial process of validation will be to determine that the requirements set for each subsystem and component are appropriate for the parent requirements so that the mission requirements can be satisfied.

Numerous simulations will be run to first analytically verify that the vehicle will survive the Venus conditions. Monte Carlo simulations are a very prominent method of testing that can be both generalized and specific and also reproducible to determine areas of structural weakness and certain edge cases. This will encapsulate the complete and hypothetical simulation of the Venus atmosphere conditions such as wind and pressure variations, and possible extreme conditions.

The overall built assembly will undergo flight testing in Earth’s atmosphere. To preserve budget and material costs and timespan, only two identical vehicles will be built. The first prototype will first conduct the flight test in Earth’s atmosphere at the same pressure to characterize the flight dynamics and control capabilities. This is vital in determining the effectiveness of the vehicle deployment, particularly with the transition from parachute to balloon, as well as the deployment of the antennas and the propulsion system. This will also characterize the flight dynamics of the balloon and propulsion system, as well as the effectiveness of the turbines.

Since all components of the vehicle should have undergone stress testing under the conditions of the Venus atmosphere, the corrosion rate and degradation should be well understood without the need to destroy a complete prototype to characterize the vehicle as a whole.

3.1.6. FMEA and Risk Mitigation

The main issue and significant point of failure is the corrosion and degradation of critical components of the vehicle in the Venusian atmosphere. This is a particularly critical challenge that the entire vehicle engineering must face since the corrosion is pervasive to every aspect and component of the vehicle. Due to this, every component's highest Risk Priority Number (RPN), set at a critical threshold of 200, is a failure as a result of corrosive degradation. Therefore, the priority in lowering risk is understanding and characterizing the decay of each component in the Venus atmosphere, and testing (as explained in 3.1.5 Verification and Validation) each component rigorously to ensure meeting the requirements of component lifetime.

Other risks include hypothetical situations, such as propellers getting caught on a loose balloon tether, or the vehicle being caught in the dark side of the planet for a longer than expected duration. These risks are unlikely and therefore can be mitigated or become a nonissue through further testing and simulations. Many of the other risks carry low consequences as a result of redundant designs, such as multiple solar panels and the secondary power generation, thus providing a good protection against complete power loss.

Below is a FMEA chart and a risk mitigation chart for the vehicle components.

Component	Function(s)	Mode(s) of Failure	Effects of Failure	Sev	Cause(s) of Failure	Occ	Design Controls (Prevention)	Design Controls (Detection)	Det	RPN	Recommended Action
Parachute	MRDC(a)(c) to bring the vehicle to deploy safely in the science altitude	Deployment failure	Vehicle will not slow down	9	Mechanical failure	1	flat-set testing, or have a secondary fail-safe deployment		10	**90**	
		Tether Entanglement	Parachutes may not deploy	9	Design Failure	2	fit and placement check		10	**180**	drop testing in Earth atmosphere
zero-pressure (ZP) and super-pressure (SP) balloon	MSC(a) to maintain the payload afloat at 50-70 km in the Venus atmosphere	Inflation Failure	Balloon System will not inflate	9	Mechanical Failure	3	verify through testing and analysis		10	**270**	research pump redundancies
		Pump Failure	Balloon will not change altitude	6	Mechanical Failure	3	verify through testing and analysis		6	**108**	research pump redundancies
Solar Panels	MSC(a) to generate electricity to charge batteries	electrical fault	string of cells do not generate electricity	2	cell / wiring failure	3	quality control and testing		9	**54**	
		degradation	no solar power generation	8	long term corrosion	9	noncorroding sealant	monitor power generation strength	3	**216**	lab testing in Venus conditions
		surface damage	diminished power generation	4	abrasion or propeller strike	3	thorough stress testing		9	**108**	physical stress testing
Batteries	MSC(a)(b)(c) to provide power to controls, communication, and science payload	electrical fault	diminished storage capacity	2	cell / wiring failure	3	quality control and testing		9	**54**	
		degradation	significant capacity loss	9	long term corrosion	9	noncorroding sealant and casing	monitor battery conditions (voltage)	3	**243**	lab testing in Venus conditions
Propulsion and Turbine	Stabilize vehicle attitude, align and propel vehicle towards different trajectories	fails to deploy	no attitude control	6	mechanical failure	3	redundant deployment mechanisms	detector monitoring latch in locked position	8	**144**	physical stress testing
		meltdown	electrical short, jammed props	8	thermal runaway	4	motor operation is periodic and only if temperature permits	thermometers in motor housing	3	**96**	lab testing in Venus conditions
		mechanical failure	loss of thrust	6	long term corrosion	6	sealed motors and non-corrosive materials	monitor motor power consumption	7	**252**	lab testing in Venus conditions
		snag balloon tethers	jammed props	6	strong wind gust	4	long booms to place props far from vehicle structure	wind monitor/IMU to detect strong jerks	8	**192**	physical stress testing
		unable locate vehicle from orbiter	no attitude control	6	signal interference	6	redundant communication systems	monitor signal strength	8	**288**	research localization in with singular satellite
	Secondary power generator as turbines	no power generation	less charging power	2	no wind gust	8	pause secondary tasks to preserve power	wind monitor/IMU to detect strong jerks	3	**48**	
Antennas	MSC(a)(b)(c) Communication to Venus orbiter	snagging/breaking	Smaller zone of communication	4	Deployment or extreme storm	3	Redundant antenna and attached to very sturdy pole	Less consistency data being sent to sat	3	**36**	Test with model

Figure 19. Failure modes and effects analysis of the vehicle.

ID	Summary	L	C	Criticality	Trend	Approach	Risk Statement	Status
1	Balloon fails to deploy or hold pressure	1	5	Med	↓	Mitigate	Due to the low TRL from lack of flight heritage of such a system in the Venus atmosphere, it is at high risk of failure for a critical component. Research and verify materials used for the balloons and the transfer pump system.	
2	Vehicle fails to maintain altitude (50-70 km) during main mission	2	5	Med	→	Mitigate	Research and verify capabilities of the variable altitude balloon to maintain the vehicle at desired altitudes even through fluctuating wind gusts	
3	Vehicle cannot sustain power (due to battery degradation, being stuck in dark side of planet, etc.)	3	4	Med	↓	Watch	Vehicle and instruments can power down to conserve power as turbine charges battery	
4	Vehicle location cannot be determined from orbiter	4	2	Med	NEW	Research	Research technologies and methods for vehicle localization with single satellite	
5	Vehicle is unable to navigate over to volcanic sites	4	1	Low	NEW	Accept	Need to determine Risk 4 - vehicle location, in order to determine vehicle target trajectories	
6	Vehicle loses communication with orbiter	3	5	High	→	Accept	Vehicle will lose communication with orbiter on a regular basis, as expected. However will not be able to determine when vehicle systems fail and thus not transmit new data.	

Figure 20. Risk characterization of the vehicle.

Likelihood	**5**							**Criticality**	**LxC Trend**
	4	5	4					HIGH	↓ - Decreasing (improving)
	3				3↓	6→		MED	**↑ - Increasing (worsening)**
	2					2→		LOW	→ - Unchanged
	1					1↓			NEW - Added this month
		1	**2**	**3**	**4**	**5**			
		Consequence							

Figure 21. Risk matrix of the vehicle.

3.1.7. Performance Characteristics and Predictions

In regards to the vehicle descent and balloon system, the performance characteristics and predictions specified in 3.1.1 and 3.1.2 are high in confidence with respect to the tactics in the venusian environment. Due to the already slow rate of descent when the vehicle is expected to not have significant challenges in its deployment. The subsonic parachute shall deploy at 78 km and the vehicle will begin balloon inflation and will be slowed to 30 m/s at an altitude of 65 km above the surface. At 55 km above the surface, and the vehicle will be slowed to 10 m/s, and the subsonic chute will be jettisoned. The Balloon System shall be in full control of the ascent/descent of the vehicle for the remainder of the mission.

The vehicle descent approach is predicated on a similar system to be done by the Venus Flagship Mission's Aerobot without the complications of a heat shield or supersonic parachute due to the low altitude of deployment as a secondary payload. Existing confidence in this design approach, in addition to ratifications made specifically for this mission generate high expectations of success for this descent maneuver.

Once in the scientific altitude, the vehicle is expected to maintain a relatively stable attitude as it is carried throughout the planet by the high speed Venusian currents. The shear speeds of these winds vary by altitude, and reach around 110 m/s at an altitude of 60 km, as seen below in the figure. Due to the high drag factor and the inclusion of the turbines, the vehicle and balloon should be capable of maintaining a steady orientation facing with the wind gust direction.

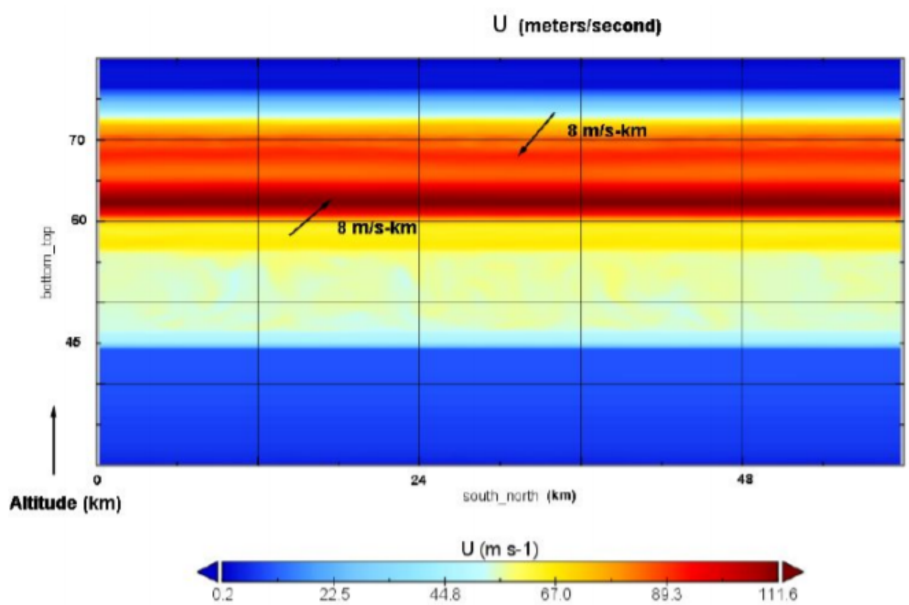

Figure 22: Wind shear mapped in altitude and distance. (Bullock et al., 2020).

The vehicle, as described in Section 3.1.2 Subsystem Overview, will generate power. Using estimates from data sheets available online from the COTS manufacturers, as well as through estimation, the power consumed and generated by components of the vehicle only are shown below.

Sub-system	Component	Quantity	Expected Power (Watts)	Maximum Power (Watts)
Balloon	Helium Pump and Stored Gas	1	20	50
Power	MPPT Charger Module	2	0.15	0.25
Propulsion	BLDC Motor	2	80	300
Propulsion	Electric speed controller (ESC)	2	2	5
Propulsion	Thermometer	2	2.9	3.8
Control	Flight computer	2	1.5	2
Control	IMU/Inertial Navigation System	2	2.6	4
Communication	Data transmitter	2	1.5	2
Communication	Antennas	2	2	5
	Total Power Consumed (W)		**205.3**	**25047.46**

Sub-system	Component	Quantity	Expected Power (Watts)	Maximum Power (Watts)
Balloon	Solar Panels	6	50	82.5
Power	Turbines	2	5	7.5
	Total Power Delivered (W)		**310**	**510**

Figure 23: Total power consumed and generated by the vehicle only

3.1.8. Confidence and Maturity of Design

Confidence and maturity of design are significant factors in deciding if the team feels the vehicle is designed robustly enough to ensure its mission success once deployed into the Venus atmosphere. Since there has been no recent flight heritage of NASA missions conducted of a long duration atmospheric mission, this inherently carries a higher risk factor and low maturity. The most recent NASA atmospheric mission to Venus, the Pioneer Venus in 1978 (Williams, 2018), had only a very short lifespan as the probes and only collected scientific data in the parachuted descent to the surface. Technological maturity has improved significantly since then, and allowed for more complex yet robust systems. By using COTS components for a majority of the vehicle design, the mission leverages already flight proven systems. These components will only need to be upgraded and verified that it can meet the operating conditions in the Venusian atmosphere.

This vehicle design, with both a balloon in balloon and differential dual motor propellers similar to one on an airship, is chosen to strike a balance between the simplicity of a passive balloon while also maintaining some attitude control authority to maneuver the vehicle. The estimated technology maturity of both of these systems are moderate and low, respectively, as shown below,

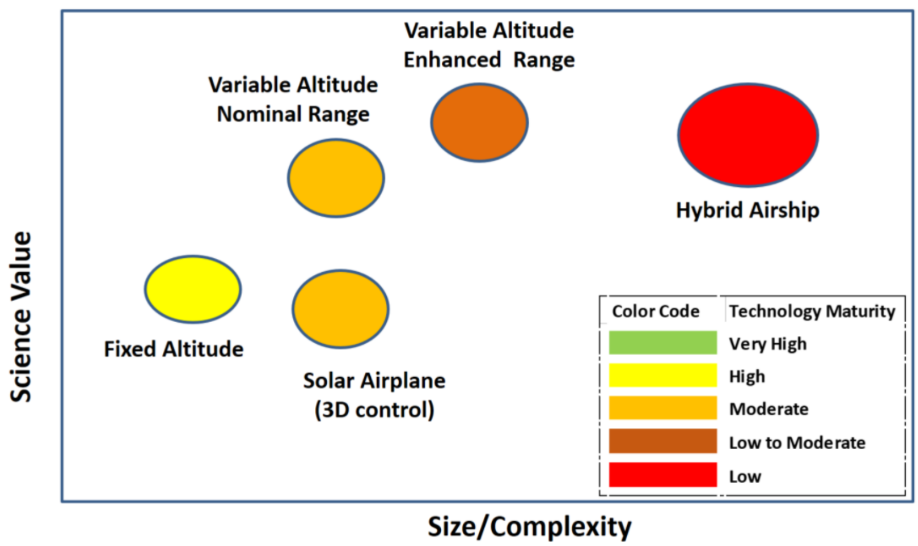

Figure 24: Comparison of science value vs. size/complexity and technology maturity. Figure 5-1 (Venus Aerial Platforms Study Team, 2018).

However, the vehicle design does not incorporate the full utilization of a hybrid airship system. The variable altitude component of the balloon, the “superpresure” interior balloon will be used with a pump to pump the Helium gas back in to decrease or out to increase the “zero-pressure” balloon volume. The dual motors of an airship will not be a critical subsystem, but a secondary objective to adjust the position of the vehicle in currents of the high speed winds that carry the vehicle. By incorporating the control aspects of the airship without the fixed wing aspect. This design serves to further the technological readiness level (TRL) of the very low maturity of the hybrid airship.

Therefore, this mission would serve to mature both the variable altitude balloon and airship controls technologies without fully deploying either; should either fail, neither will jeopardize the mission, but only limit the scope of the mission to the primary mission.

For the other components, such as the solar panels, batteries, and flight controller, the parts chosen have considerable flight heritage and technological readiness from past missions in satellites in various sizes. The most significant concern is to mature the shielding and coating that will protect the components from corrosion as a result of the Venusian atmosphere. However, since the vehicle is not intended to operate at the surface, where the strongest concentration of acid is located, this mission carries less risk and rigor than a surface mission. However, they must still be scrutinized to ensure that the system will be capable of carrying out the mission.

3.2. Recovery/Redundancy System

Due to budget, volume, and mass constraints the payload will have a limited recovery or redundant system. The most critical component is the communication system to ensure data is sent back to the orbiter. Redundancy and a recovery process for the computer and antenna has high priority due to the function in ensuring all other subsystems can operate and communicate.

The SC-SPARC8 Spacecraft Controller, which will process all onboard operations of the mission, is designed robustly with numerous memory interface types that are all error detection and correction (EDAC) protected (*Single Board Computers*, 2021). This will ensure minimal loss of data as it is stored on the computer when not transmitting. Due to the small form factor of this SBC controller, it is feasible to fly this mission with two independent controllers controlling the vehicle, if the budget allows, to provide for redundancy in the event one fails. The flight data transmitter will also have the capability to monitor the status of the flight computer. If the controller(s) fail, the data transmitter will have the ability to transmit tones or signals to indicate the failure of the flight controller.

The antenna is redundant in that there are two identical antennas positioned on opposite sides of the vehicle. This redundancy should enhance the reliability of data transmission and prevention of complete data loss if one antenna fails.

Another significant system of the vehicle is the power generation, which has been designed with redundancy in both the number of generation sources and types of generation, with both the six solar panels and two turbines. If any fail, the vehicle still has capability to generate power. The flight controller will automatically detect the decrease in power and alter scheduling and operation of the vehicle will have to be modified to allow longer recharge periods so the vehicle maintains sufficient power.

The entry and descent maneuver and balloon is another significant system that requires redundancy. The balloons must incorporate a factor of safety since a redundant balloon is not feasible. Therefore, the balloon material must be designed thick enough to withstand the corrosion for at least the mission timeline with a factor of safety of 2. This would ensure the balloon will be less prone to leakage over the mission duration, and possible in the extended mission duration as well.

The pump between the zero pressure pressure and super pressure balloon must be redundant to prevent the leakage of gas which will cause the vehicle to possibly deviate from the required science altitude. One redundant mechanism designed is to incorporate multiple throughput valves and seals. Should one valve become damaged or malfunctioning, it can be sealed off completely, while the other valves continue to operate.

The tethers that connect the balloon to the vehicle are to be fabricated from multiple materials, and redundantly attached to multiple points on the vehicle. This composite will provide a more robust strength to the vehicle and prevent any unexpected corrosion or deformation of one certain material across the range of conditions that could exist in the Venusian atmosphere.

