Preliminary Design Review

NASA L'SPACE Mission Concept Academy Spring 2025

TEAM **V.E.L.A.Z.Q.U.E.Z.**

V*enus* ***E****nvironmental* ***L****ight and* ***A****tmospheric* ***Z****onal* ***Q****uantification* ***U****nder* ***E****xtreme* ***Z****ones*

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Table of Acronyms

Acronym	Definition
ADV	Advisory
AON	Aluminum Oxynitride
ASM	Aerospace Specification Metals
BoE	Basis of Estimate
CAD	Computer Aided Design
CCB	Change Control Board
CDH	Command and Data Handling
CDR	Critical Design Review
CER	Cost Estimation Relationship
cFS	Core Flight System
CIRS	Composite Infrared Spectrometer
ConOps	Concept of Operations
COTS	Commercial Off-the-Shelf
CRC	Cyclic Redundancy Check
CRM	Continuous Risk Management
CS	Chief Scientist
CY	Calendar Year
DAVINCI	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DC	Direct Current
DoD	Department of Defense
DPMR	Deputy Project Manager of Resources
DR	Decommissioning Review
DRR	Disposal Readiness Review
DSS	Decision Support System
EDI	Entry Descent and Insertion
EM	Electromagnetic
EMI	Electromagnetic Interference
ERE	Employee Related Expenses
ESA	European Space Agency
FL	Florida
FMEA	Failure Mode and Effect Analysis
FPGA	Field Programmable Gate Arrays
FRR	Flight Readiness Review
FY	Fiscal Year
GNC	Guidance, Navigation, and Control
GRC	Glenn Research Center

GSFF	Goddard Space Flight Facility
HCT	Helical Communication Technologies
I/O	Input/Output
IR	Infrared
ISARA	Integrated Solar Array and Reflectarray
ISO	International Organization for Standardization
ITAR	International Traffic in Arms Regulations
JHU APL	Johns Hopkins Applied Physics Laboratory
JMARS	Java Mission-planning and Analysis for Remote Sensing
JPL	Jet Propulsion Laboratory
KDP	Key Decision Point
LCR	Life Cycle Review
LEO	Low Earth Orbit
LOTO	Lockout Tagout
LRR	Launch Readiness Review
LSE	Lead Systems Engineer
MAVEN	Mars Atmosphere and Volatile EvolutioN
MCA	Mission Concept Academy
MCCET	Mission Concept Cost Estimate Tool
MCR	Mission Concept Review
MD	Maryland
MEDA	Mars Environmental Dynamics Analyzer
MG	Mission Goal
MIDEX	Medium Class Explorer
MISS	Mission
MLI	Muli-Layer Insulation
MRR	Mission Readiness Review
MSDS	Material Safety Data Sheet
NASA	National Aeronautics and Space Administration
NICM	NASA Instrument Cost Model
NMS	Neutral Mass Spectrometer
NPD	NASA Policy Directive
OBC	On-board Computer
OMERE	Outil de Modélisation de l'Environnement Radiatif Externe
ORR	Operational Readiness Review
PCB	Printed Circuit Board
PD	Pressure and Density
PDR	Preliminary Design Review

PLAR	Post-Launch Assessment Review
PM	Project Manager
PPE	Personal Protective Equipment
psi	Pounds per square inch
QHA	Quadrifilar Helix Antenna
RF	Radio Frequency
RFA	Request for Action
RIDM	Risk-Informed Decision Making
RPA	Retarding Potential Analyzer
RPN	Risk Priority Number
RTG	Radioisotope Thermoelectric Generator
SA	Surface Area
SAFC	Software Architecture Flow Chart
SAR	Synthetic Aperture Radar
SEE	Single Event Effect
SER	Schedule Estimating Relationship
SEU	Single Event Upsets
SIR	System Integration Review
SMA	Safety and Mission Assurance
SME	Subject Matter Expert
SNR	Signal-to-Noise Ratio
SPENVIS	SPace ENVironment Information System
SRR	Systems Readiness Review
SS	Science Suite
STEM	Science, Technology, Engineering, Mathematics
STM	Science Traceability Matrix
TID	Total Ionizing Dose
TCS	Thermal Control System
TMS	Thermal Management Subsystem
TRL	Technology Readiness Level
TVAC	Thermal Vacuum
UV	Ultraviolet
VELAZQUEZ	Venus Environmental Light and Atmospheric Zonal Quantification Under Extreme Zones
VIBE	Vibration Testing
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
VMR	Volume Mixing Ratio

VR	Virtual Reality
WSTF	White Sands Test Facility

1 Mission Overview

1.1 Mission Statement

Venus is a planet that has been of high interest for NASA research for many decades, with the first successful interplanetary mission being in 1962 (“Venus: Exploration - NASA Science” 2017). It is a unique planet because it shares many similar qualities with Earth, despite it being an inherently volatile planet (Garner 2016). There have been ongoing explorations into the deviation between Earth and Venus’ history in the hopes that uncovering this mystery can provide insight into how solar system atmospheres evolve over time, especially since Venus has such a perplexing geologic and planetary history due to its lack of impact craters despite being 4.6 billion years old (Alden, n.d.).

This Venus reconnaissance mission’s proposed aerobot aims to explore how the planetary interior and surface of Venus interact with its host atmosphere. The goals of this mission are to investigate the planetary climate feedbacks and atmospheric interactions by determining the rate of dust lifting and sand motion in the near-surface atmosphere via dust and sand fluxes. It will also investigate volcanic outgassing by quantifying near-surface sulfur dioxide via ultraviolet/visible absorption spectroscopy and analyze high thermal emissivity regions indicative of active volcanism through infrared radiometry during the descent phase. The mission shall record the dynamic volcanism, atmospheric interactions, and dense, sulfuric acid-laden atmosphere.