3.3. Payload Integration

The vehicle structure is designed with the main goal of supporting the science payload in order to meet the mission requirements. Thus, the vehicle allocates a significant portion of the structure of the vehicle to the scientific payload. The instruments are mounted on the faces of the main structure’s upper portion that is exposed to the atmosphere to allow for adequate sampling by the instruments. Each scientific instrument is wired to the power distribution board that manages power consumption, and also connected to the central flight computer that controls the timing and operation of all scientific instruments.

The vehicle is also required to provide sufficient power for all the science instrumentation needs, and be capable of deciding when and what instruments will operate should the power not be sufficient. This is achieved through various schedule modes that the flight controller is programmed with.

The magnetometer, which measures the traces of possible magnetic fields on Venus, must be positioned with the maximal distance from the vehicle and other electronics. Thus it is integrated on the vehicle via a boom similar to the antenna, and placed on the opposing end of the vehicle. When the magnetometer is to make a measurement, the flight controller will conduct a sequence that halts all motor output and limits as much operation by other electronics to allow the magnetometer to measure with the least amount of interference noise possible.

The Aerosol Mass Spectrometer (AMS) requires access to the atmosphere and also a tank of calibration gas. Thus, the AMS Tank is positioned adjacent to the AMS to limit extraneous tubing necessary.

The figures below show the labeled CAD renders of the scientific payload in tertile views.

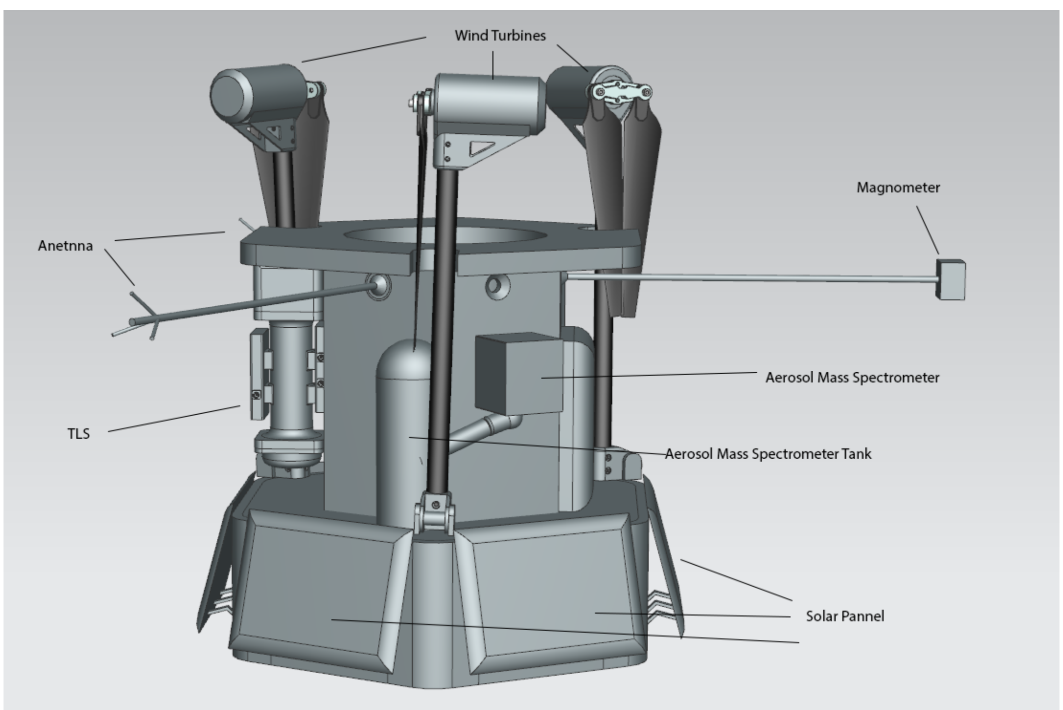

Figure 25. Labeled CAD render of vehicle with scientific payload, first tertile view.

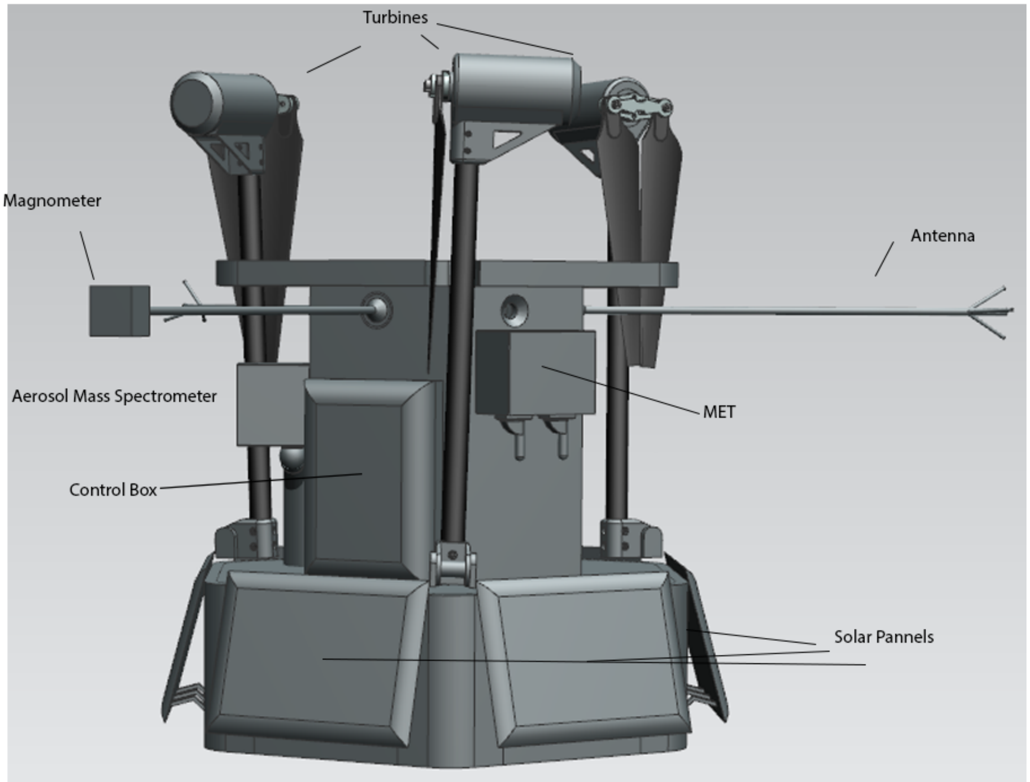

Figure 26. Labeled CAD render of vehicle with scientific payload, second tertile view.

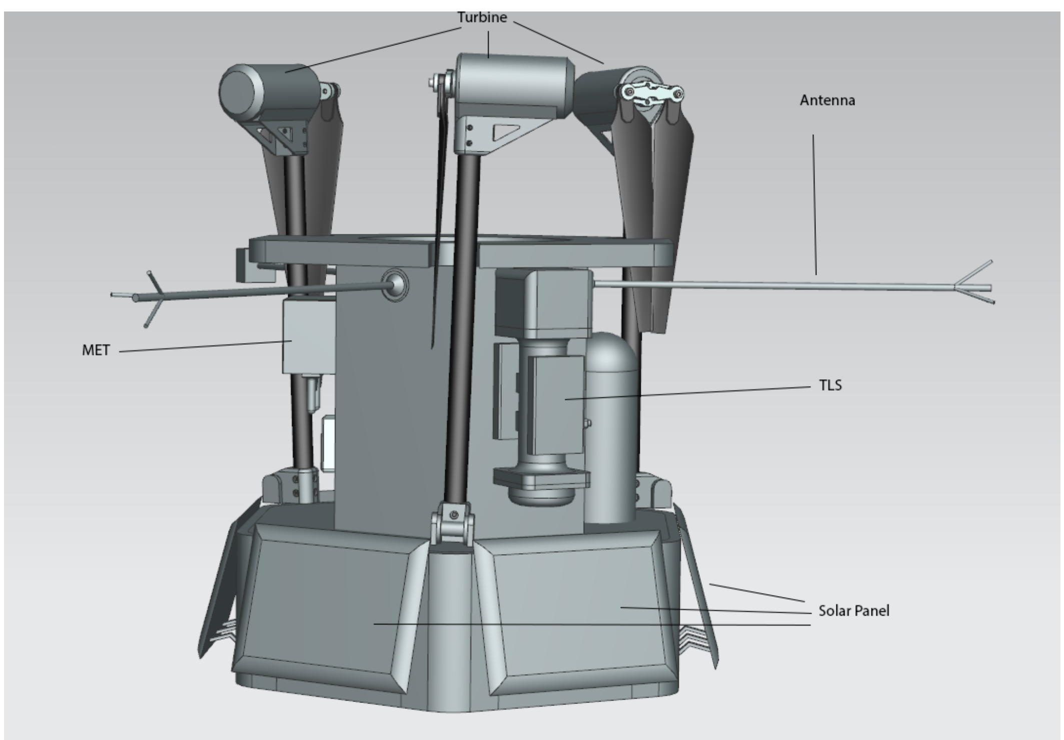

Figure 27. Labeled CAD render of vehicle with scientific payload, third tertile view.

4. Payload Design and Science Instrumentation

4.1. Selection, Design, and Verification

4.1.1. System Overview

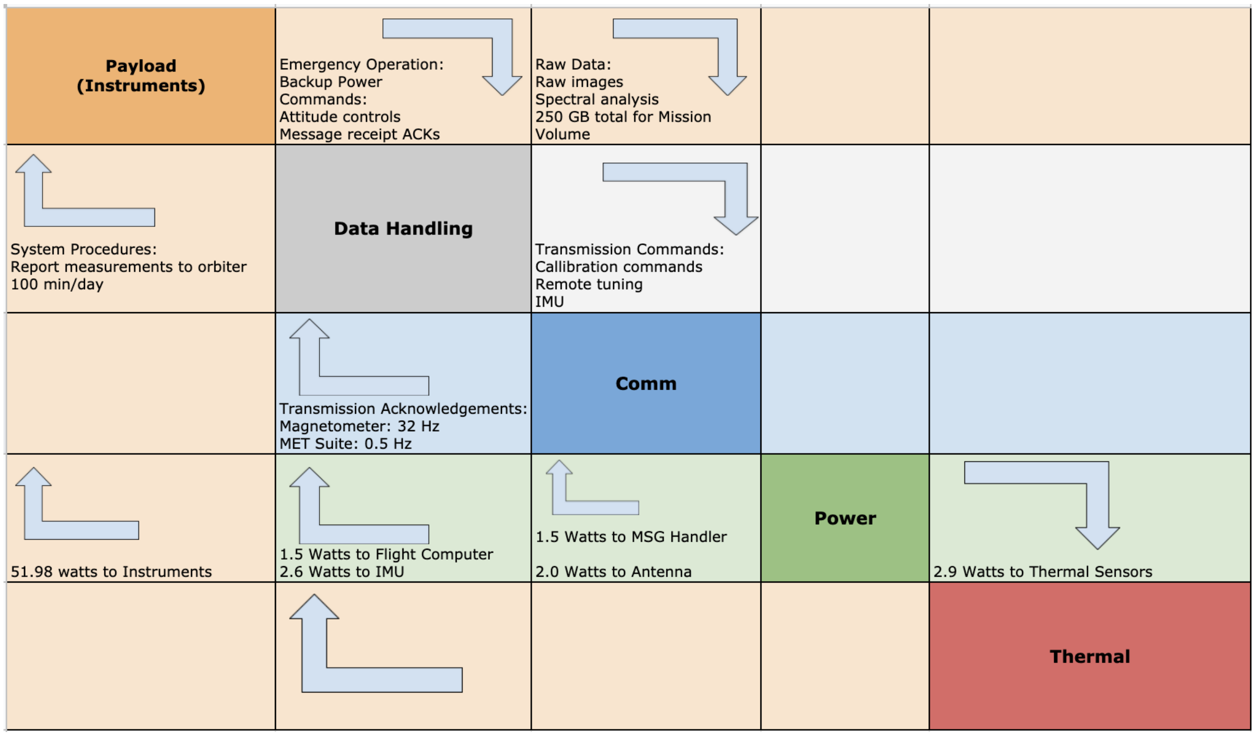

Figure 28: N^2 chart.

The vehicle will be fully capable of providing sufficient power for its onboard electronics and scientific payload through its solar panels and turbines, with sufficient power to both power all electronics simultaneously and also have extraneous power to charge the batteries. The expected and maximum anticipated power consumption and generation by the vehicle with the scientific payload is presented in Section 4.1.2 Subsystem Overview.

The scientific payload will be composed of the four scientific instruments: two mass spectrometers, a meteorological suite, and magnetometer. Each of these instruments will work in tandem in order to characterize the atmospheric composition of the Venusian cloud tops as well as the geological characteristics. The TLS and the AMS-N will work to both create a wide survey of the atmospheric particles present in the cloud deck and a targeted detailed analysis of the particle characterization. The MET Suite will provide data of the atmospheric conditions including the barometric pressure, wind speed, and ionization energy. The Magnetometer will provide a characterization of the geological characteristics through the collection of data of the magnetic fluxes as well as the energy emitting from any lighting present near the balloon.

4.1.2. Subsystem Overview

Payload (Instruments):

The Tunable Laser Spectrometer (TLS) will be used to characterize the atmosphere at cloud level and target specific species in the atmosphere, and isotopic ratios. This will work in conjunction with the Aerosol Mass Spectrometer with Nephelometer (AMS-N) to measure the vertical profiles of D/H ratios and provide multiple profiles of gas and cloud composition, refractive index and size distribution of particles (this will be provided by the Nephelometer). It will further identify unknown particles absorbing UV and non-liquid particulates. The AMS-N's wide survey capabilities will work with the targeted methods of TLS to provide both a complete and precise characterization of the cloud deck.

The Meteorological Suite (MET) measures a broader range of the variable environmental phenomena as it is equipped with sensors to measure wind velocity and temperature and to monitor volcanic, tectonic activity, and ionization levels. Similarly, the magnetometer will search for the presence of magnetic fluxes.

TLS:

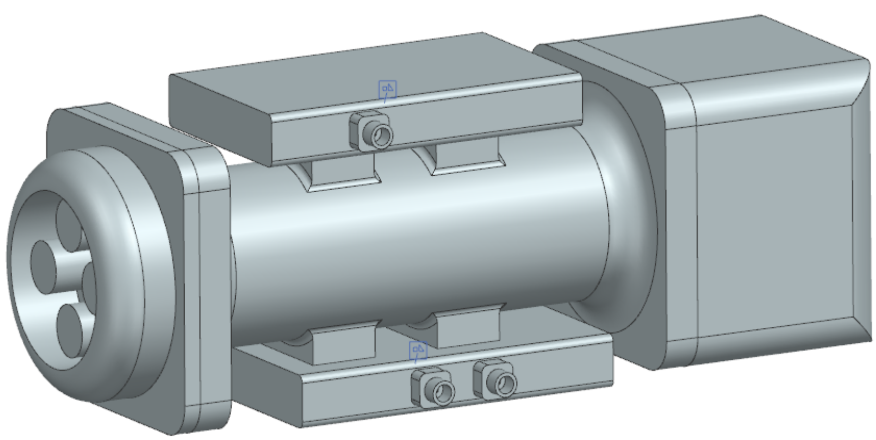

Figure 29. CAD render of TLS.

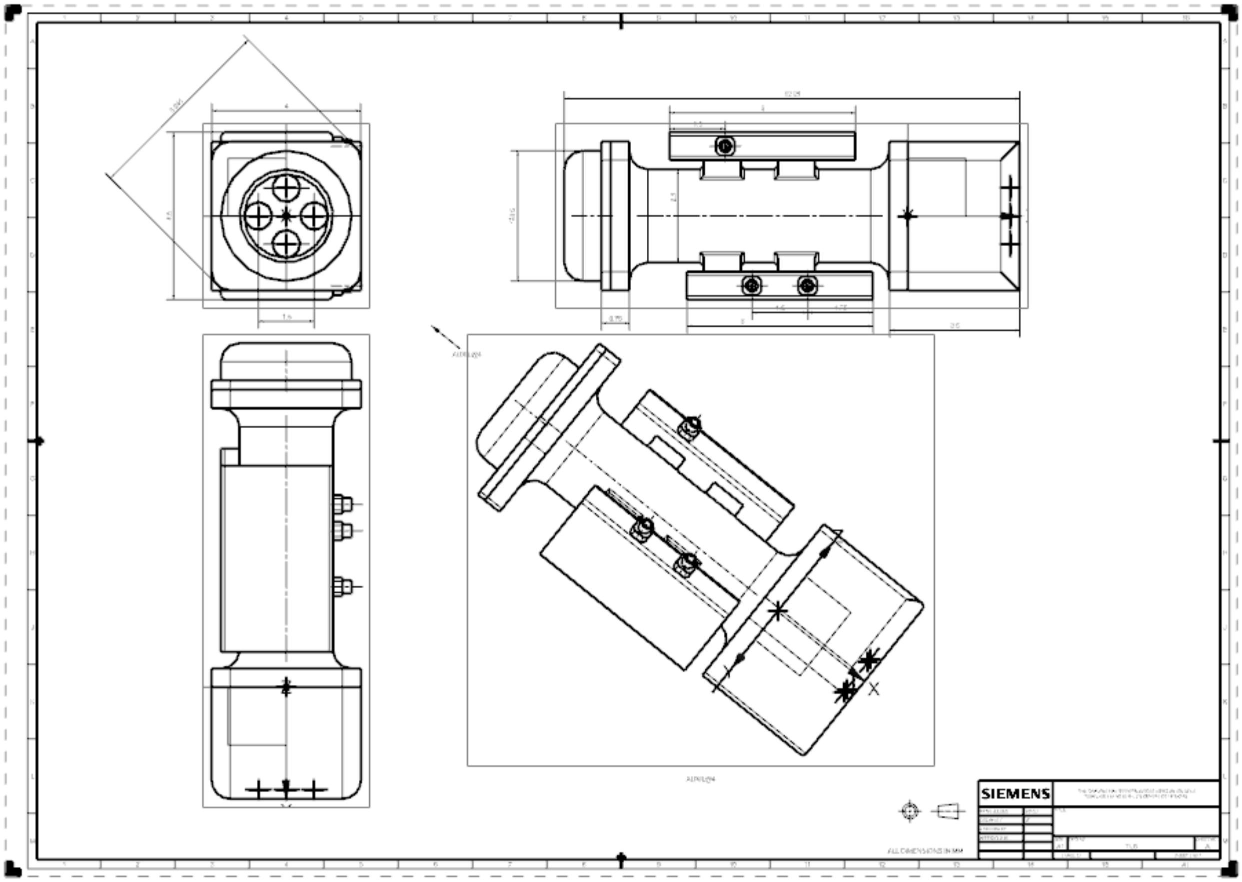

Figure 30. Engineering drawing of TLS.