These measurements are significant because they provide an understanding of the mechanisms of planetary resurfacing, the scale of sulfur dioxide injections into the atmosphere, and the resulting climatic effects. In turn, this knowledge informs models of terrestrial planet evolution under extreme greenhouse scenarios, offering analogs for both Earth’s past and potential exoplanet climates. The collected data will ultimately guide NASA’s future exploration strategies by clarifying how interior-driven volcanism and atmospheric chemistry interconnect, thereby deepening the comprehension of planetary habitability throughout the solar system.

1.2 Science Traceability Matrix

The primary scientific goal of this mission is to focus on addressing the specific question from the NASA Decadal Survey, “How do planetary surfaces and interiors influence and interact with their host atmospheres?” (The National Academies Press 2023). The team believes that this focus strikes a balance between providing valuable insight into scientific underpinnings underlying the formation of Venus, derived from the stakeholder constraints, while producing novel science. The focus on atmospheric conditions, resurfacing history, and their combined interaction are topics that have been covered in foundational literature (Noack et al. 2012), but with room for novel science discovery (“Ongoing Venus Volcanic Activity Discovered With NASA’s Magellan Data,” n.d.). The following objectives have been derived with these considerations in mind while maintaining appropriate scope. Specifically, this drives the two main motivations behind the science objectives:

1. To determine the composition and interaction of Venus’ atmosphere, through processes such as outgassing (Faruki 2025).

2. To determine the thermal exchange processes from within Venus' interior and how it interacts with the atmosphere (Wilson 2024).

As such, the three objectives detailed in the STM focus around fully covering these motivations: an objective providing insight into atmospheric processes (A), an objective providing insight into interior processes (B), and an objective providing insight into surface interactions with the atmosphere (C).

To quantify (A), the team has chosen to focus on the outgassing that occurs from volcanic injections from SO_2. This objective was chosen because sulfuric dioxide is a major contributor to why Venus's atmosphere and surface is composed in the way it is. Sulfuric dioxide forms acid rain and in turn negatively affects the surface. Acid rain causes major erosion on Venus which could potentially contribute to why Venus is composed in the way it is. If the team can understand the specific composition of sulfuric dioxide in the atmosphere then a greater understanding of how much of an impact sulfuric dioxide is causing towards Venus's environment both directly and indirectly. A UV/VIS Spectrometer will help the team quantify the amount of sulfuric dioxide in the atmosphere.

To quantify (B), the team will focus on thermal emission from Venus' interior at a volcanic location. This was chosen due to the correlation between the surface of Venus and its atmosphere. Thermal emission can display energy in the form of infrared radiation which not only has been used in previous missions, but also helps with temperature monitoring and heat dissipation. A radiometer and spectrometer will be used to help with quantifying the composition of the cloud layer of the Venusian atmosphere. Infrared sensing then allows for the study of surface characteristics by identifying high thermal emissivity from the specific areas on the surface. A viable instrument will allow for data to be measured from several kilometers away and still provide quantifiable data. A radiometer will also help understand atmospheric and surface profiles which directly influence each other.

To quantify (C), the flux of dust and surface particles in the atmosphere can help produce insights into how the surface might interact with the atmosphere. This might also have implications for the existence of water in Venus' atmosphere. Granule directly causes Venus's air density to be dry and incapable of sustaining water. For water to exist exponentially in Venus' atmosphere, there has to be a minimum level of controlled temperatures and humidity. However, this is not the case on Venus. If the team can directly quantify how dust and surface particles in Venus interact with the surface and the atmosphere then the team can further analyze the generalized effects. To quantify the flux of dust and the surface, the team decided to use and adapt a MEDA Dust Radiance Tool to directly measure its body.

Table 1 outlines the above objectives flowing down into requirements.

Table 1: Science Traceability Matrix

<table>
<tr><th rowspan="2">Science Goals</th><th rowspan="2">Science Objectives</th><th colspan="2">Science Measurement Requirements</th><th colspan="2" rowspan="2">Instrument Performance Requirements</th><th rowspan="2">Predicted Instrument Performance</th><th rowspan="2">Instrument</th><th rowspan="2">Mission Requirements</th></tr>
<tr><th>Physical Parameters</th><th>Observables</th></tr>
<tr><td rowspan="8">From the Decadal Survey: Origins, Worlds, and Life, Question 6: Solid Body Atmospheres, Exospheres, Magnetospheres, and Climate Evolution.

6.4a: How do planetary surfaces and interiors influence and interact</td><td rowspan="4">Determine the amount of outgassing that occurs from volcanic injections of sulfur dioxide.

(6.4a)</td><td rowspan="4">Quantify the amount of SO2 in the near-surface venusian atmosphere in the local region of the aerobot.</td><td rowspan="4">Collect the absorption spectrum in the 170 - 320 nm wavelength range for regions within 25 km of the aerobot.</td><td>Wavelength range:</td><td>170 - 320 nm</td><td>118 - 320 nm</td><td rowspan="4">UV/Vis Spectrometer for SO_2 Measurement (GSFC Advanced UV/Vis Spectrometer – collaboration with Horiba Scientific)</td><td rowspan="3">Aerobot shall maintain instrument aperture in downwards direction required for key science targets</td></tr>
<tr><td>Integration time</td><td>~ 1 s</td><td>11.2 ms</td></tr>
<tr><td>Sensitivity:</td><td>SNR > 20</td><td>R = 2000</td></tr>
<tr><td>Spatial resolution:</td><td>0.5 nm</td><td>0.2 - 0.3 nm</td><td rowspan="3">Mission must collect images for at least 13 hours.</td></tr>
<tr><td rowspan="4">Determine the amount of modern volcanic outgassing from the venusian interior via thermal emission