The TLS uses long-pathlength infrared laser absorption to record the spectral lines of specific gases and their isotopic species (Mahaffy et al., 2021, 439). Spectral lines are dark or bright regions within an otherwise uniform spectrum that indicate the absorption of light. They are atom-specific and will be used to identify the composition of samples from the Venusian atmosphere.

There are three subcomponents that make up the TLS. The first is the fore optics chamber which stores reference gas cells and four infrared lasers that are used to shoot beams into sample gases. The next subcomponent is a chamber called a multi-pass herriott cell. This is where samples are pumped into and out of the instrument via vacuum pumps. On each end of the herriott cell, two mirrors reflect beams of infrared light from the lasers back and forth, allowing the light to move through the samples multiple times. The beams enter the cell through small holes in the mirrors. The final subcomponent is a detector connected to the herriott cell opposite the foreoptics chamber (Dunbar).

The TLS will not perform readings until the herriott cell is filled to a certain pressure. After a reading, the TLS will pump some of the sample out and perform more readings at various pressures. The TLS will perform readings in the lower (~50 km), middle (~56 km), and upper cloud decks (~62 km). This will help determine any vertical variation in composition.

AMS-N:

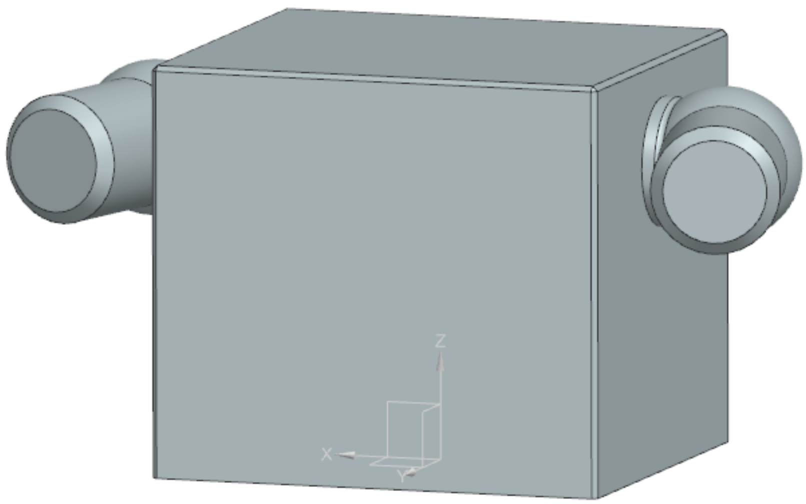

Figure 31. CAD render of AMS-N.

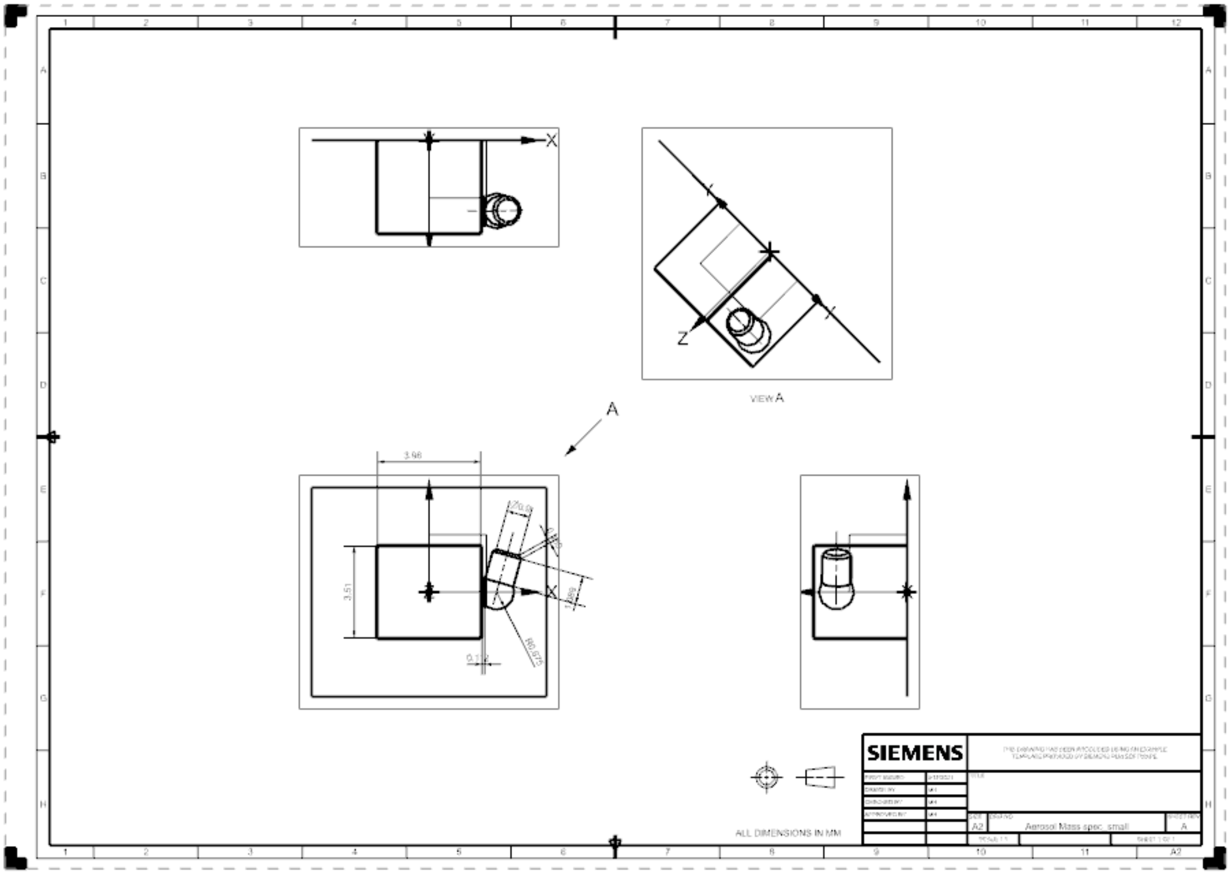

Figure 32. Engineering drawing of AMS-N.

Mass spectrometers are very useful instruments with wide survey capability. The AMS-N is an aerosol mass spectrometer that will work in tandem with a nephelometer to not only measure the composition of gases in the atmosphere but also aerosols and cloud droplets. There are two inlets, one for gases being analyzed by the mass spectrometer, and one inlet for aerosol particles. When passing through the nephelometer, the shape, size, and refractive index of particles will be measured. This will help distinguish between different particles such as volcanic ash or sulfuric acid (Gilmore et al., 2020).

Outside of the nephelometer, the mass spectrometer will be made of three subcomponents. The first is called an ion source. The ion source is where samples are taken in and ionized. The ions are taken out of the sample and the next component, the mass analyzer, separates the ions by their mass to charge ratio. Finally, the detector provides data determining the abundances of the ions .

The AMS-N will also work in tandem with the TLS to measure and compare vertical profiles of the D/H ratio in the clouds.

Magnetometer (MAG):

Figure 33. CAD render of MAG.

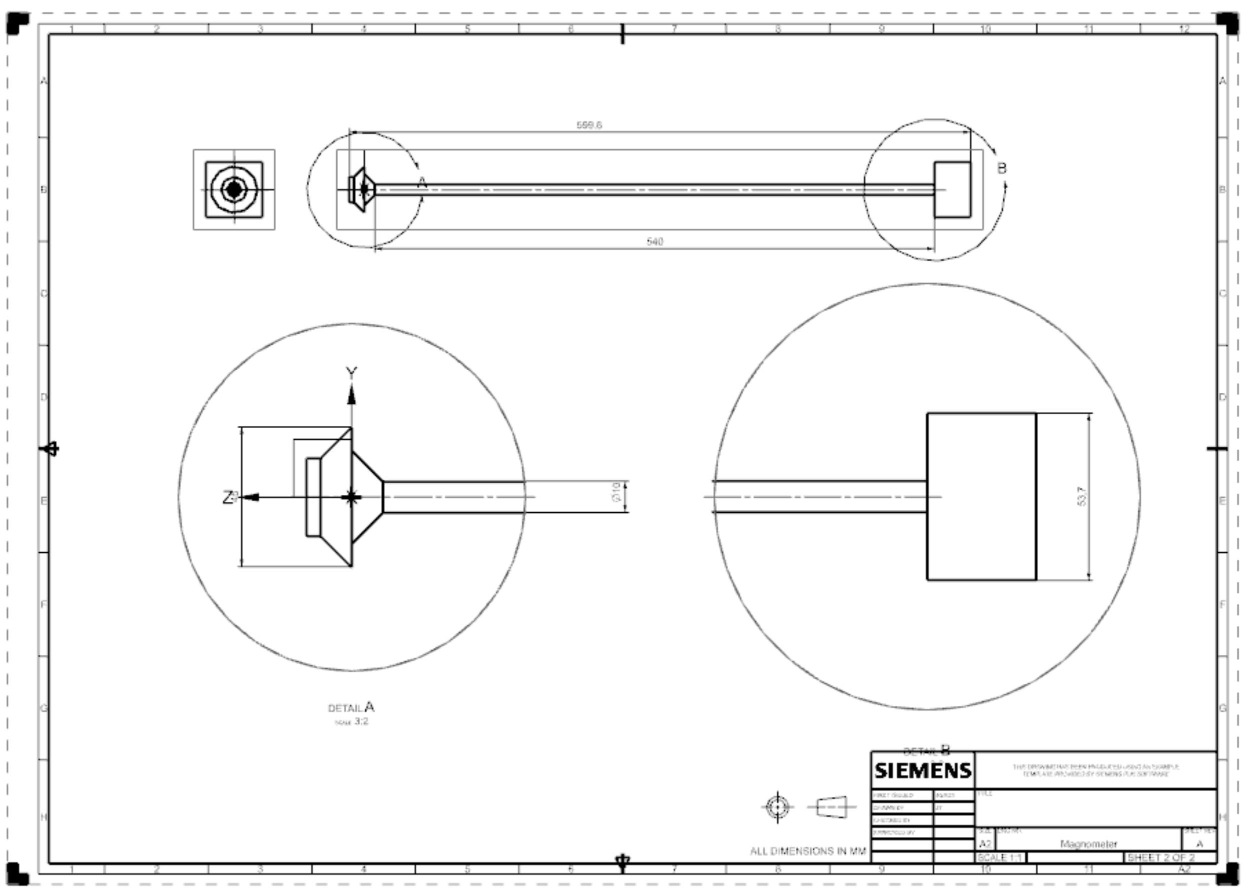

Figure 34. Engineering drawing of MAG.

The 3-D fluxgate magnetometer will determine the existence of remnant crustal magnetic fluxes as well as determine any magnetic signals emitted from lightning. The MAG will have a 32 Hz sampling rate over the course of the sixty day mission and will generate an estimated 325 Mbits in data volume.

Meteorological Suite (MET):

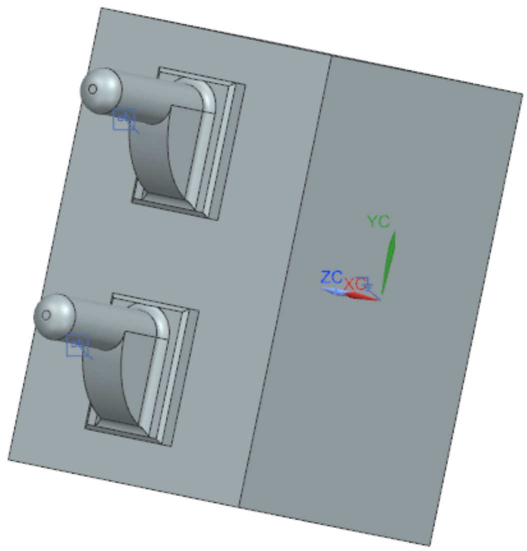

Figure 35. CAD render of MET.

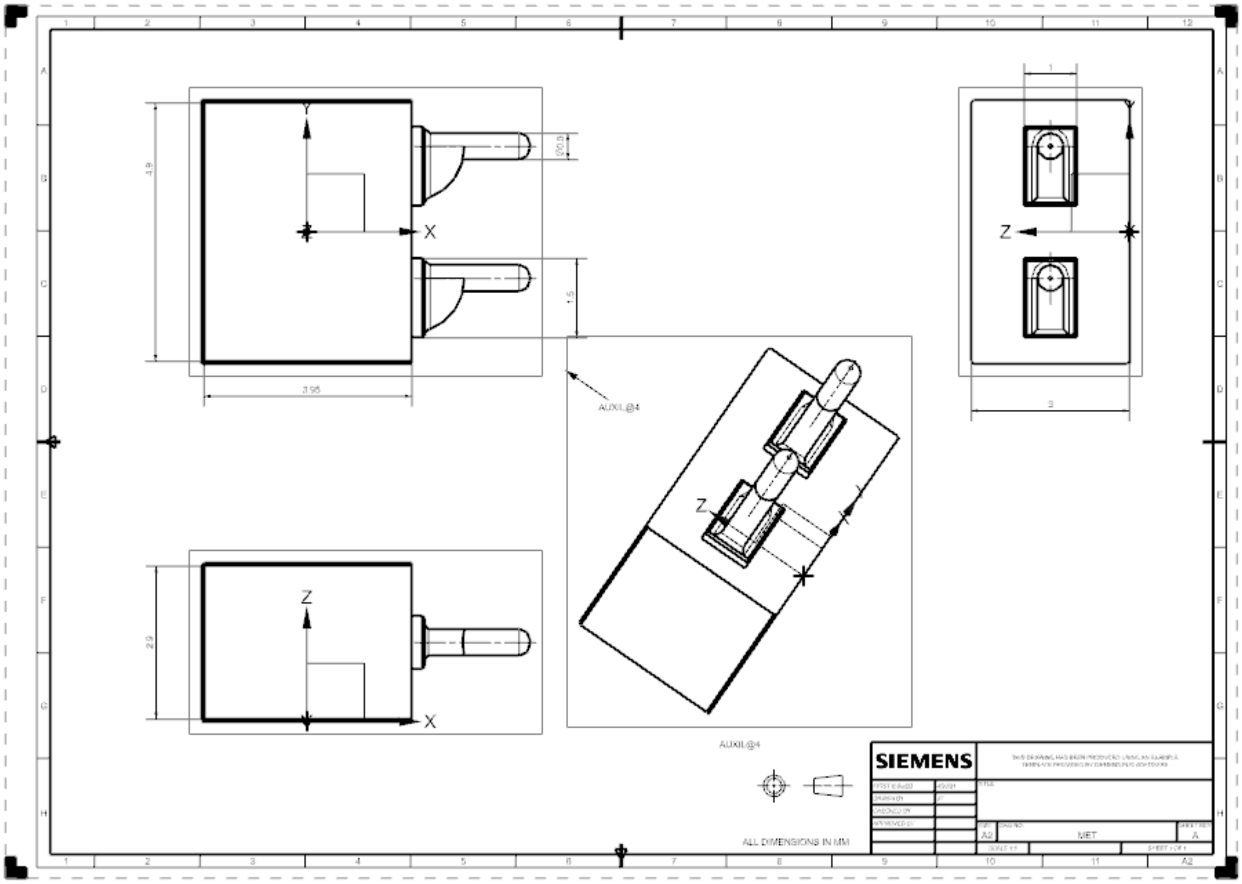

Figure 36. Engineering drawing of MET.

The Meteorological Suite will be equipped with various sensors, all of which will be measuring simultaneously during the sixty day mission. The barometric pressure and air temperature sensors will measure the ambient air pressure and temperature. The radiometer will measure fluxes and assess solar and thermal spectral ranges. The wind velocities will be measured using the attached GPS, that is, the wind patterns will be determined by the movement of the balloon itself. The radiation dosimeter will measure the radiation levels. All of these MET sensors will be taking measurements at a constant 0.5 Hz and sending it to the single data handling unit of the suite of sensors.

Systems Control Instruments:

The system control instruments are modeled from equipment that has been used extensively in other missions and therefore has substantial flight heritage. The estimated necessary storage capacity for data acquired is 250 MB, and the vehicle is expected to transmit the stored data for one interval per Earth day.

The total mass of the scientific instruments are tabulated below.

Instrument	Expected Mass (kg)	Max Mass (kg)	Expected Power (Watts)	Max Power (Watts)
Magnetometer	1	1.3	10	13
Meteorological Suite (MET)	3	4	5	6.5
TLS Spectrometer	4.5	5.8	26.1	34
AMS-N (Mass Spec + Neph)	11	14.3	10.8	14
Totals	**19.5**	**25.4**	**51.9**	**67.5**

Figure 37. Scientific instrument mass.