(6.4a)</td><td rowspan="4">Identify surface regions with high thermal emissivity.</td><td rowspan="4">Intensity of infrared radiation from the venusian surface in the 0.1 - 2 millimeter wavelength range for regions within 45 km of the aerobot.</td><td>Wavelength range:</td><td>0.1 - 2 microns / mm</td><td>0.1 micron - 2 mm</td><td rowspan="4">Infrared Radiometer/Spectrometer for Thermal Emissivity (Ball Aerospace Infrared Thermal Emission Spectrometer – Adapted design)</td></tr>
<tr><td>Integration time:</td><td>1 s</td><td>~ 1 s</td></tr>
<tr><td>Sensitivity:</td><td>1 K</td><td>R = 100</td><td rowspan="2">Aerobot will be inserted 70 km distance from target location</td></tr>
<tr><td>Spatial resolution:</td><td>.01 micron / 2 cm</td><td>~ 1 cm</td></tr>
</table>

with their host atmospheres? *Citation: (National Academies of Sciences, Engineering, and Medicine. 2023. Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. Washington, DC: The National Academies Press.* [https://doi.org/10.17226/2652)](https://doi.org/10.17226/2652)	Determine the rate of dust lifting / sand motion in the near- surface atmosphere via dust and sand fluxes. (6.4c) Determine if water was ever present? This has atmospheric implications.	Quantify the wind speed and granule (dust, sand) number densities in the near-surface atmosphere.	Determine the amount of obscuration/scattering due to dust particles in the optical wavelength range (170 - 900 nm).	Wavelength range:	N/A (optical, 170 - 900 nm)	255 - 750 nm	MEDA Dust and Radiance Tool (Adapted Design)	
				Spatial resolution:	0.1 nm	12 Mb image		Aerobot must cover at least 4,795 km of infrared imaging coverage.
				Integration time:	1 s	57 kb/s		
				Sensitivity:	< 2 W/m^2	.5 W/m^2		

1.3 Summary of Mission Location

Venus remains one of the most enigmatic and compelling bodies in the solar system, its dense atmosphere and dynamic surface processes providing a unique laboratory for studying planetary evolution. This document provides a comprehensive trade study that evaluates candidate landing sites based on a confluence of scientific, operational, and environmental criteria. Analysis is driven by the imperative to satisfy both atmospheric and surface measurement objectives, which include the quantification of sulfur dioxide (SO_2) via UV/Vis spectroscopy and the mapping of thermal emissions through infrared radiometry. By synthesizing data from high-resolution imaging platforms such as JMARS with rigorous instrument performance metrics, a robust framework is established for site selection. This narrative is designed to be modular and extendable, allowing the incorporation of new findings and continuous refinement of the mission parameters.

The overarching scientific challenge addressed herein is to understand how surface and interior processes on Venus interact with and modify its atmosphere. Recent research, including studies featured in the Decadal Surveys and by leading planetary institutes, emphasizes the importance of:

- Measurement of SO_2 concentrations through ultraviolet and visible spectral analysis, thereby providing critical insight into volcanic outgassing and chemical weathering processes.
- High-resolution infrared measurements to detect localized thermal anomalies, offering a window into active or recent volcanic events and enabling the reconstruction of thermal histories.
- Quantification of dust and sand fluxes within the near-surface atmosphere, which informs models of sediment transport, atmospheric dynamics, and past hydrological activity.

These objectives are underpinned by a suite of precision instruments namely, a UV/Vis spectrometer with a wavelength range of 170--320 nm, an infrared radiometer/spectrometer sensitive to thermal emissions in the 0.1--2 mm range, and the MEDA Dust and Radiance Tool operating in the optical spectrum. The integration of these instruments facilitates a comprehensive study of both the atmospheric composition and the surface geology of Venus.

The chosen methodology integrates quantitative performance criteria with qualitative environmental assessments to rigorously evaluate candidate sites. The trade study involves a detailed analysis of high-resolution imagery to discern geological stratigraphy and surface textures, an assessment of the local atmospheric conditions to determine the stability necessary for high-precision spectroscopic measurements, and simulations that predict the operational performance of the instrument suite under varying Venusian conditions.

The candidate sites, Idunn Mons, Artemis Corona, and Alpha Regio, are evaluated along three principal dimensions:

- The consistency of local atmospheric conditions, including dust content and turbulence, which is critical for obtaining reliable UV/Vis spectral data.

- The clarity and distinctiveness of thermal emissivity signals, essential for infrared measurements and for identifying areas of active volcanism.
- The practical feasibility of instrument deployment, maintenance of calibration, and overall mission safety in the context of harsh environmental conditions.

This integrative approach ensures that every facet of the mission from raw data acquisition to the interpretation of geological processes is optimized for scientific yield.

The following table depicts the trade study conducted to determine which mission location best suits the needs of the mission. The primary criteria chosen were defined geographic topography, stable atmospheric conditions and expected instrument interference. The science objectives require that the chosen location is well defined and contain volcanic activity. It is also required that the location has stable atmospheric conditions yet is able to provide the team data indicating Venus's harsh conditions above the surface. These were the primary decisive factors which is why the chosen weight was 35% each. These locations cannot be considered in the first place if they don't contain the environmental conditions required by the science objectives. The last criteria was that the instrument would be able to function without interference. If the team can't capture data then the environmental conditions cannot be studied. The weight was not too different from the primary ones and was decided to be 30%. Idunn Mons received a grade of 96.5%, Artemis Corona of 61% and Alpha Regio of 65%. This trade study concluded that the chosen mission location will be Idunn Mons.

Table 2: Mission Location Trade Study

Mission Location Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**Idunn Mons**	**Artemis Corona**	**Alpha Regio**
Defined Geographic Topography	The location must contain well defined, layered and volcanic zones within its topographical features to collect data to answer science objective(s).	10 = Defined Topography, 5= Rough Terrain but some defined topography, 0= Flat Surface	35%	10	9	10
Stable Atmospheric Conditions	The atmosphere must be able to relay data for SO2, wind speeds, granule fluxes, etc. without interfering with the instruments primary functions.	10 = Suitable, 5=Partially Suitable, 0=Not Suitable	35%	9	5	6
Expected Instrument Interference	Although we require harsh conditions for the studies, they must not affect the ability of the aerobot system to relay data back to headquarters.	10 = No expected interference, 5= Moderate expected interference, 0= Severe expected interference	30%	10	4	3
		TOTALS:	**100%**	96.50%	61.00%	65.00%

1.3.1 Analysis of Candidate Locations

Idunn Mons

Idunn Mons emerges as the preeminent candidate owing to its synergistic combination of favorable atmospheric and surface conditions. The elevated terrain of Idunn Mons not only minimizes the impact of dust interference on spectral measurements but also provides a clear stratigraphic record that is essential for deciphering volcanic history. High-resolution imagery reveals well-defined layers indicative of episodic outgassing events, while thermal maps indicate pronounced hotspots that correlate with recent volcanic activity. These characteristics collectively ensure that the UV/Vis spectrometer can achieve its high signal-to-noise ratio (SNR > 20) and that the infrared radiometer/spectrometer can capture detailed thermal profiles with the required sensitivity (Figures 1-4).

Artemis Corona

Artemis Corona is distinguished by its expansive, radially symmetric structure, a testament to deep mantle dynamics and convective upwelling processes. However, the region's inherent atmospheric variability poses significant challenges. Elevated turbulence and particulate concentration introduce uncertainties in the spectral data, potentially compromising the fidelity of SO_2 measurements. Despite these drawbacks, Artemis Corona remains an important site for understanding the internal dynamics of Venus, though its operational challenges render it less favorable when compared to the stable conditions observed at Idunn Mons (Figures 5-7).

Alpha Regio

Alpha Regio is characterized by its rugged, geologically complex terrain, which is strongly associated with intense volcanic activity. Thermal imaging indicates high emissivity across several zones, suggesting areas of active or recent volcanism. However, the elevated dust and sand fluxes observed in this region can impede both optical and infrared data acquisition. The complex topography further complicates instrument alignment, leading to potential calibration issues. As a result, while Alpha Regio holds significant scientific interest, its operational risks outweigh the benefits relative to the more stable environment of Idunn Mons (Figures 8-9).

1.3.2 Visual Data and Photographic Evidence

The visual evidence is integral to the analysis, providing direct insight into the morphological and atmospheric conditions at each candidate site. The following figures, Figure 1- 9, offer high-resolution views that corroborate the analytical findings in the standalone following pages and correspond to a specific candidate location.

Iduun Mons (FIG 1-4):

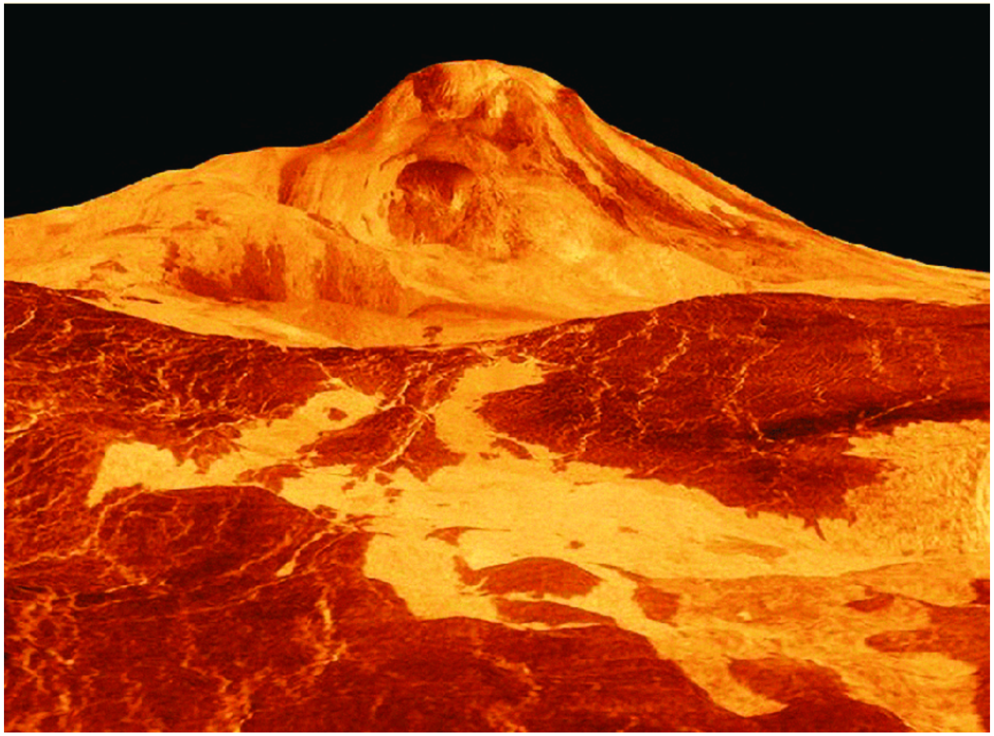


Figure 1: 3D-rendered perspective view of Idunn Mons, a volcanic peak on Venus, based on radar data from NASA's Magellan spacecraft.

Figure 1 highlights the planet's geologically active surface, with lava flows and tectonic features illuminated in false color to emphasize topography.