4.1.3. Manufacturing Plan

There is a budget of eighty eight million dollars for all instruments, combining the costs of science instruments, other COTS components, materials and supplies, manufacturing facility cost and test facility cost. Given the large majority of instruments that have experienced flight heritage, most of the systems control instruments will be Commercial-Off-The-Shelves (COTS). Using many COTS instruments will help decrease the amount of cost and time spent on the mission. While the power components have flight heritage as well and are technologically mature, due to the configuration of the balloon, the team will be designing this component, but not in any significant measure with the actual solar technology. In addition, the instruments such as the magnetometer and the TLS are mature technologies and these will also be planned as COTS. The team plans to design the AMS-N as it is the least mature of the instruments and requires the most calibration which will be adjusted to meet the specific mission requirements and objectives.

Magnetometer

Geometrics Inc., from San Jose, California, was searching for an office to test its magnetometers, gadgets used to quantify attractive fields. Iufer carried the organization to the consideration of Ames authorities, taking note of that the organization would consent to utilize the offices on a neutrality premise: the structures would be being used and kept up by Geometrics, however NASA would have need if the Agency expected to lead testing. The instrument has an integration time that can fluctuate from two seconds to one hundred seconds.

Aerosol Mass Spectrometer

Aerosol Mass Spectrometer (AMS) is commercially manufactured by MKS Instruments, Inc. MKS Custom Vacuum Solutions provides UHV-compliant machining, welding,cleaning, and finishing, as well as component subassembly, assembly, and device checking. MKS offers reliable, high-quality vacuum solutions through expert engineering, custom subcontract production, and oriented project management. The AMS produced by MKS Instruments may be modified to include a nephelometer that is similar to the commercial nephelometer produced by Particle Measuring Systems, Inc. (PMS) of Boulder, Colorado.

TLS

VSAUCE will implement a TLS similar to that used aboard the Curiosity rover. Thus, while modifications and calibrations will be made accordingly, it will be primarily be using parts from Honeybee Robotics, NASA Goddard Space Flight Center, the Laboratoire des Atmosphères Milieux Observations Spatiales (LATMOS), and may use commercial parts or similar design to the commercial TLS produced by AMETEK Process Instruments Inc.

MET Suite

Similar to the TLS, VSAUCE will use a MET Suite instrument that will be similar in most characteristics with the instrument of the Mars Environmental Dynamics Analyzer (MEDA) and it's sister mission to Mars. Using an instrument suite developed by the Spanish Astrobiology Center at the Spanish National Research Council in Madrid, Spain and will be manufactured though Airbus Inc. and it's compliance with the U.S. Space & Defense contract.

4.1.4. Verification and Validation Plan

Verification:

The instruments used will go through calibration requirements, after calibration requirements have been processed the vehicle instruments will be tested in order fulfill mission requirements. Each instrument will be calibrated separately, tested separately and vehicle tested as a whole. The instruments will be tested in a controlled environment test facility that simulates a launch, entry environment and venus habitat. The instruments will be tested at the Johnson Space Center Engineering test Facility. The integrated environment testing will consist of vibration test, acoustic testing, modal testing, structural testing, thermal environment testing, radiant heating test. The testing verification will provide vehicle performance evaluation and defects if any. Most of the vehicle parts are COTS, the verification process will be essential to meet mission requirements.

1. Vibration test - This test will be performed in the Spacecraft Vibration

Laboratory. The testing includes simulations of vibrations on external spacecraft by acoustic or aerodynamic pressures, shock pulses are also introduced to test ground handling. The test will include High-force vibrations (random and sine), shock vibrations.

2. Acoustic test - Acoustic testing will perform a range of different tests to evaluate the audio communication system from flight of vehicle with exposure to harsh acoustic environments. The testing will be performed in the Spacecraft Acoustic Laboratory that will include the following test, progressive wave acoustic test, electroacoustic and audio processing equipment test.
3. Modal test - The modal testing will determine the resonance frequencies corresponding to mode shapes and damping values for the vehicule structure. This will be performed in the Modal Operations Laboratory, the data analysis is provided by a test structure with an electrodynamic shaker and measuring the input force and the structural response.
4. Structural test - The test will be performed in the structure test laboratory. The test evaluates static load tests of instruments. It will test mechanical properties of material to full scale verification test of the spacecraft structure.
    a. Structural Dynamic testing - Launch Environment Testing.
5. Thermal environment test - Environment testing is performed by exposing the vehicle to simulated thermal, thermal vacuum and partial pravity and analyzing its performance. The test can provide temperature and humidity cycling, accelerated electrical component burn-ins and life-cycle testing, environmental cycling (thermal) test and battery performance and abuse test. The testing laboratory includes different testing chambers that include programmable temperature enclosures for instruments alone.
    a. Thermal-Vacuum Environment- The Thermal-Vacuum testing can be performed in large Chambers that can test the entire vehicle.
6. Radiant heating test - The radiant heating test will be performed in the Radiant Heating Test Facility. The facility will expose the vehicle to a controlled pressure environment and high temperature profiles and thermal gradient. The test will provide Venus planetary entry testing (CO_2 gas test), material testing, conductivity decay test, development testing of seals/gaps/attachments and clipped hardware. The facility will provide simulation of reentry heating/pressure, pressure and heating decay.

Validation:

Once calibration requirements have been approved and fulfill the testing requirements. The instrument's validation will be determined by the data collected through calibration and testing (National Aeronautics and Space Administration, n.d.).

4.1.5. FMEA and Risk Mitigation

The most significant problems the instrument package may face are environmental conditions that may cause the instruments to produce either inaccurate readings or fail entirely. The AMS-N is a technology that is not yet fully mature so thorough testing and further research will be required to fully understand how to make certain it operates correctly.

The primary concern for the AMS-N is that because of its low technology maturity, it may be more likely to not operate correctly. This could be because of the environmental conditions or because calibration was unsuccessful and the result could be inaccurate readings.This risk should also lower with time as thorough calibration tests are completed and the inclusion of calibration gas within the payload. Fortunately, mass spectrometers have a long history of being utilized in aerospace missions.

Other risks include magnetometer failure, TLS failure, and errors caused to MET suite, while these are still indeed risks, they are a much lower ranking because of the high TRL levels of the TLS and magnetometer and also the instrument package is semi-redundant because primary mission goals are still within reach in case of failure of an instrument. Below is a FMEA chart and a risk mitigation chart for the instruments.

Component	Function(s)	Mode(s) of Failure	Effects of Failure	Sev	Cause(s) of Failure	Occ	Design Controls (Prevention)	Design Controls (Detection)	Det	RPN	Recommended Action
Tunable Laser Spectrometer	Characterize the atmosphere at cloud level, Target specific species in the atmosphere, isotopic ratios,	Fails to power up	Measurements critical for mission success are no longer possible	7	Loss of power,	3	Semi-redundant instrumentation, some instruments have more than one purpose, may overlap with others	Check if instruments return data from measurements	8	**168**	Backup power
		Incorrect or uncertain readings	Unreliable data	5	Instrument not properly calibrated	2	Calibration gas	Compare any overlapping measurements between TLS and AMS-N	2	**20**	Store extra tanks of calibration gas, thorough environmental testing
Aerosol Mass Spectrometer + Nephelometer	Measure vertical profiles of D/H ratio, multiple profiles of gas and cloud composition, refractive index and size distribution of particles (Neph), Identify unknown particles absorbing UV, Identify non-liquid particulates	Fails to power up	Measurements critical for mission success are no longer possible	7	Loss of power	3	Semi-redundant instrumentation, some instruments have more than one purpose, may overlap with others	Check if instruments return data from measurements	8	**168**	Backup power
		Inaccurate readings	Unreliable data	5	Instrument not properly calibrated	2		Compare any overlapping measurements between TLS and AMS-N	8	**80**	Store extra tanks of calibration gas, thorough environmental testing
Meteorological Suite of Instruments (MET)	Sensors to measure wind velocity, temperature, monitor volcanic and tectonic activity, ionization levels,	Fails to power up	Unable to collect data	8	Loss of power	3	Backup Power, instruments won't all run simultaneously	Check if instruments return data from measurements	8	**192**	Backup power
		Sensor errors	Unable to collect data	8	Radiative exposure	4	Protect instruments from radiation with aluminum shielding		8	**256**	Protective aluminum shielding from radiation
Magnetometer	Search for presence of magnetic field	Fails to power up	Unable to collect data	4	Loss of power	3	MET suite carries another magnetometer	Check if instrument returns data from measurement	8	**96**	Backup Power
		Boom fails to deploy	Inaccurate measurements	2	Mechanical Failure	5			8	**80**	Backup Magnetometer

Figure 38. Failure Modes and Effects Analysis of Instrumentation

ID	Summary	L	C	Criticality	Trend	Approach	Risk Statement
1	AMS-N instrument failure	3	3	Med	↓	Mitigate	The Aerosol mass spectrometer and Nephelometer are a low maturity technology. There is no guarantee this instrument will meet success criteria because it is at such a low TRL. In the case that it malfunctions, the other instruments (especially the TLS) will be able to still complete primary mission goals but to a lesser extent.
2	Magnetometer failure	2	2	Low	→	Mitigate	The boom may fail to extend leading to unreliable measurements. Fortunately, the magnetometer is a technology at TRL 9 and the MET will carry an extra magnetometer.
3	Meteorological Suite of Instruments (MET) failure	2	3	Med	↓	Mitigate	The sensors are susceptible to errors caused by radiative exposure. Aluminum shielding will be one of the mitigation methods implemented to protect these sensitive instruments.
4	Tunable Laser Spectrometer failure	1	4	Low	→	Mitigate	The TLS is unlikely to fail but if so, the Aerosol mass spectrometer will still be able to complete primary mission goals
5	Corrosion from sulfuric acid	2	5	Med	↓	Mitigate	The sulfuric acid is a large concern however there are many methods of corrosion control that can be implemented such as protective coatings on instruments
6	Damage from high temperatures	1	5	Med	→	Mitigate	To avoid overheating, instruments will be turned of if they get too hot

Figure 39. Risk Characterization of Instrumentation

Likelihood									
	5							**Criticality**	**LxC Trend**
	4							HIGH	↓ - Decreasing (improving)
	3			1 ↓				MED	**↑ - Increasing (worsening)**
	2		2→	3 ↓		5 ↓		LOW	→ - Unchanged
	1				4→	6 →			NEW - Added this month
		1	**2**	**3**	**4**	**5**			
		Consequence							

Figure 40. Risk Matrix of Science Instruments

4.1.6. Performance Characteristics

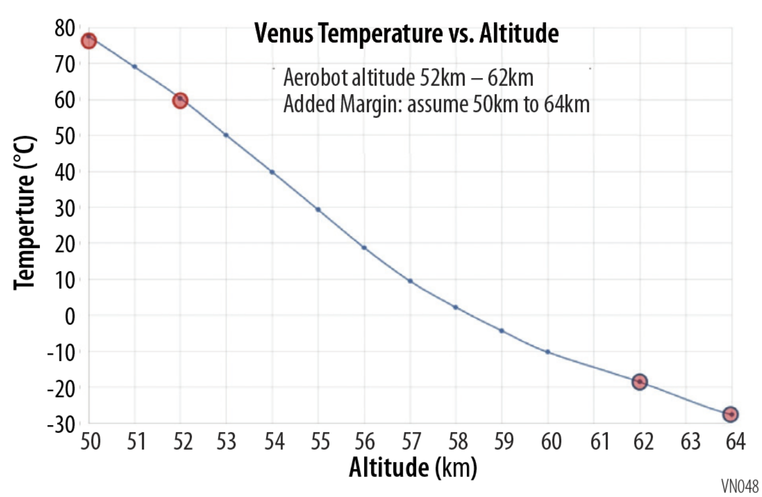

Figure 41. Temperatures vs Altitude (Gilmore et al., 2020)

The science payload consists of instruments with long histories at NASA. These instruments have been utilized in many aerospace missions and in various environmental conditions.

The primary mission will be carried out in the atmosphere from altitudes ~50 km to ~62 km. According to the 2020 Venus Flagship Mission Study, the temperatures that the balloon will encounter range from about 75°C at 50 km to -20°C at 62 km.

The TLS has a high TRL and a version of it is operating on Mars' Curiosity rover at an average surface temperature of about -63°C, much colder than what is expected for this Venus mission (*Mars Facts*, n.d.). Although the AMS-N is a lower TRL instrument, mass spectrometers are used often and the Curiosity rover even uses one along with its TLS.

Wind, air temperature, and pressure sensors are also being used on Mars so the MET suite's similar instruments will be able to handle the colder altitudes in the atmosphere.

In 1985, the Vega balloons survived the temperatures, pressure, and the acid within the clouds of Venus for at least 46 hours (Williams, 2021). The instruments included on these balloons were nephelometers and various sensors for meteorology. Many instruments including mass spectrometers were aboard the Vega descent crafts. One of these landers sent data for almost an hour, surviving on the harsh surface of Venus where temperatures reached about 467°C and a pressure of 95 atm. These feats were accomplished many years ago and the environment this payload will operate in is not nearly as harsh. Backed by over 35 years of improvements in instrument quality and durability as well as innovations in the development of anti-corrosion protective coatings (Kohler, n.d.), this science payload will be fully capable of meeting its success criteria.

4.2. Science Value

4.2.1. Science Payload Objectives

This mission's scientific goals will address the major goals outlined by the 2020 Venus Flagship Mission Report and is to check the :

(a) Habitability: To determine the history of water on Venus and the Venusian capabilities to support organic life through characterization of atmospheric composition

(b) Atmosphere and Energy Exchange: To understand the current composition of Venus' atmospheric composition and energy exchange

(c) Geological Evolution: To understand the current tectonic or volcanic activity present on Venus

These goals were deemed the most important as data collected to aid in the understanding of each of these goals would allow for further progression in scientists' understanding of previous measurements as well as ensure that if the balloon were to be the only collection of Venusian high-altitude data, the mission would be able to produce a substantial outline for further research in this field. The specific payload objectives within each of these goals will be as follows:

(a) To collect spectrometric data of the the atmospheric particles and test for evidence of and other particles indicative of past life
(b) To accurately determine the percent composition of the Venusian atmosphere and understand the radiation distribution
(c) To understand the presence of volcanic activity through detection of sulfuric particulate matter in the air and to measure the magnetic field of Venus in order to understand its geologic evolution

To achieve these objectives, the vehicle will use five scientific instruments to collect data of atmospheric composition (both organic and inorganic particles), wind patterns, ionizing radiation, and magnetic fields. Again, the team hopes that this broad spectrum research approach will provide insight into further areas of research in the upper atmosphere that would garner a return mission or if further research efforts should be focused on other regions.

4.2.2. Creativity/Originality and Significance

The objectives of this mission are unique in that they will provide insight and further data collection building upon previous missions such as Vega-1 and Vega-2.

Unlike Vega-1 and 2 which used a telemetry scheme which returned only the most- or least-significant 6 bits of a 12-bit measurement for each sample. Only the 6 least significant bits were sent for 75 samples then the most significant 6 bits were sent for the 8th sample (Williams, 2021). This means that almost twice as much data may be sent back given an instrument that is measuring a relatively stable environmental phenomenon. Thus, this mission will calibrate these accordingly, and ensure that assumptions of a given measurement range do not affect the ability to collect any data on the given phenomena. In addition also ensure that the pointer used for the wrap-around output data buffer will aid in tracking the read out in each downlink, which should allow for less backend analysis and easy accessibility of data.

This mission's instrumentation will also provide more precise and accurate data collection of the upper atmosphere of Venus, attempting to meet all three major science goals of the Venus Flagship Mission.

4.2.3. Payload Success Criteria

The success criteria of the instrumentation package are closely linked with their failure modes. Across most of these modes of failure is the loss of power or damage to the instrument such that no data may be collected from the instrument. These failure modes are addressed by ensuring backup power systems and to design entry for the balloon to ensure protection from structural damage. Barring the avoidance of these failure modes, the mission moves on to the success criteria once the data collection process has begun.

TLS and AMS:

The TLS and the AMS will need to at least meet expectations for the first experiment phase. Five accurate measurements during the day and five during the night for one full circumnavigation will be a significant achievement and contribute greatly to the mission's goal of determining gas and aerosol composition in the clouds.

MET Suite:

The success of the MET suite will be evaluated by the data collected from the components within the suite. The MET will operate continuously during the day and night side of Venus. The MET will provide data collected through the following components, barometric and air temperature sensors, radiometer, wind sensor, radiation dosimeter. The metrological suite will collect data from temperature during its vertical cycling, study vertical winds, turbulence, radiative balance and composition. Success of this instrument will also be characterized by the accurate measurements of the external conditions of the balloon such that adjustments may be made to the experiments and other scientific instruments accordingly.

Magnetometer:

The success of the on-board magnetometer will be determined by the quality of data captured and the duration of the data collection interval. Provided that it lasts its minimum lifespan, the magnetometer should map the field strength from the equator to one of Venus' poles. This should provide an accurate representation of the distribution, field strength and direction of the magnetic sources present on the Venusian crust. This should also aid in calculation of thickness and mineralogy characteristics of the crustal layer.

4.2.4. Experimental Logic, Approach, and Method of Investigation

Carried by the strong winds in the atmosphere, the balloon should circumnavigate the planet every 5 days. For the 60-Earth day duration of this mission, that amounts to around 12 circumnavigations during the balloon's expected lifetime. During these trips around the planet, the balloon will travel over the region occupied by Venus' largest volcanic feature. In 2020, the University of Maryland conducted a study which revealed 37 active volcanic features on the surface of Venus. These features are crown-shaped rings known as coronae. The largest of these features is the Artemis Corona (located at -35°N, 135°E) with a diameter of 2600 km (Gulcher et al., 2020). Targeting this region will provide the balloon an opportunity to complete all three of the mission's scientific goals. JMARS images of this site are shown below.