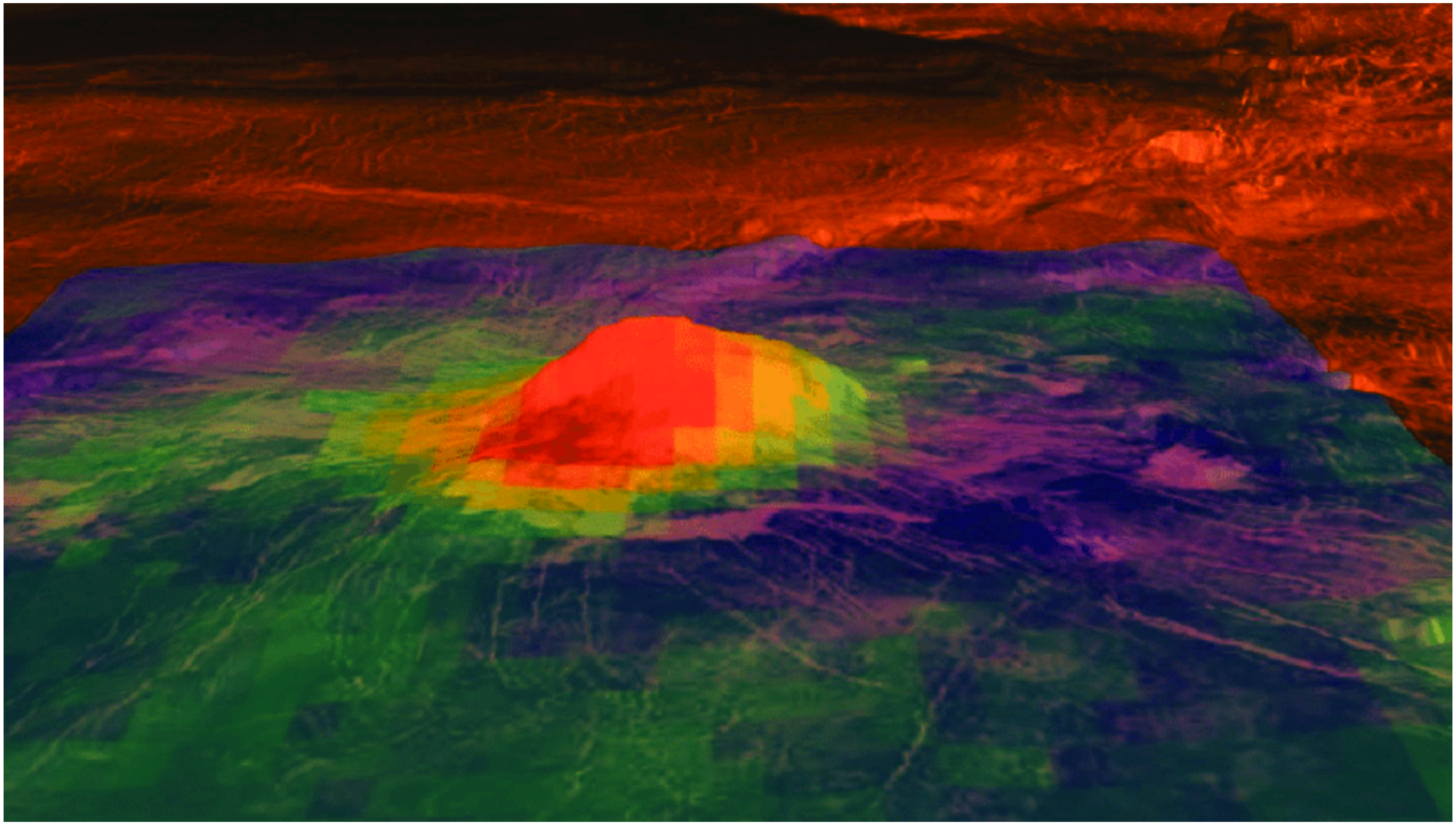


Figure 2: Infrared composite view of Idunn Mons, Venus, displaying thermal emissions indicative of recent volcanic activity.

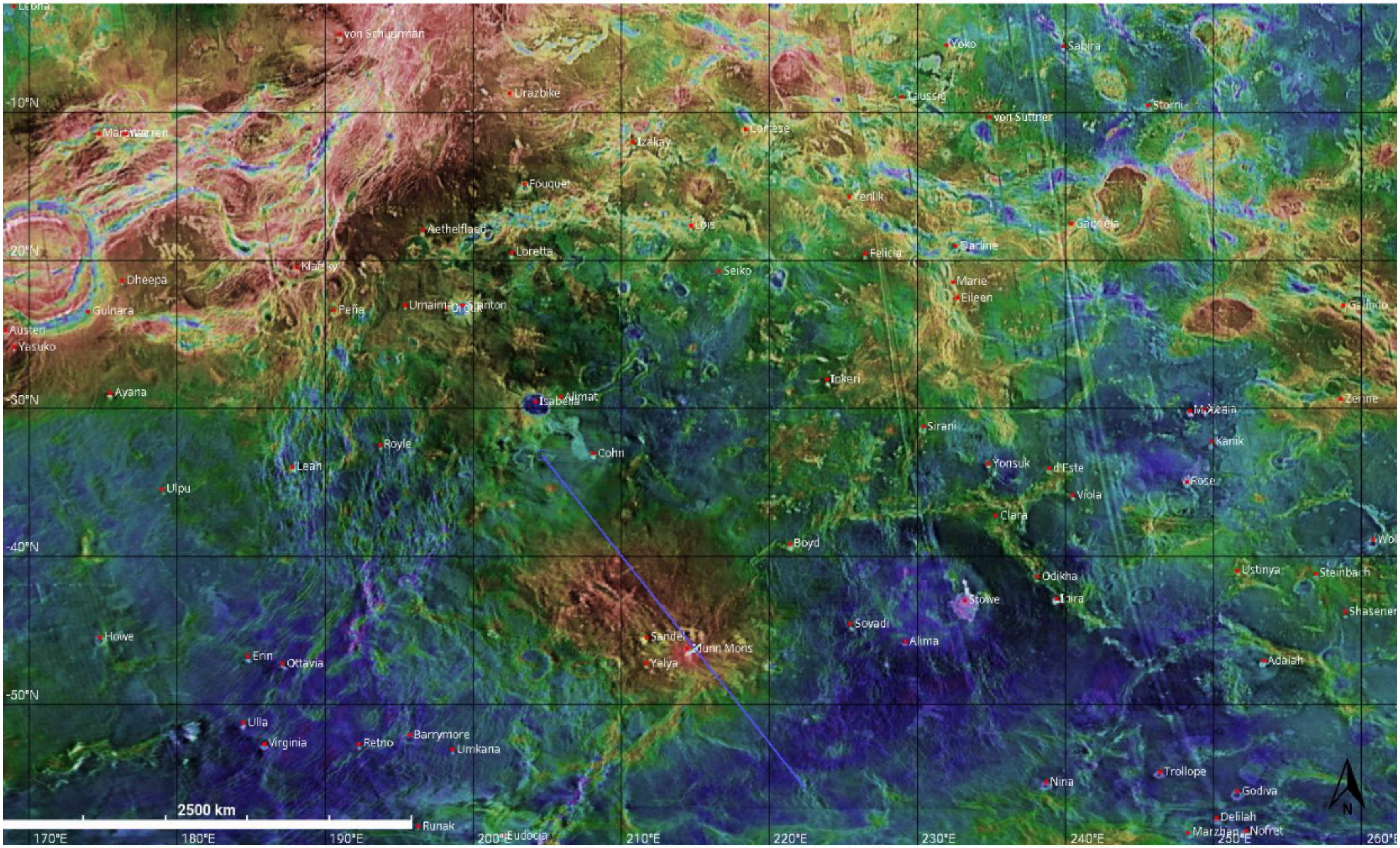


Figure 3: Global-scale topographic map of Venus, with Idunn Mons—a volcanic peak associated with recent geological activity—marked in the southern hemisphere.

The blue overlay indicates a possible fault line or tectonic feature extending across the region.

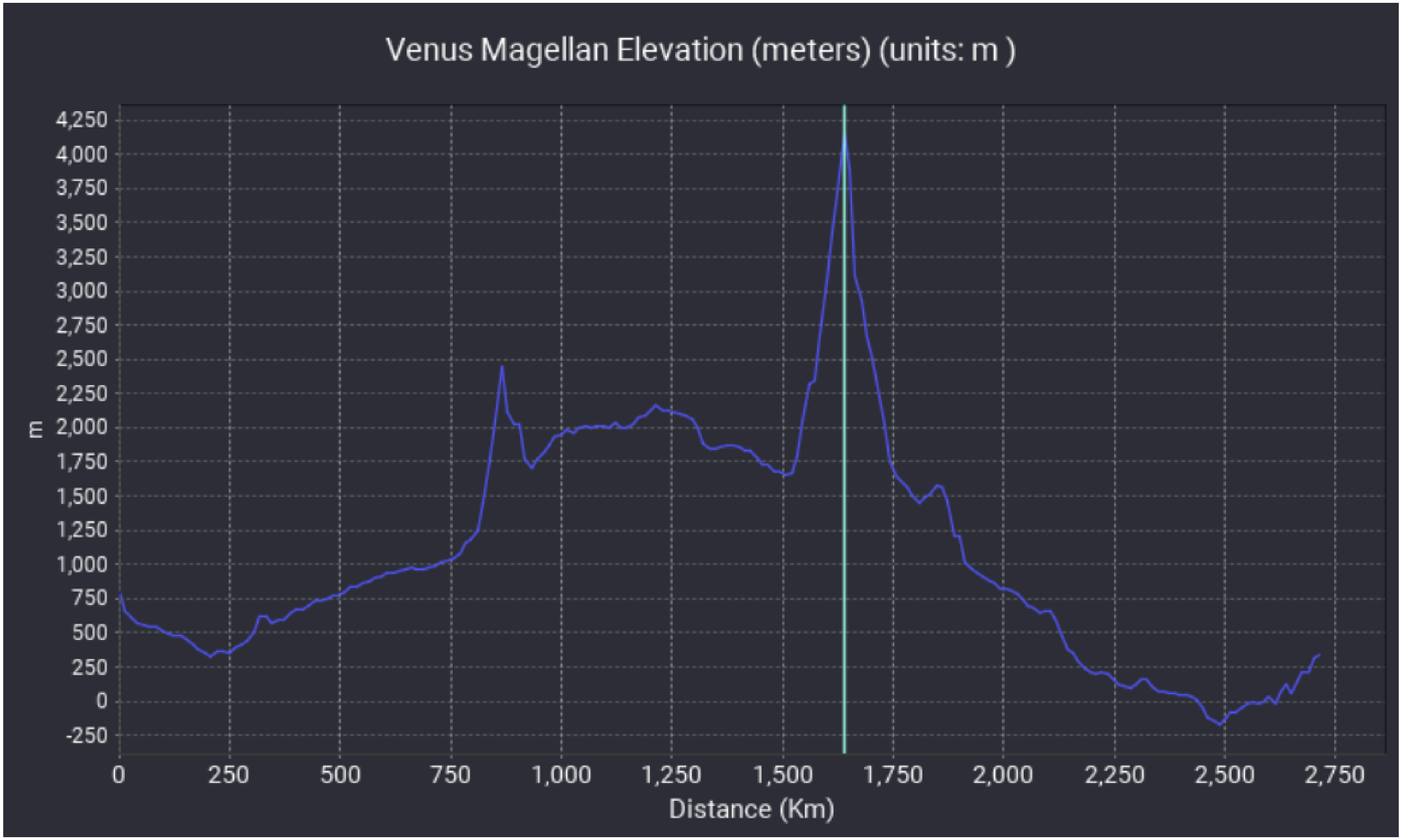


Figure 4: The graph illustrates variations in surface height across thousands of kilometers

The data from Figure 4 reveals mountainous regions and deep depressions indicative of Venus's dynamic geology, and shows a dramatic peak representing Iduun Mons' volcanic or tectonic uplift.