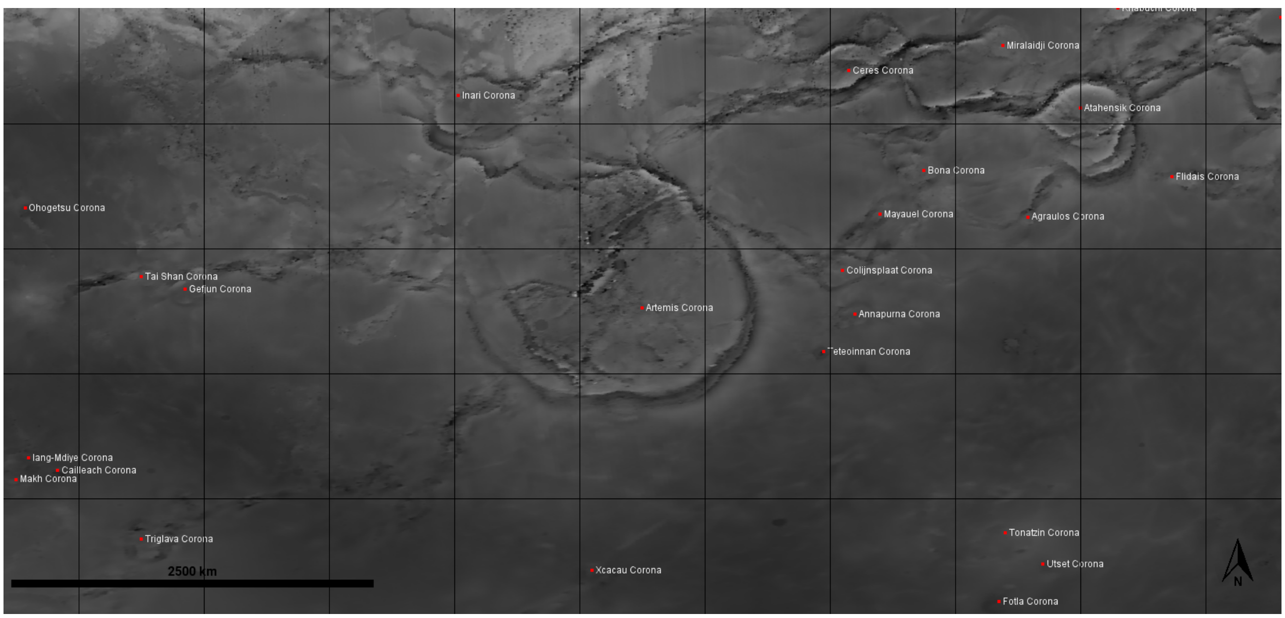

Figure 42. Artemis Corona, Venus' largest Corona (2600km diameter)

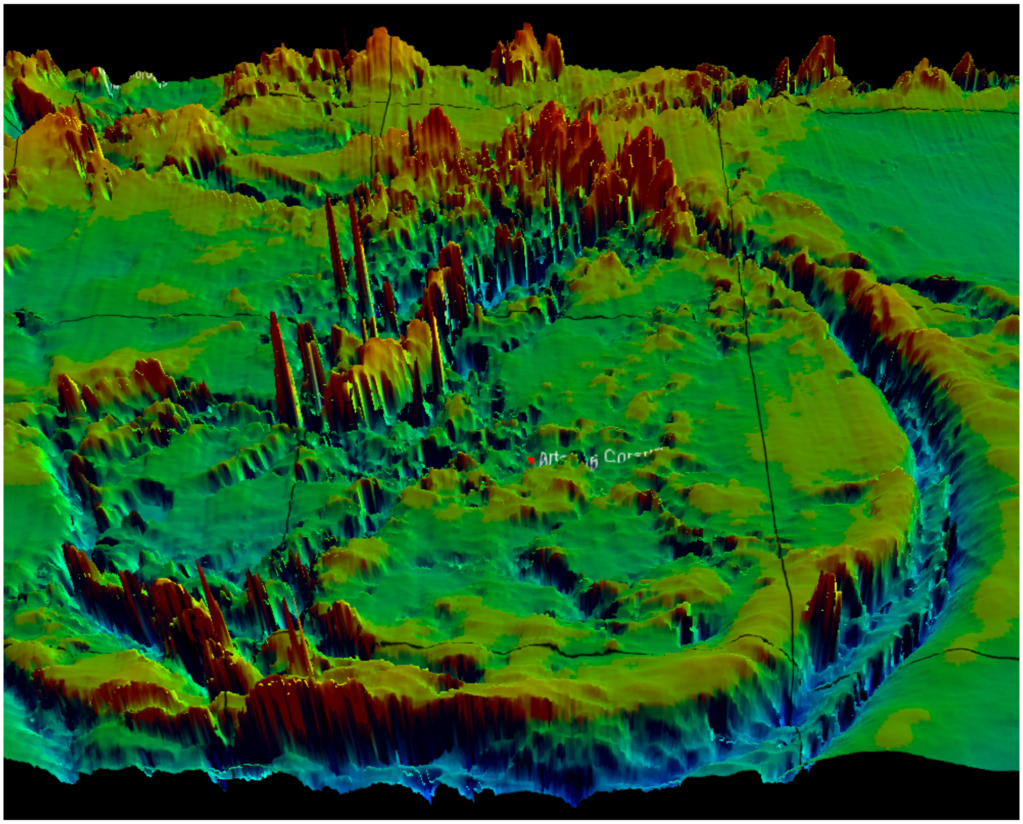

Figure 43. JMARS 3D view of Artemis Corona

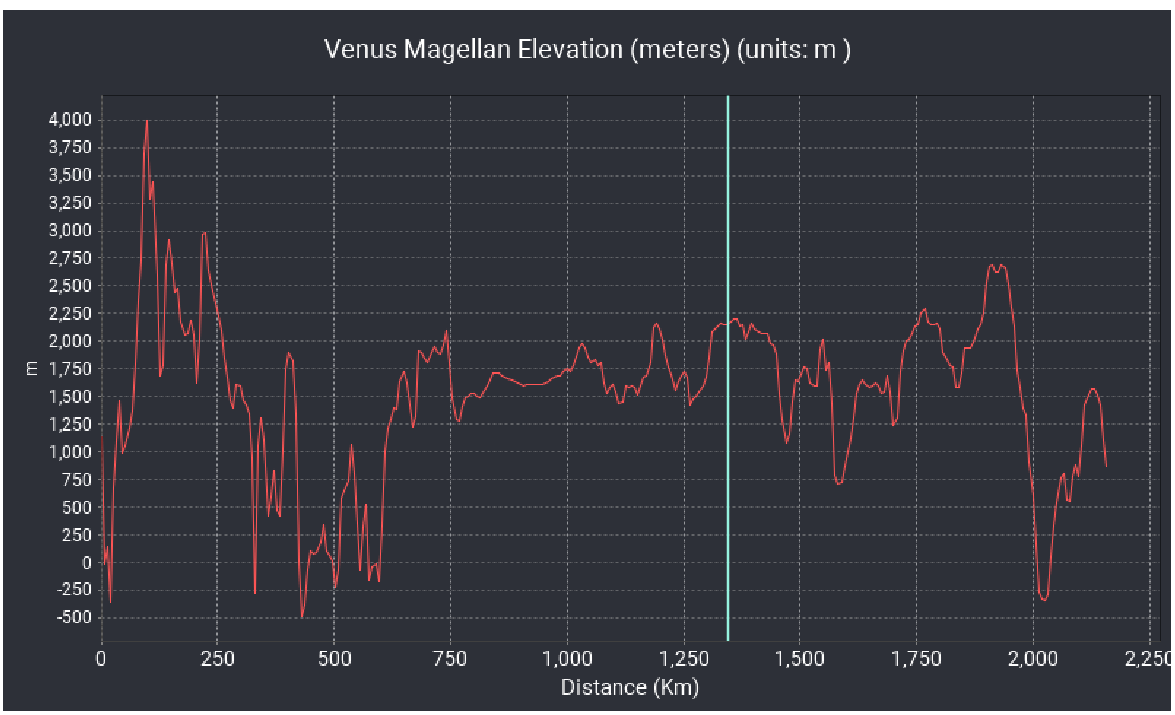

Figure 44. Elevation profile from North to South

In order to ensure reading of various altitudes recorded during time when the equipment is operating at optimal levels (i.e. the ensure that lower altitudes are not read only when the mission is at End of Life, where there is a greater chance for equipment, data processing, and telecommunications failures), the balloon will vary in altitude during its lifetime. Experiments will be carried out in phases during the duration of the mission.

Experiments Phase 1:

For the first circumnavigation, the balloon will keep a constant altitude within the middle cloud deck ~56 km to make sensitive measurements of atmospheric composition. Constant altitude allows the instruments to operate at a near-constant temperature and gives them time to make the most significant measurements in the main cloud layer. Checking if the instruments are properly calibrated will also be easier while the balloon is at a constant altitude. In this phase, the **TLS** will make at least 5 measurements during the day and 5 measurements during the night for its first trip around Venus. The **AMS-N** will also make 5 measurements during the day and 5 during the night. The **Meteorological Suite** will run continuously so that its sensors can determine the conditions of the atmosphere in the middle cloud deck and search for volcanic and seismic activity. It will be important that the MET suite is running continuously so that data logs of the external conditions (temperature and pressure on the most basic level) are being monitored and thus any issues arising at any point within each phase may be recorded and understood if caused by unforeseen external forces. The MET Suite will share a common DH unit thus it will monitor events at a lower rate unless triggered by a spike event in which it would begin collecting data at an accelerated rate. The **Magnetometer** will run continuously during this first phase as the nature of the instrument requires a 1-meter boom which may become difficult to ensure its lifetime given the strong vertical winds. Thus, this phase will ensure that it will be able to characterize at least the vicinity of the landing location. Completion of the phase will be marked by the successful downlinking of the data from this first circumnavigation with the orbiter, which will occur approximately at the end of the 5th day. While the downlinking will not all occur during this one point in time, the phase will be completed once all of the data from this phase is successfully received.

Experiments Phase 2:

After the first circumnavigation, the balloon will descend to the lower cloud deck ~ 50 km and begin measuring vertical profiles of the composition of the atmosphere all the way up to ~62 km. While moving vertically, the **TLS** will primarily focus on measurements at 3 different altitudes within the clouds: the lower cloud deck ~50 km, the middle cloud deck ~56 km , and the upper cloud deck ~62 km. It will continue this altitude variation process for two additional circumnavigations. At each of these cloud decks, the TLS will take 3 measurements. In this phase, the **AMS-N** will continue to fully characterize the main cloud layer by measuring samples at every kilometer from the lower cloud deck at ~50 km to the upper cloud deck ~62 km. The AMS-N operates more frequently in this phase to determine any signs of vertical variation in the atmospheric composition. Measurements of isotope ratios and abundances from the TLS and AMS-N will give scientists a better understanding about the history of water on Venus, the evolution of its atmosphere and provide insight into the processes involved in surface-atmosphere interactions. These measurements will be necessary to achieve the first and second goals of this mission. Thus, these will be prioritized in data collection. In this phase, the **Magnetometer** will continue to be operating continuously as it will be encountering new geographical locations during each circumnavigation. However, it must be noted that the data from the spectrometers will be prioritized over the magnetometer and thus, if in this phase it is necessary, the sampling rate of this instrument may be decreased. Science data rate will be reduced to 0.05 kpbs (the lower margin of the contingency rate) in order to prioritize the data from the two spectrometers. The **Meteorological Suite** is still operating continuously. Once again, the completion of the phase will be marked by the successful downlinking of the data from these two circumnavigations.

Experiments Phase 3:

Completion of the first two experiment phases will result in a complete mission success. If the balloon survives beyond these two phases, the third experiment phase will commence. The focus of this phase is to provide further insight into the composition of the atmosphere **below** the clouds as well as further study of surface-atmosphere interactions[MGA8] in the previous phases. Here the **TLS** will continue to make 3 different measurements at each of the three altitudes above, however, after each circumnavigation, all altitudes will shift down 1 km. That is, after the first circumnavigation in this phase, the balloon altitude will then drop to measuring ~49km in the lower cloud deck, ~55km in the middle cloud deck, and ~61km in the upper cloud deck. Each of these altitudes will continue to drop with each circumnavigation. The **AMS-N** will continue to operate as it did **Phase 2**, by measuring samples each kilometer. Similarly, the **Magnetometer** and **Meteorological Suite** will also continue to operate continuously during this section.

Magnetometer:

The magnetometer will search for remnant crustal magnetic fluxes as well as determine any magnetic signals emitted from lightning. The MAG will have a 32 Hz sampling rate over the course of the sixty day mission and will generate an estimated

325 Mbits in data volume.

Meteorological Suite (MET):

The Meteorological Suite will be equipped with various sensors, all of which will be measuring simultaneously during the sixty day mission. The barometric pressure and air temperature sensors will measure the ambient air pressure and temperature. The radiometer will measure fluxes and assess solar and thermal spectral ranges. The radiation dosimeter will measure the ionizing radiation levels. Finally, the wind sensor will measure the vertical winds to determine the turbulence encountered along the way. All of these MET sensors will be taking measurements at a constant 0.5 Hz and sending it to the single data handling unit of the suite of sensors.

4.2.5. Testing and Calibration Measurements

TLS and AMS-N:

To ensure that both spectrometers are accurate, calibration gases will be stored for in-situ calibrations. Pre-launch calibrations will also be carried out to complement in-situ calibrations. Calibration gases will also be used in various performance tests in a wide range of temperatures and pressures to make sure the spectrometers can operate as long as possible on Venus. Calculations using the high-resolution transmission molecular absorption database (HITRAN) will provide the team with a standard to compare calibration test results to (Mahaffy et al., 2010).

AMS-N Calibration:

Due to the combination of the AMS-N structure, both the spectrometer and the nephelometer will need to be calibrated separately. For the aerosol mass spectrometer, calibration of individual parts of the instrument will be necessary.

For the mass concentration calibration, the spectrometer will be calibrated using sampling mixtures of NH_4NO_3, $(NH_4)_2SO_4$, H_2SO_4, CO_2, SO_2, and one or two organic aerosols in order to produce response curves that may be analyzed.

For the electron multiplier calibration, there will be a focus on the DH readout to measure the gain of the electron multiplier and calibrate it as needed. The absolute ion intensity of known gases in the atmosphere (N2 and O2) as well as those expected to find in the Venusian cloud deck (H2SO4 and SO2) will need to be monitored. These values should remain constant during calibration to ensure that the gas intake flow is constant.

This leads to the final calibration methods of the inlet flow calibration for the aerosol mass spectrometer. The flow rate of the sample entering the aperture will be calibrated and monitored and then analyzed using laminar flow elements, calibrated by a Gilibrator (Drewnick & Jayne, 2001).

Nephelometer Calibration:

Two considerations must be made in the nephelometer calibration, the calibration of the backscattering capabilities of the instrument itself. The nephelometer will be calibrated using the scattering coefficients of dry CO_2 gas which will be adjusted according to the well documented standard for the total scatter and backscatter of CO_2 for the three wavelengths of 700, 550, and 450 nm across a range of sample times, air pressure, and temperature (U.S. Department of Energy, 2016).

Magnetometer:

To test and calibrate the magnetometer, Helmholtz coils will be used for anticipated 3-axis configuration. An electrical current will be run through the coil such that a given magnetic field may be produced to calibrate the magnetometer to the given specifications: a resolution of ± 5 nT and a 30 Hz sampling rate is anticipated. Standard calibration methods are used for this TRL 9 technology.

MET Suite:

The MET suite consists of different sensors, each sensor will be calibrated separately.

1. **Barometric and Air temperature sensors Calibration:**
   Temperature sensor will be calibrated by using a comparison method in temperature range -40 to + 50 ℃, the procedure will consist of a liquid thermostatic bath and a climatic chamber (Grykałowska, 2015).

2. **Radiometer Calibration**:
   The radiometer can be calibrated by exposing it to a known optical flux, which is introduced by a laser beam against a trap detector (Berg et al., 2019). Previous research found Venus flux 0.4 to 1.8 μm measured though solar flux radiometer.

3. **Radiation Dosimeter:**
   The radiation dosimeter will be calibrated by emitting electron, x-ray and gamma ray decay products from an 80 curie cobalt-60 radioisotope (Moldonado, 2020). The dosimeter should be able to differentiate between types of radiation and its energy level obtained from rays. The radiation dosimeter will be housed in an

aluminum case that will protect it from harming radiation and affect the instrument. The radioisotope will emit rays from distances of 3.41 to 1.02m to evaluate its sensitivity.

4. **Wind sensors Calibration**:
   A low density wind tunnel of varying winds can be used to calibrate wind sensors used for the MET suite (Wilson, 2008). The testing will verify if the sensor can measure Venus-wind like speed. The wind tunnels can provide an optimized test site and the laminar flow of both air and CO2 at pressure of 60 - 95 bar will be used, with the atmospheric pressure of Venus reaching ~93 bar at the surface. The wind tunnel design was previously used to calibrate Mars wind sensors. Previous research states that wind around Venus' atmosphere circulates quickly as Venusian wind speeds can reach up to 85 m/s (300 km/h; 186.4 mph) at cloud tops.

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

TLS:

The TLS will use four channels to target specific species in the Venusian atmosphere. The following list details the precision at which it will measure each species:

Channel 1 - isotopic ratio of ^{18}O /^{17}O/ ^{16}O in H2O and CO2, D/H in H2O, $^{13}C/^{12}C$ in CO2 (+/- 1 per mil precision)
Channel 2 - isotopic ratio of $^{34}S/^{33}S/^{32}S$ in OCS, $^{13}C/^{12}C$ in CO and OCS (+/- 5 per mil precisions)
Channel 3 - SO_2 abundance and $^{34}S/^{33}S/^{32}S$ ratios (+/- 5 per mil)
Channel 4 - HCl and $^{37}Cl/^{35}Cl$ ratio (+/- 10 per mil)

TLS will need at least three samples at each of the three cloud decks within the cloud layer. Any measurements that the TLS and AMS-N have in common such as D/H profile, can be compared.