Artemis Corona (FIG 5-7):

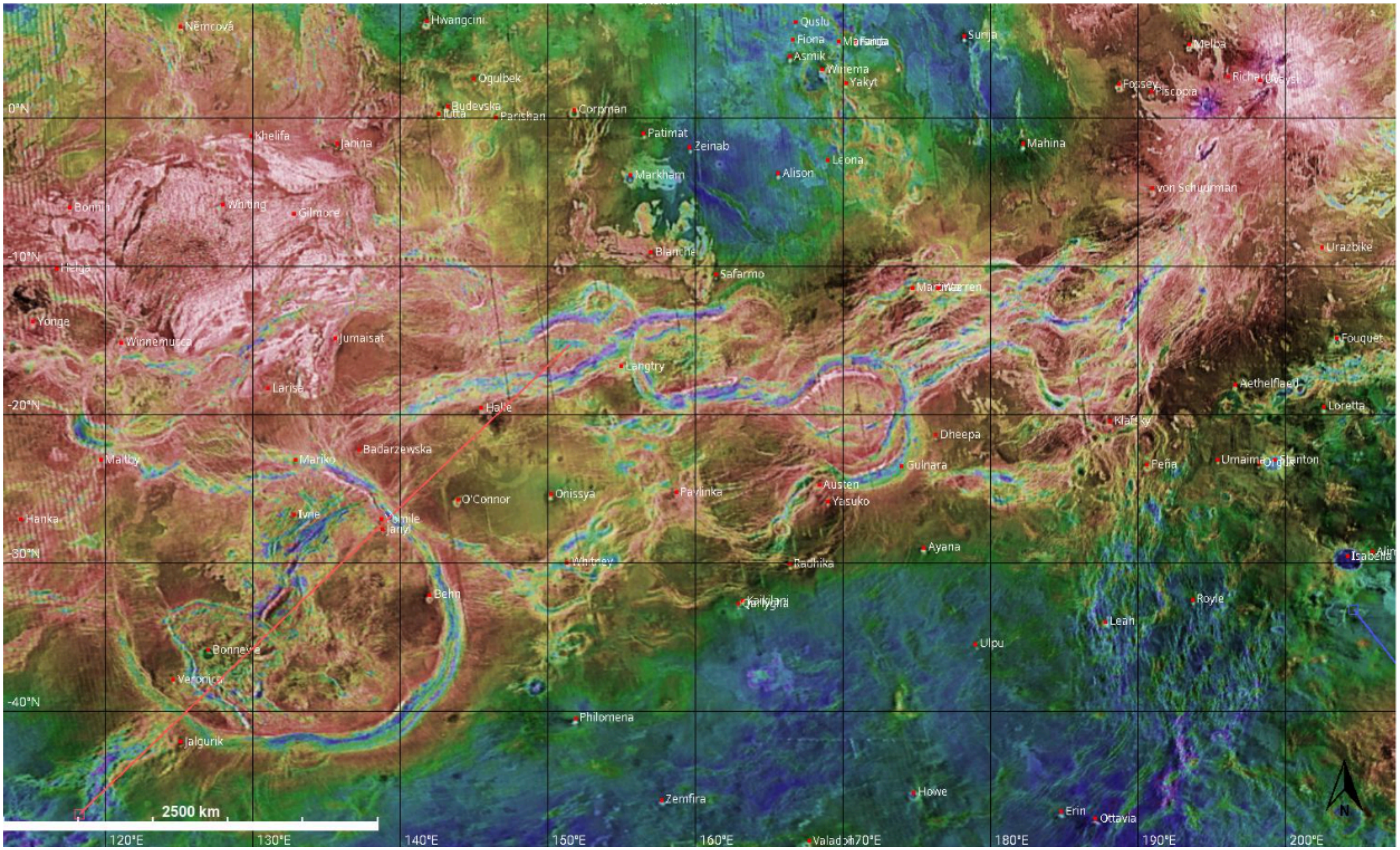


Figure 5: False-color radar topographic map of Venus, emphasizing the planet's tectonic and volcanic features. The winding, brightly colored structures indicate extensive deformation zones, possibly linked to past geological activity.