If still functional, TLS can begin to measure abundances of SO_2, SO, SO_3, OCS, CO, H_2O, HDO, NO, HCl, HF and more below the clouds during the bonus missions of experiment phase three. These measurements are not required for mission success.

TLS Recovery:

The Aerosol Mass Spectrometer and Nephelometer instrument (AMS) will also be capable of characterizing the atmosphere and comparing results with the TLS. In the case of failure, the Aerosol mass spectrometer will also be measuring D/H profiles at various altitudes. This will allow information about the history of water on Venus to still be revealed.

AMS-N:

The AMS-N will measure species such as SO_2, SO_3, HCl, CO, OCS, H_2O, HDO, H_2S, multiple vertical profiles of the D/H ratio, and noble gas isotopic ratios ($^{20}Ne/^{22}Ne$, $^{82}Kr/^{86}Kr$, $^{36}Ar/^{38}Ar$, Xe) to a sensitivity of 1 ppm. It will also be required to measure H_2SO_4, H_2O, $FeCl_3$, and sulfur (S_3, S_4, S_x) to a sensitivity of better than 1%.

Nephelometer (AMS-N):

Measure particle size distribution with a resolution of 0.1 μm. Will also measure refractive index of particles to a resolution < 0.02

Magnetometer:

An estimate of 30% variation in calibration and instrumentation and data collection is expected. The magnetometer is required to be magnetically clean with a greater than 1 meter boom with 32 Hz sampling rate and a resolution of ± 5 nT.

MET Suite:

Since the MET Suite consists of various individual instruments, they are listed in detail below.

1. **Barometric and Air temperature sensors:**
   Temperature sensors will be designed with high temperature electronics and long duration to survive Venus ambient. Cooling system design in temperature sensors will allow long duration. Temperature thermocouple sensitive up to 1500℃, from previous studies done in Mariner 2 (1962) predicted temperatures of 800℉.

2. **Radiometer:**
   A radiometer measures UV flux absorption on the solar system, it also measures the radiative spectral ranges and the relation between cloud level dynamics. Images of different wavelengths of radiation activity in Venus will be obtained. The radiometer can potentially detect volcanic, seismic and lightning activity. Radiometers (advanced microwave radiometers) are very precise for deep

space exploration. Error contributions can be related to uncalibrated noises. From the previous 1962 Mariner 2 spacecraft, the expected emission wavelengths of Venus are 13.5 and 19 mm.

3. **Wind sensors:**
   Wind sensors are important for this mission to distinguish vertical wind changes. Wind sensors will meet the scientific goals by collecting data that consist of wind speed, air temperature, wind direction. Wind sensors have high precision on measurement rate because of its unique sphere structure that does not interfere with wind patterns. Because of the high pressure and high temperature of Venus the sensors will be made of miniaturized silicon carbide sensors and thin film sensors that will be able to survive Venus environment.

4. **Radiation dosimeter:**
   The dosimeter measures radiation levels in the cloud level. Radiation dosimeters are important for this mission to interpret dosimeter measurement of radiation, high levels of radiation can potentially damage some instruments needed to complete the mission. Calibration plays a role in precision, with proper environmental conditions the disometer can give higher precision. Aluminum cover on sensors can protect them from radiation damage.

4.2.7. Expected Data and Analysis

Expected Data of the TLS:

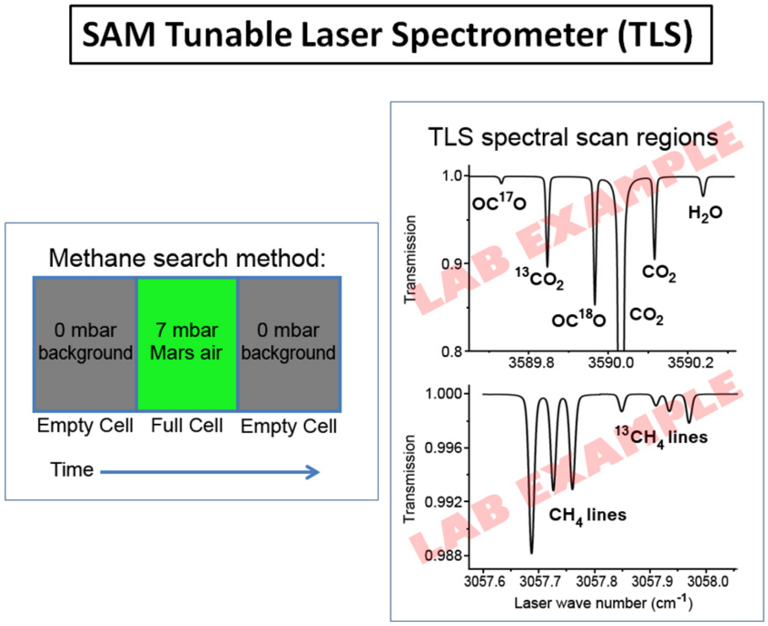

Figure 46. Example TLS Data (NASA/JPL-Caltech, 2012)

The image above is an example of data expected from the TLS (NASA/JPL-Caltech). When taking measurements, the TLS produces an infrared spectrum which is illustrated in the graph above. The vertical axis represents the transmittance of the molecules. Transmittance is the percentage of light that is allowed to pass through the molecules. The vertical axis ranges from 0 to 1 (0% to 100%). Any light that does not pass through the molecules, is absorbed. The sum of the transmittance of a molecule and the percentage of light absorbed, is equal to 100%. The horizontal axis represents the wave number which is the reciprocal of the wavelength of the laser.

The TLS will find precise isotope ratios at a data rate of 1.62 kbps with a 40% contingency or 2.1 kbps without contingency.

TLS data consists of time series records taken during the course of the experiment. It includes raw ADC values for direct and harmonic absorption spectra for the sample and reference cell.

The top graph shows isotopes in CO_2, and H_2O. The bottom graph shows the isotopes in methane. Each isotope has a unique signature which allows them to be identified. Many of these isotopes may be identified within the cloud layer during the mission because the clouds of Venus are composed primarily of sulfuric acid and an estimated 5% to 25% water (VFM). Where these signatures may differ are when the TLS identifies the signatures of sulfur isotopes.

The TLS will also determine isotopic ratios. Instruments like the TLS, can find the relative absorbances of isotopes and use them to calculate isotopic ratios (Sauke et al., 1992). Identifying these ratios is crucial for scientists to further understand the complex dynamics and chemistry associated with the formation and evolution of Venus (Webster & Mahaffy, 2012). Spectrometers are often used to express isotope abundances as ratios. An isotopic ratio, ***R***, is defined in terms of the proportion of a rare isotope with respect to the most abundant. Equation (1) below is the formula that represents the isotopic ratio, ***R***. An example using the rare ^{13}C isotope and the more common ^{12}C isotope is also shown.

$$\textbf{(1)}\ R = \frac{Rare\ isotope\ abundance}{Abundant\ isotope\ \ abundance}$$

$$R = \frac{^{13}C}{^{12}C}$$

It is important to note that molecules with different isotopes will also have different masses which means these molecules will react at different reaction rates. When chemical or physical processes involving these molecules occur, isotope fractionation can also occur, causing variation in isotope abundances.

The TLS is also necessary for comparing the variation in stable isotope concentration to that of a known standard. This comparison is shown using **δ** (delta) notation. This expresses an isotope's concentration as the relative difference between the isotopic ratios of a sample and a known standard (*Stable Isotope Geochemistry*, 2017). Equation (2) below shows the notation and it is followed by an example using ^{13}C and ^{12}C.

$$\textbf{(2)}\ \delta = \left(\frac{R_{Sample}}{R_{Standard}} - 1\right) \times 1000\ ‰$$

$$\delta\ ^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{Sample}}{\left(\frac{^{13}C}{^{12}C}\right)_{Standard}} - 1\right) \times 1000\ ‰$$

Fractionation causes only very slight variations in isotopic concentration so delta values are expressed as parts per mil. A positive delta value indicates that there is a higher concentration of the isotope in the sample and the sample is therefore **enriched.**

A negative delta value indicates that the sample has a lower concentration of the isotope compared to the standard so the sample is therefore **depleted**. These changes in concentration suggest a reaction or phase change has occurred. This is why isotopic ratios are so significant.

Another example graph below shows lab measurements of isotopes from a tunable diode laser. The graph shows changes in isotope concentration with respect to time. The upper graph is for the ^{13}C isotope and the lower graph represents changes in concentration for the ^{18}O isotope. Both samples appear to be depleted in comparison to their standards because of their negative delta values and the slight changes with respect to time suggest there is some reaction or phase change happening.

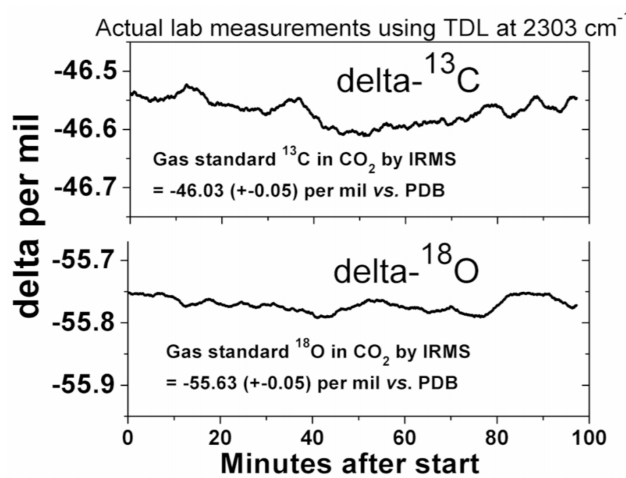

Figure 47. Tunable diode laser measurements via Methane on Mars workshop (Webster & Mahaffy, 2009)

Using the TLS to measure the D/H ratio in the clouds will provide insight into the history of water on Venus. Identifying and measuring other light element isotopes and ratios such as the oxygen isotopes in CO_2 and H_2O and the Carbon isotopes in CO_2 will give strong constraints needed to model the formation of Venus, the evolution of its atmosphere, its past habitability, and even the timing of its loss of water (Gilmore et al., 2020). Also, oxygen isotope ratios hold the key to knowing the history of fractionating loss and atmospheric interactions with the surface. Using the TLS will give better understanding to both of these processes. Lastly, the TLS will calculate sulfur isotope ratios which are all necessary to provide constraints on not only atmospheric composition but also atmospheric processes. This collection of data will allow the TLS to address at least two of the three goals for this mission and allow scientists to further understand not only Venus but the processes needed to produce and maintain habitable worlds like Earth (VFM study).

The TLS will find precise isotope ratios at a data rate of 1.62 kbps with a 40% contingency or 2.1 kbps without contingency.

AMS-N:

This mass spectrometer and nephelometer combination will be used to fully characterize the cloud layer, measuring both the composition of aerosol, gas and other particles as well as the size and refractive index of these samples as well. The image below is an example of the data expected from the mass spectrometer. This graph is called a mass spectrum and is an example using the compound CO_2.

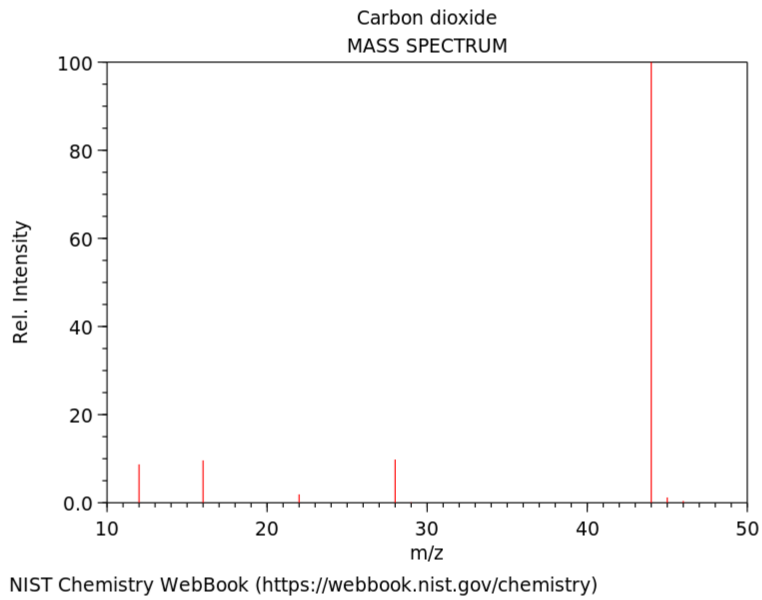

Figure 48. CO_2 Mass Spectrum (NIST Mass Spectrometry Data Center, 2018)

As stated in the subsystem overview, the mass spectrometer ionizes compounds. This is done by sending the sample through a beam of high energy electrons which knock away an electron from the molecule during collision (Reusch, 2013). After losing an electron, the molecule becomes a positive **molecular ion**, $[CO_2]^+$. It's important to note that these collisions can even break bonds**,** causing the molecular ion to break up into pieces called **fragment ions.** After ionization, a component called the **mass analyzer** sorts the ions by their mass-to-charge ratio, **m/z**. Usually in spectrometers, ions have a single positive charge so sorting them only depends on the mass of the ions. The **ion detector** then measures the relative abundances of the ions. Once the spectrometer sorts and counts the ions, a mass spectrum is generated.

Expected Analysis of the AMS-N:

The horizontal axis of this graph represents the mass-to-charge ratios (**m/z**) measured by the spectrometer. The vertical axis represents the relative abundance of the ions detected. The red vertical lines are peaks that represent the relative abundance of detected ions at certain **m/z** values. The **molecular ion peak** has the largest m/z ratio and in this example, belongs to the molecular ion $[CO_2]^+$. Notice this peak is at the mass to charge ratio 44 which is equal to the molecular mass of a CO_2 molecule (12 + 16 + 16 = 44 amu). The **base peak** is the largest peak in the spectrum and represents the most abundant fragment ion in the sample. It is given a relative abundance of 100% and the abundance of other fragment ions is measured relative to it. In this case, the base peak is also the molecular ion peak which means CO_2 is the most abundant ion.

Figure 49. Molecular diagram of CO_2.

Other significant fragment ions are represented by the peaks at m/z values 28 amu, 15 amu , and 12 amu. These fragments were detected after either one or both bonds in a carbon dioxide molecule were broken during ionization. When a single oxygen atom breaks away, CO may become a fragment ion (CO^+) with a mass of 28 (12 + 16 = 28 amu). The opposite is also possible. Oxygen can become the fragment ion (O^+) but the reason for the peak appearing at 15 instead of 16 means that the detector identified and measured the abundance of the ^{15}O isotope. When bonds break between the carbon and both oxygen atoms, the fragment ion becomes C^+ with a mass of only 12.

Notice that since mass spectra can also identify isotopes, these abundances can be used to identify isotopic ratios. Vertical profiles of D/H will identify any variation and provide further information on the history of water on Venus.The AMS-N will attempt to also detect and measure any noble gases in the cloud layer and possibly below it (If still functional during the bonus mission phase). Noble gas isotopic ratios are very significant because they also provide significant constraints on the formation and evolution of Venus.

On Venus, mass spectra of the wide range of compounds in the atmosphere will provide the abundances of many different species needed to fully characterize the cloud layer and further understand the chemical and physical processes that have led to the conditions on Venus today.

Nephelometer (AMS-N):

Particulates in the atmosphere are not all one uniform size or shape. The nephelometer will be necessary to record the various sizes of these particles and determine the **particle size distributions.** The particle size distribution is a plot showing the percent of particles that are smaller than an indicated size as a function of the particle sizes. An example of the particle size distribution plot of coal-fired fly ash is shown below.

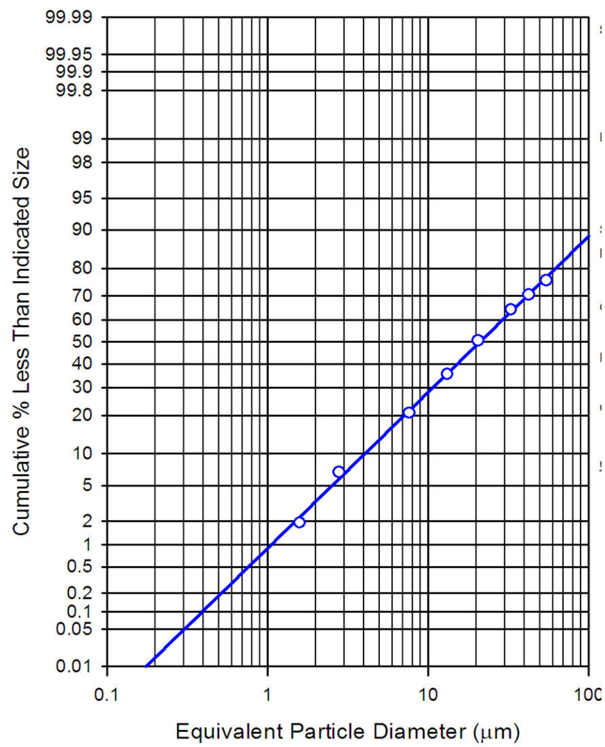

Figure 50. Example Particle Size Distribution of coal-fired fly ash (Rhoades 500, 2009).

The horizontal axis represents the ash particle sizes measured by the nephelometer. The vertical axis represents the percentage of ash particles that are less than those sizes. So for particles with a diameter of 1 μm, the vertical axis shows that about 1% of other measured particles are smaller than 1 μm.

Particle size distribution is significant because it can help scientists further understand the physical and chemical properties of a sample so the nephelometer is a very useful support instrument for characterizing the cloud layer.

Another significant measurement the nephelometer will be making is the **refractive index** of particles. The refractive index is essentially a measure of how fast light can travel through a material and is defined as:

$$n = \frac{c}{v},$$

where ***c*** is the speed of light in a vacuum and ***v*** is the phase velocity of light in the material. The refractive index is inversely proportional to the phase velocity so, the higher the refractive index, the slower that light will be when passing through the material.

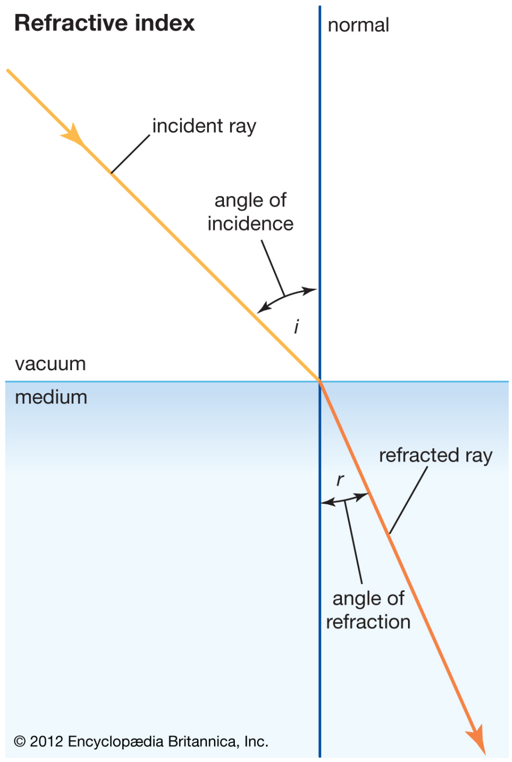

Figure 51. Refraction of light at interface between two media (Encyclopaedia Britannica)

One reason why the refractive index is so significant is because it can be used to determine how much light is refracted when entering a material. As a ray of light strikes a surface, the **angle of incidence**, Θ_1, between the ray and the normal to the surface, is created. While passing through the surface and into the material, the path of the light is refracted, creating an **angle of refraction**, Θ_2, between the normal to the surface and the refracted light. The image above illustrates this and Snell's law of refraction describes this below:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where $\mathbf{n_1}$ and $\mathbf{n_2}$ are the refractive indices of the two different media. Notice that the angle of refraction can be solved for when the refractive indices are known.

The refractive index is a fundamental physical property that can be used to identify substances. On Venus, evidence suggests there is more than just sulfuric acid and water within the clouds. There is an unknown substance absorbing UV in the cloud tops, large abundances of P, Cl, and Fe may be within the lower and middle clouds, and volcanic ash and other particulates that may indicate volcanic activity could be present within the clouds (Gilmore et al., 2020).

Both the particle size distributions and refractive indices of these various particulates will be significant in order to confirm the identity of these substances.

Magnetometer:

The magnetometer is expected to have an average science data rate of between 0.06 kbps and 0.8 kbps, and also to read the overall change in magnetic flux as it passes over the various topography of Venus.

MET Suite:

Barometric and Air temperature sensors: Expected data will consist of Atmospheric temperature sensors and will identify turbulences (Mock, 2020). Atmospheric pressure will be predicted by the collection of temperature and environment characteristics. Barometric readings rely on the aviator altimeter. It will use the barometric pressure to measure altitude reading, altitude fluctuates depending on the weather. Temperature sensor will be needed for barometric data. Altitude will be converted to pressure by $A = f(P)$, f is from the international atmosphere which represents how pressure changes over a range of altitude.

Radiation dosimeter:

Radiation measurements will be monitored closely to obtain data on volcanic/lightning activity and protect instruments from high radiation levels. Radiation dosimeter will perform to measure the total ionizing dose (TID), TID consists of combined flux of protons, electrons, cosmic rays that will penetrate the interior of the sensor that will monitor in order to keep the instrument healthy while mapping regions of radiation. The dose is presented to three DC linear output and a pseudo-logarithmic output. The dosimeter will integrate the absorbed does by the energy deposits. The radiation dosimeter includes a silicon detector and pulse architecture to create a Gausian-shaped pulse that responds to ionizing radiation.

Wind sensors:

The spherical wind sensor must be surrounded in air to successfully collect data. Its unique spherical will facilitate data interpretation (Domínguez-Pumar et al., 2020).

The heat flux components will operate on the surface of the wind sensors. The sphere surface will be forced to work at a temperature, some total heat will be transferred to the surface. The wind sensor splits into three flux components:

$$Q_{SURF} = Q_{CON} + Q_{RAD} + Q_{COND}$$

Q_{CONV} is the heat exchanged between the sphere sensor and ambient due to heat transfer, Q_{COND} represents the conduction of heat loss of supporting structure , Q_{RAD} represents the radiation heat loss. Q_{CONV} is only due to wind. Richardson number is used and defined as:

$$Ri = \frac{g\beta\Delta TD}{v2}$$

The g represents Venus gravitational acceleration, βrepresents the thermal expansion coefficient, and ΔTrepresents the change temperature between the sensors and ambient, D represents the length of the sensor and lastly V is the wind velocity. A combination of Newton's cooling law and the first equation the following equation is created:

$$Q_{SURF} = Q_{CON} = G_{th} \times (T_{SURF} + T_{AIR})$$

G_{th} represents the overall heat transfer coefficient, G_{th} is the rate which depends on wind velocity and pressure. T_{SURF} represents the temperature of the sensor's surface and T_{AIR} is the temperature of the air.

The analysis is derived for analytical research used for Mars wind sensors, the analytical expressions are derived from Reynold, Nusselt and Prandtl numbers. The analytical expression derives data collected such as viscosity, forces, wind speed, pressure, mass and temperature. The analytical expression derives the following expression relates the obtained data to wind temperature and pressure.

$$G_{th} = h * A_{sph} = Nu * k * \boldsymbol{\pi} D$$

A_{sph} represents the area of the sensor sphere, h is the convection heat, Nu is the Nusselt number that depends on pressure/temperature/speed, and k is the thermal conductivity. The results are illustrated in graphs that relate the overall convective heat and the wind velocity in a CO_2 environment. Expected data from wind sensors consist of high pressure and high temperature of (93 bar; the surface atmospheric pressure of Venus), the wind sensors will measure wind velocities to keep balloon buoyancy under control.

5. Safety

5.1. Personnel Safety

5.1.1. Safety Officer

Hazards are an inevitability that each team will face while constructing instruments and parts of the balloon. The safety officer will be required to identify and mitigate these hazards by conducting hazard assessments at the workplace and ensuring that everyone is following standards set by the U.S. Department of Labor’s Occupational Health and Safety Administration (OSHA) and directives from NASA’s Office of Safety and Mission Assurance (OSMA). Team 35 has assigned Dequan Jones as the Safety Officer for this mission. As safety officer, Dequan Jones will remain on-site during manufacturing and testing. The list below describes potential hazards the team may encounter during the mission.

5.1.2. List of Personnel Hazards

The list of personnel has been combined with the associated mitigation plans in the following section, *5.1.3. Hazard Mitigation*.

5.1.3. Hazard Mitigation

Personnel Hazard	Mitigation
Physical Hazards - Can lead to trips, falls, head injuries, leg/arm injuries, hand/foot injuries as well as electrical, mechanical, or even thermal hazards.	**Solution:** To limit the risk of serious injury or death, teams should follow the Department of Labor's Occupational Safety and Health Administration's (OSHA) safety standards. OSHA's personal protective equipment (PPE) requirements mandate that workplace hazard assessments must be done in order to provide workers with the necessary PPE (i.e. Hard hats, foot guards, leggings, goggles, gloves, etc) (Occupational Safety and Health Administration, 2006).

Electrical Hazards - Overhead or buried power lines, electrical equipment that is not grounded, lack of ground-fault protection, and improper use of electrical equipment are all examples of hazards that can cause electrocution and/or electrical burns and fire, even death	**Solution:** The Occupational Safety and Health Administration has a set of electrical standards that must be followed to protect workers from electrocution, fire, and/or explosions. Training the team to identify common electrical hazards is also necessary to reduce the risk of serious injury or death. Also, OSHA provides information on various solutions that may reduce the risk of electrical hazards when implemented. These include the use of: Insulation, guarding, grounding, electrical protective devices, and safe work practices (Occupational Safety and Health Administration, n.d.).
Chemical Hazards - Air contaminants, asbestos, vinyl chloride, lead and other harmful and toxic substances are examples of chemical hazards that may cause irritation, sensitization, flammability, corrosion, explosibility and more.	**Solution:** Chemical hazards and toxic substances are each addressed specifically in OSHA's industry safety standards. OSHA's Hazard Communication Standard must be followed to ensure workers are well informed about such hazards and the appropriate measures taken to prevent serious injury .
Fire Hazards - Flammable substances, explosives and blasting agents, faulty electrical equipment or improper use of electrical equipment are examples of fire hazards.	**Solution:** OSHA standards on fire safety should be followed by the team, workers should be trained to identify fire hazards and what to do in case of a fire. Evacuation plans must be provided to ensure the safety of the entire team. Hazard assessments should be done before starting any work.
Compressed Gas Hazard - Compressed gases can lead to a number of hazards including oxygen displacement, fires, explosions, toxic gas exposure, and even physical injury associated with high pressure systems.	**Solution:** OSHA's standards for the use, handling, and storage of compressed gases will need to be followed to ensure the safety of the team. Compressed gas should be handled with care and stored in a safe place.

5.2. Vehicle/Payload Safety

5.2.1. Environmental Hazards

Launch Hazards

A number of weather factors can jeopardize the safety of the launch. For example, high wind speeds are considered a hazard because of the possibility that the rocket is pushed off-course. The spacecraft is also at serious risk when thunderstorms are present within ten miles of the launch site.

Spaceflight Hazards

In space there are a number of hazards that can harm the spacecraft while in transit to its destination. Radiation exposure from the sun can harm spacecraft hardware with highly energetic particles that cause electronics to short circuit, space dust clouds can shower spacecraft with meteoroids, causing significant damage to the spacecraft and trajectory errors may occur, putting the spacecraft at extreme risk.

Entry/Descent Hazards

Entry and descent calculation errors can cause spacecraft to burn up during entry.

Sulfuric Acid Clouds

Venus' clouds are primarily composed of sulfuric acid which can eat through materials that are not resistant to corrosion. Sending a balloon that is not properly protected from corrosive substances will result in a mission failure.

High temperatures below cloud level

The lower Venusian cloud layer increases greatly in temperature as altitude decreases, reaching 373 K at roughly 40 km altitude, which is just 10 km below the desired science altitude. Due to the highly fluctuating and strong wind shears, it is very likely that the vehicle will encounter these high temperatures, which may melt and damage components, leading to instrument failures or possibly communication failures.

High pressures below cloud level

The cloud layer from 70 km to 50 km sees a pressure range from 0.1 bar to 1 bar which is relatively within Earth's normal range of pressures. However, this pressure increases exponentially, and the pressure range below 50 km intensifies. This is an issue for instruments such as the TLS and AMS-N which manipulate gas through chambers, which are pressure driven. High pressures may cause these instruments to produce inaccurate measurements or cause damage.

Hurricane force winds

The Venusian atmosphere rotates at about 60 times the speed of the planet's rotation, winds reach up to 360 km/hour at the cloud tops. These may also include sudden turbulence or powerful vertical winds.

Radiation Exposure

Some instruments including the MET Suite may be susceptible errors caused by radiation exposure.

Calibration of Instrumentation

The calibration of the measurements are made on locations on Earth and calibration methods are similarly tested. Therefore, there may be unforeseen challenges with miscalibration and unusable data collection techniques.

5.2.2. Hazard Mitigation

ID	Environmental Hazard	Mitigation
1	**Launch Hazards**	Launch windows allow time for poor weather conditions to improve. Postponing a launch is always a better option than risking safety.
2	**Spaceflight Hazards**	Layers of aluminum shielding can provide the spacecraft with protection from harmful radiation, tracking the orbits of space dust clouds will lower the chance that the spacecraft will encounter them, and daily monitoring of the spacecraft will allow the team to correctly adjust the flight while in transit to Venus.
3	**Entry/Descent Hazards**	Entry angle calculations will be confirmed numerous times to ensure the spacecraft does not burn up.
4	**Sulfuric acid clouds**	Use corrosion resistant resistant materials. Test sub assemblies in laboratories simulating Venus atmospheric conditions which can also reproduce the atmospheric temperature and pressures.
5	**High temperatures below cloud level**	Use high temperature resistant materials. Test sub assemblies in laboratory simulating Venus atmospheric conditions. Program the flight computer to only spend minimal time in lower altitudes by tracking altitude and inflating the balloon.
6	**High pressures below cloud level**	Test sub assemblies and payload in laboratory simulating Venus atmospheric conditions to ensure components can withstand high pressures.
7	**Hurricane force winds**	Design balloon tethers and turbines to sustain sudden strong loads and shears. Use monte-carlo simulations on full physics simulator to verify vehicle can remain stable in the winds.
8	**Radiation Exposure**	Layered aluminum shielding to protect instruments from exposure to radiation. Thorough radiation testing will be conducted to assess instrument performance and ensure they operate properly.
9	**Calibration of Instrumentation**	Testing and calibrating the instruments in an environment simulating the temperatures, pressures, and acidity within the clouds of Venus will be crucial for achieving scientific goals.

6. Activity Plan

6.1. Budget

The tentative budget of the project, with a maximum of $250,000,000, is shown below. A base salary of 80,000 is paid to each team member and a fringe benefits rate of 28% must be added into the budget to account for any employee related expenses. With ten team members receiving the base salary for three years along with the benefits rate, total personnel costs amount to $3,069,840. For travel expenses, the ticket prices for each team member ranged from $153 - $317 depending on location (Delta Airlines). The cost to fly all ten members to Orlando is estimated at $2,204 (Delta Airlines, n.d.). The launch will occur in January 2024 so to account for any increase in ticket prices after the COVID-19 pandemic, the flight cost was rounded up to $2,500. In order to save money on hotel expenses, a pair of teammates will share each room. Five rooms at $135 per night for four nights adds up to $2,700. For meals and incidentals, each team member will receive $53.25 on the first and last days of the trip and $71 dollars for the other three days. This adds up to $319.50 per person so for a ten member team, the total is $3,195.

For transportation the team will split into two groups of five and rent two compact, 5-seat cars for traveling to Cocoa Beach, Cape Canaveral, and the surrounding area. Each car will be a Nissan Versa or similar compact car. Renting will cost almost $380 per car for the duration of the trip (Enterprise Car Rentals). The average regular gas price per gallon in Orlando is $2.59 (source below) so with a tank size of around 10.8 gallons, the tanks of each car can be filled for almost $30 each. Also, with a fuel-efficiency of 27 mpg, the cars will be able to travel about 290 miles on a full tank. So, two cars at $380 each plus $30 to fill each tank adds up to $820 but extra gas money may be necessary considering the traffic. Transportation expenses are expected to be no more than $1,200 (Enterprise, n.d.).

Other direct costs include instruments, materials, and COTS components for the balloon. Using the Nasa Instrument Cost Model, and the Venus Flagship Mission Study, the team calculated that the total cost for instrumentation would sum up to $88,720,379.14 (Habib-Agahi et al., n.d.). A yearly breakdown of this cost is included in figure ## below the main budget sheet. The materials required for the manufacturing of the balloon will cost the team approximately $7,554,659.49 over three years. COTS components for the balloon will total $30,178,642.71.

Considering the technologies that need to be matured and the considerable amount of money left to spend, $3,000,000 was allotted to both the manufacturing facility cost and test facility cost. This sums up to a total equipment cost of $6,000,000.

To attract more youths to be involved in STEM, the team would like to expand its reach every year. Running social media campaigns on multiple platforms costs around $4,500 per month and the team wants to run this campaign every year of the mission. That brings the yearly cost to $54,000 each year. For the school visits, all of the equipment costs such as the LEGO MINDSTORM kits and Arduino kits as well as estimated costs to hold these events in at least ten schools sums up to about $100,000 each year. For the summer program, renting a community center for 8 weeks and purchasing lunch and supplies for students reaches about $150,000. After year 1, the team would like to expand the program to two more communities so the estimated cost of doing so would be $45,000. After year two the team wants to expand to two more communities for a total of 5. This would cost around $750,000 to do. This brings the outreach budget to $1,787,000.

Adding up all of the total costs and the final cost for the entire budget reaches $204,867,897.90. If any calculations were wrong or there are any unexpected expenses, the team will have plenty of money left from the $250,000,000 limit to cover the costs.

**Updated: 4/20/2021				
Additional Information				
	# People on Team	FTE Year 1	FTE Year 2	FTE Year 3
Science Team:	3	1	1	1
Engineering Team:	4	1	1	1
Admin Team:	3	1	1	1
NASA L'SPACE Mission Concept Academy Budget - *VSAUCE*				
Year	**Yr 1 Total**	**Yr 2 Total**	**Yr 3 Total**	**Cumulative Total**
PERSONNEL				
Science Team	$ 240,000.00	$ 240,000.00	$ 240,000.00	**$ 720,000.00**
Engineering Team	$ 320,000.00	$ 320,000.00	$ 320,000.00	**$ 960,000.00**
Admin Team	$ 240,000.00	$ 240,000.00	$ 240,000.00	**$ 720,000.00**
Total Salaries	$ 800,000.00	$ 800,000.00	$ 800,000.00	**$ 2,400,000.00**
Total ERE	$ 223,280.00	$ 223,280.00	$ 223,280.00	**$ 669,840.00**
TOTAL PERSONNEL	$ 1,023,280.00	$ 1,023,280.00	$ 1,023,280.00	**$ 3,069,840.00**
TRAVEL				

Total Flights Cost	$ -	$ -	$ 2,500.00	$ 2,500.00
Total Hotel Cost	$ -	$ -	$ 2,700.00	$ 2,700.00
Total Transportation Cost	$ -	$ -	$ 1,200.00	$ 1,200.00
Total Per Diem Cost	$ -	$ -	$ 3,195.00	$ 3,195.00
Total Travel Costs	$ -	$ -	$ 9,595.00	$ 9,595.00
OTHER DIRECT COSTS				
Total Outsourced Manufacturing Cost	$ 20,839,537.99	$ 77,703,579.54	$ 20,355,904.32	$ 118,899,021.85
|> Science Instrumentation	$ 4,526,758.79	$ 67,997,474.80	$ 16,196,145.55	$ 88,720,379.14
|> Other COTS Components	$ 16,312,779.20	$ 9,706,104.74	$ 4,159,758.77	$ 30,178,642.71
Total In-House Manufacturing Cost	$ 4,078,194.80	$ 2,426,525.00	$ 1,039,939.69	$ 7,544,659.49
|> Materials and Supplies	$ 4,078,194.80	$ 2,426,525.00	$ 1,039,939.69	$ 7,544,659.49
Total Equipment Cost	$ 1,750,000.00	$ 2,500,000.00	$ 1,750,000.00	$ 6,000,000.00
|> Manufacturing Facility Cost	$ 1,250,000.00	$ 1,250,000.00	$ 500,000.00	$ 3,000,000.00
|> Test Facility Cost	$ 500,000.00	$ 1,250,000.00	$ 1,250,000.00	$ 3,000,000.00
Outreach Cost	$ 279,000.00	$ 604,000.00	$ 904,000.00	$ 1,787,000.00
In-House Manufacturing Margin	$ 2,914,097.40	$ 2,463,262.50	$ 1,394,969.85	$ 6,772,329.75
Total Direct Costs	$ 30,884,110.19	$ 86,720,647.04	$ 26,477,688.86	$ 21,089,318.98
Total MTDC	$ 28,259,110.19	$ 82,970,647.04	$ 23,852,688.86	$ 15,089,318.98
FINAL COST CALCULATIONS				
Total F&A	$ 2,825,911.02	$ 8,297,064.70	$ 2,385,268.89	$ 13,508,244.61
Total Projected Cost	$ 33,710,021.21	$ 95,017,711.74	$ 28,862,957.74	$ 157,590,690.69
Total Cost Margin	$ 10,113,006.36	$ 28,505,313.52	$ 8,658,887.32	$ 47,277,207.21
Total Project Cost	$ 43,823,027.57	$ 123,523,025.27	$ 37,521,845.06	$ 204,867,897.90

Instrument	Year 1 (2021 - 2022)	Year 2 (2022 - 2023)	Year 3 (2023 - 2024)	Total cost	Source
TLS	$1,147,974.37	$17,518,088.89	$4,293,424.14	$22,959,487.40	NICM
AMS-N	$2,523,383.06	$38,506,825.42	$9,437,452.63	$50,467,661.10	NICM + 2020 VFM
MET Suite	$639,257.04	$8,938,383.53	$1,637,395.23	$11,215,035.80	NICM + 2020 VFM
Magnetometer	$216,144.33	$3,034,176.96	$827,873.55	$4,078,194.84	NICM + 2020 VFM
Totals	**$4,526,758.79**	**$67,997,474.80**	**$16,196,145.55**	**$88,720,379.14**	

Outreach Plan	Year 1	Year 2	Year 3	Total Cost	Source
School Visits	$75,000.00	$100,000.00	$100,000.00	$275,000.00	Approximation
Summer Program	$150,000.00	$450,000.00	$750,000.00	$1,350,000.00	Approximation
Social Media	$54,000.00	$54,000.00	$54,000.00	$162,000.00	Approximation
Totals	**$279,000.00**	**$604,000.00**	**$904,000.00**	**$1,787,000.00**	

6.2. Schedule

1. **Pre-Phase A: Conceptual Study** - Jan 12, 2021
    a. Perform the conceptual studies analyzing previous and current mission concepts proposed. Research previous mission concepts relating to Venus failures and mission concepts to related fields (such as mission concepts to Mars) successes.
2. **Phase A: Preliminary Analysis** - Jan 19, 2021
    a. Develop the mission proposal based on credible sources, and tailor design to fit with the Flagship Mission Study in order to ensure a contribution to the major interests of study within the field.
3. **Phase B: Preliminary Design and Technology Completion** - February 8, 2021
    a. Develop design and fabrication techniques to be used for the aerial platform. Begin CAD designs and prototyping and testing to determine if the mission will successfully be operational in atmospheric conditions.
    b. **Preliminary Design Review (PDR)** - April 19, 2021
        i. The PDR demonstrates that the overall program preliminary design meets all design requirements, is within cost and schedule constraints, and satisfies the customer.
    c. **Tech Completion** : April 19, 2021 - October 25, 2021

        i. Ensure all technologies are matured enough to be included in the final designs and fabrication process.

4. **Phase C: Final Design and Fabrication** - October 25, 2021
    a. **Critical Design Review (CDR) -** October 25, 2021
        i. The CDR is a technical review that ensures the system can proceed into fabrication, demonstration, and testing while meeting all performance requirements within cost, schedule, and risk.
    b. **Fabricate and Code Products** - Oct 25, 2021 - April 26, 2023
    c. **System Integration Review (SIR) -** April 26, 2023
        i. The SIR verifies that the system is ready to be integrated and is conducted at the end of the final design phase. All segments, components, and subsystems must be available and ready for integration.
5. **Phase D: System Assembly, Integration and Testing, Launch** - May 3, 2023
    a. **Assembly and Integration** - May 3, 2023
        i. All components are assembled/integrated according to integration plans after being verified by the SIR. Verification and validation must be performed on the integrated system according to the V&V plans and procedures.
    b. **Test Readiness Review** - July 5, 2023
        i. The TRR determines if the system is ready to proceed into formal testing by deciding whether test procedures are complete and comply with test plans and descriptions.
    c. **Formal Testing Stage -** July 5 2023 - September 6, 2023
    d. **Flight Readiness Review** - September 6, 2023
        i. The FRR assesses the readiness to begin flight tests and flight operations.
    e. **Flight Tests and Operations -** September 13, 2023 - December 14, 2023
    f. **Launch** - Jan 11, 2024
6. **Phase E: Operations**
    a. **Primary Mission** - 60 days duration, May 11, 2024 - July 10, 2024
    b. **Extended Mission** - July 10, 2024 - TBD

6.3. Outreach Summary

Social Media - The team will use popular social media platforms such as Instagram, Twitter, Youtube, and TikTok to share educational STEM content as well as information about current and upcoming NASA events to increase public awareness and inspire

K12 students to participate in STEM events. The social media campaign will be run every year until the completion of the mission.

School Visits - This team will reach out to ten schools chosen by each member, to organize fun and educational events to inspire more students to take an interest in STEM. During these events, students will be involved in various activities that teach them important skills. The team will aim to visit at least ten schools each year. Activities include:

- **Build-a-Bot racing** - Middle school and high school students will form teams, work together to build bots using LEGO MINDSTORM kits and learn how to program their final product which will compete with others in various obstacle courses.

- **Sumo Bots** - Middle school and high school students will form teams, work together building robots from LEGO MINDSTORM kits, and learn how to program their sumo bot which will face off with others.

- **JMARS Scavenger Hunts** - Students will go through a tutorial to learn how to use JMARS software and use the internet to learn about and view sites visited by NASA missions.

- **Skill Workshops -** Many STEM students would feel more confident if they can build their skills outside of the classroom. This team will organize and host workshops that will teach students about coding, excel/google sheets, simple circuits and more.

- **NCAS Alumni Presentations -** Alumni from the NASA Community College Aerospace Scholars program will share their experience with NCAS and why it is such a valuable opportunity. This is a great learning opportunity for students going to community college that strengthens students' abilities to work with a team and provides them with a wealth of information

- **L'Space Alumni Presentations -** L'Space alumni will share their great experiences and explain to high school seniors and current college students the importance of this program and its value to STEM students and their growth.

Summer Program - All of the STEM events listed above and more will be included in an 8-week STEM summer program where middle school and high school students can stimulate their minds and also have fun during break. Students will form groups and be taught valuable skills through tutorials. Then they will use what they learn to solve engineering challenges that will enhance their problem solving, critical thinking, and teamwork skills. Along with those activities, students will work together to complete small STEM projects every week. Students will be provided with a lunch and each day is concluded with team building activities such as dodgeball, volleyball, badminton, and more. Many kids will need something to do for the summer and this program is a great opportunity to inspire them to take on challenges and learn from them, a great opportunity to show kids that STEM subjects can be fun.

Days: Monday - Friday
Hours: 10:00 AM - 4:00 PM

Schedule:

- **Tutorials/Challenges:** 10:00 AM - 12:00 PM
- **Lunch:** 12:00 PM - 1:00 PM
- **Projects:** 1:00 PM - 2:30 PM
- **Team Building:** 2:30 PM - 4:00 PM

Note: On Fridays, the team building activity is replaced with “Film Fridays”, where students vote on a film to watch at the end of day.

The cost for these outreach activities are broken down in the budget section.

6.4. Program Management Approach

Although team 35 assigned individual tasks during meetings, many tasks were completed with teamwork. Team members often asked lots of questions and provided each other with feedback and other assistance. Despite all of the challenges, the result was a complete PDR. Each member had very busy schedules so good communication and being able to work together made it easier to avoid falling behind on certain parts of the project.

To assist the team in keeping track of tasks for each week, sub-team leaders used Trello to list tasks and assign them to team members. Each week, sub-teams would have at least one short meeting to assign new tasks, discuss questions, or work on the PDR. These meetings were very helpful in keeping the team focused and at a good pace for completion of the PDR. Despite being down two members, the great work ethic of each member made it possible for the team to meet most deadlines on time.

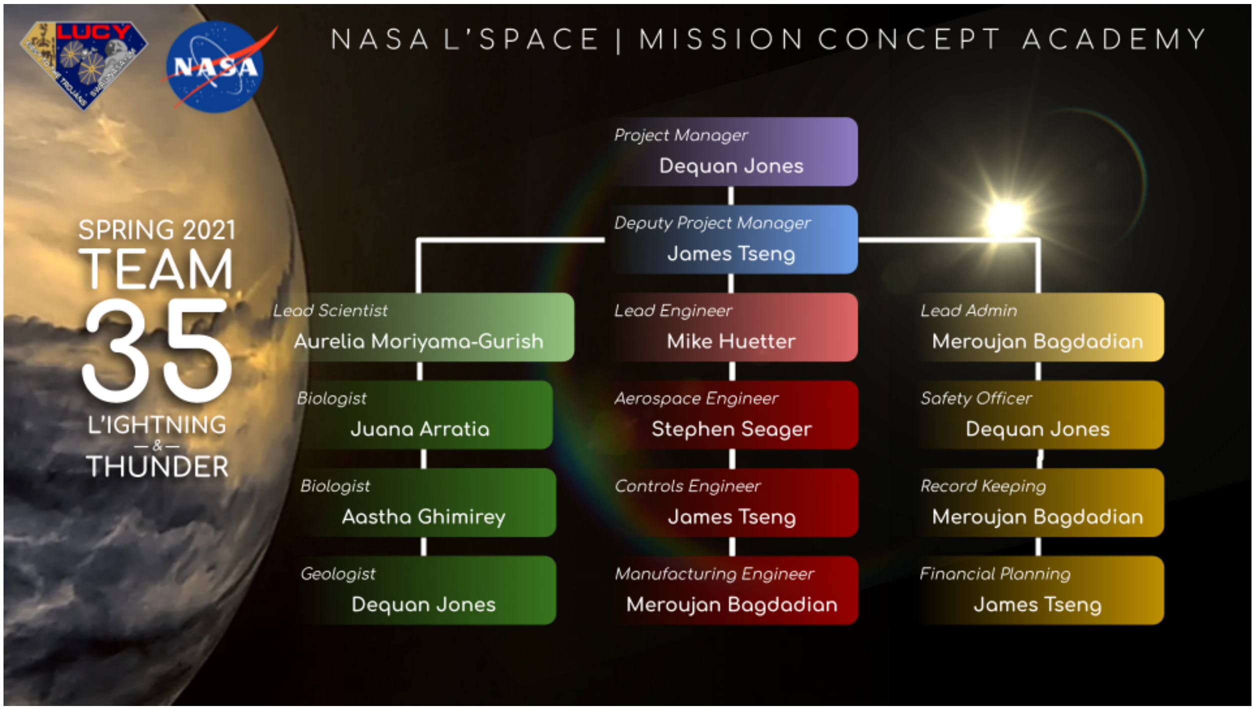

Figure 44. Team Organization chart.

7. Conclusion

7.1 Summary of Mission

Mission Statement

VSAUCE will further the understanding of the habitability, atmospheric composition and energy exchange, and geological evolution of Venus through the analysis of the Venusian cloud deck.

Vehicle and Payload

The vehicle as a whole meets the mission requirements in all aspects, with a volume dimensional constraint of 60 cm x 70 cm x 90 cm, a mass budget of 175 kg, and a monetary budget limit of $250 Million.

The vehicle design has a stowed dimension of 60 cm x 66 cm x 81.8 cm, which are within the volume constraints. The expected and maximum anticipated all-up mass of the vehicle with the scientific payload is presented below.

Sub-system	Component	Quantity	Expected Mass (kg)	Maximum Mass (kg)
Vehicle				
Structure	Vehicle Housing	1	25	30
Structure	Shielding and Insulation	1	0.5	1
Balloon	Parachute	1	7	10
Balloon	Zero-Pressure (ZP) balloon	1	14	16
Balloon	Super-Pressure (SP) balloon	1	7	8
Balloon	Helium Pump and Stored Gas	1	18	22
Balloon	Tethers	6	0.1	0.3
Power	Solar Panels	6	1	1.5
Power	300 Ah Battery with BMS	6	6	9
Power	MPPT Charger Module	3	0.3	0.8
Propulsion	BLDC Motor	3	0.3	0.5
Propulsion	Folding Propellers	3	0.18	0.2

Propulsion	Electric speed controller (ESC)	3	0.07	0.1
Propulsion-Structure	Carbon Fiber booms	3	0.08	0.2
Propulsion-Structure	Motor housing and structure	3	0.2	0.4
Propulsion	Thermometer	3	0.07	0.1
Control	Flight computer	2	0.05	0.1
Control	IMU/Inertial Navigation System	2	0.32	0.5
Communication	Data transmitter	2	0.75	1
Communication	Antennas	2	0.5	1
Structure	Wiring	1	0.5	1
Science Payload				
Science Payload	Magnetometer	1	1	1.3
Science Payload	Meteorological Suite (MET)	1	3	4
Science Payload	TLS Spectrometer	1	4.5	5.8
Science Payload	AMS-N	1	11	14.3
	Total Mass (kg)		**140.94**	**190.3**

Figure 45. Total Vehicle and Payload All-Up Mass

The mission requirement mass of 175 kg is met with an expected mass of roughly 141 kg, with a worst case of 190 kg expected. This range indicates that the vehicle is very likely to remain within the mass allocation with its large buffer gap of 34 kg.

The vehicle is also fully capable of providing sufficient power for its onboard electronics and scientific payload through its solar panels and turbines, with sufficient power to both power all electronics simultaneously and also have extraneous power to charge the batteries. The expected and maximum anticipated power consumption and generation by the vehicle with the scientific payload is presented below.

Sub-system	Component	Quantity	Expected Power (Watts)	Maximum Power (Watts)
		Vehicle		
Balloon	Helium Pump and Stored Gas	1	20	50
Power	MPPT Charger Module	2	0.15	0.25
Propulsion	BLDC Motor	2	80	300
Propulsion	Electric speed controller (ESC)	2	2	5
Propulsion	Thermometer	2	2.9	3.8
Control	Flight computer	2	1.5	2
Control	IMU/Inertial Navigation System	2	2.6	4
Communication	Data transmitter	2	1.5	2
Communication	Antennas	2	2	5
		Science Payload		
Science Payload	Magnetometer	1	10	13
Science Payload	Meteorological Suite (MET)	1	5	6.5
Science Payload	TLS Spectrometer	1	26.1	34
Science Payload	AMS-N	1	10.8	14
	Total Power Consumed (W)		**257.2**	**761.6**

Sub-system	Component	Quantity	Expected Power (Watts)	Maximum Power (Watts)
		Vehicle		
Balloon	Solar Panels	6	50	82.5
Power	Turbines	2	5	7.5
	Total Power Delivered (W)		**310**	**510**

Figure 47. Total Vehicle and Payload Power Consumption and Generation

The scientific payload will be composed of the four scientific instruments: two mass spectrometers, a meteorological suite, and magnetometer. Each of these instruments will work in tandem in order to characterize the atmospheric composition of the Venusian cloud tops as well as the geological characteristics. The TLS and the AMS-N will work to both create a wide survey of the atmospheric particles present in the cloud deck and a targeted detailed analysis of the particle characterization. The MET Suite will provide data of the atmospheric conditions including the barometric pressure, wind speed, and ionization energy. The Magnetometer will provide a characterization of the geological characteristics through the collection of data of the magnetic fluxes as well as the energy emitting from any lighting present near the balloon.

7.2 Next Milestones and Pathway Forward

In preparation for the CDR, the team will complete the detailed design of the balloon, and begin fabricating the product and coding software. The design will be validated using trade study results to ensure the design can meet mission goals and engineering test units will be built and tested to build confidence in the design. Plans to integrate crosscutting and engineering specialty analysis will be carried out. Manufacturing processes and controls will also be implemented. As the design continues to be refined, constraints will be monitored to make certain that there is enough time to correct any unexpected trends.

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