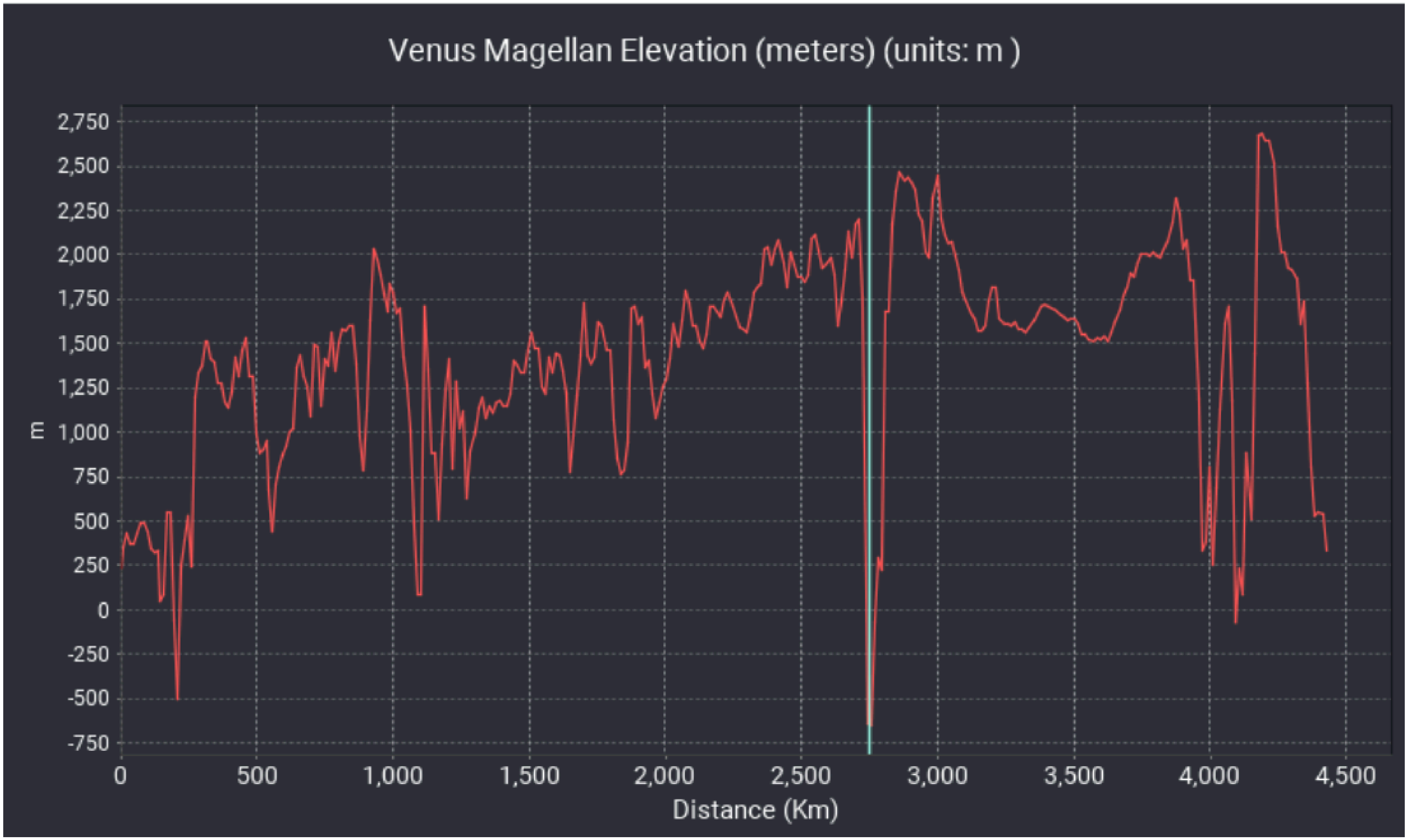


Figure 6: Another graph illustrating variations in surface height across thousands of kilometers, but now around Artemis Corona

The data from Figure 6 reveal mountainous regions and deep depressions indicative of Venus's dynamic geology.

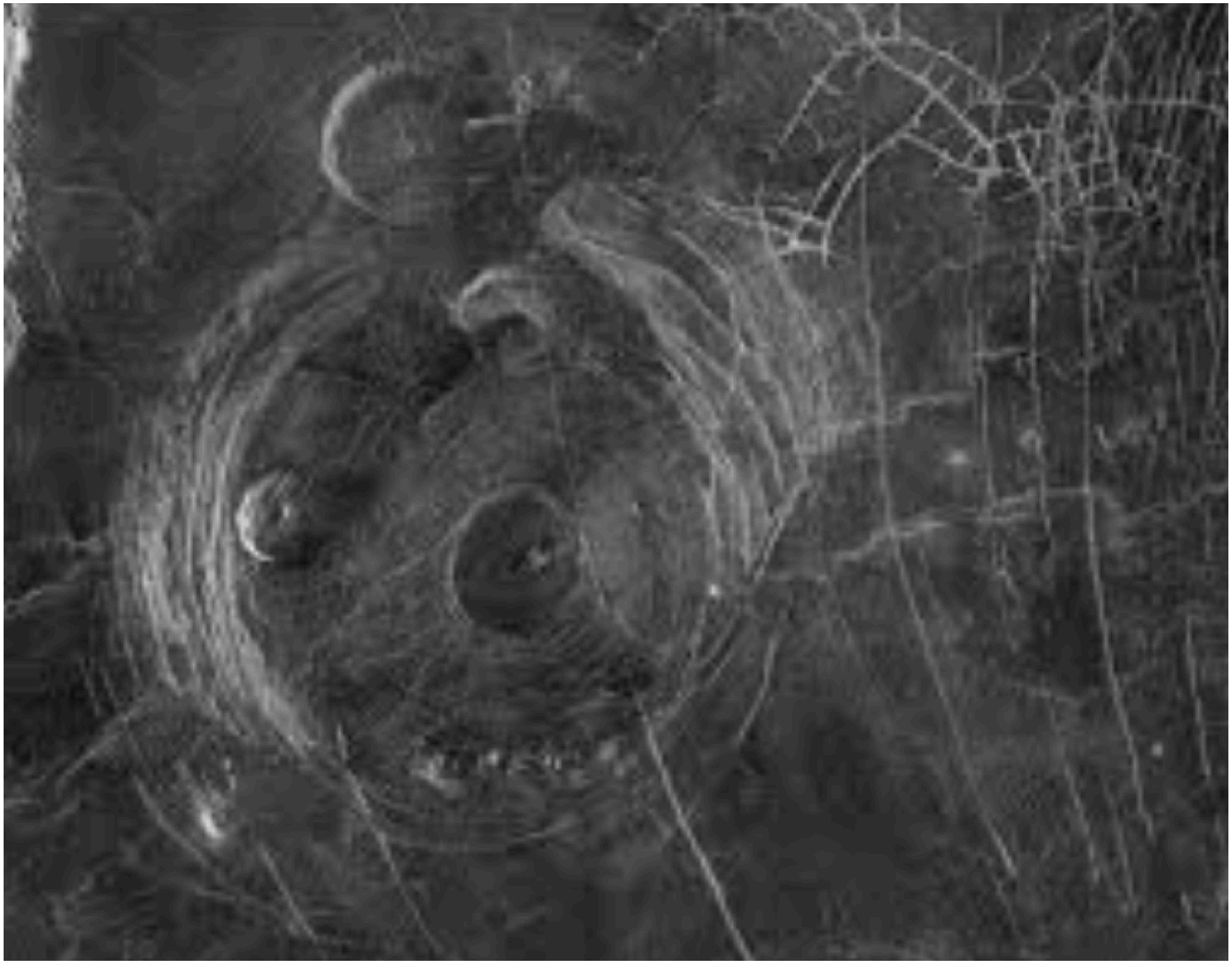


Figure 7: Radar image of a large Venusian impact crater displaying multiple concentric rings and complex structural deformation, likely formed by a high-energy impact and post-impact surface modifications.

Alpha Regio (FIG. 8-9):

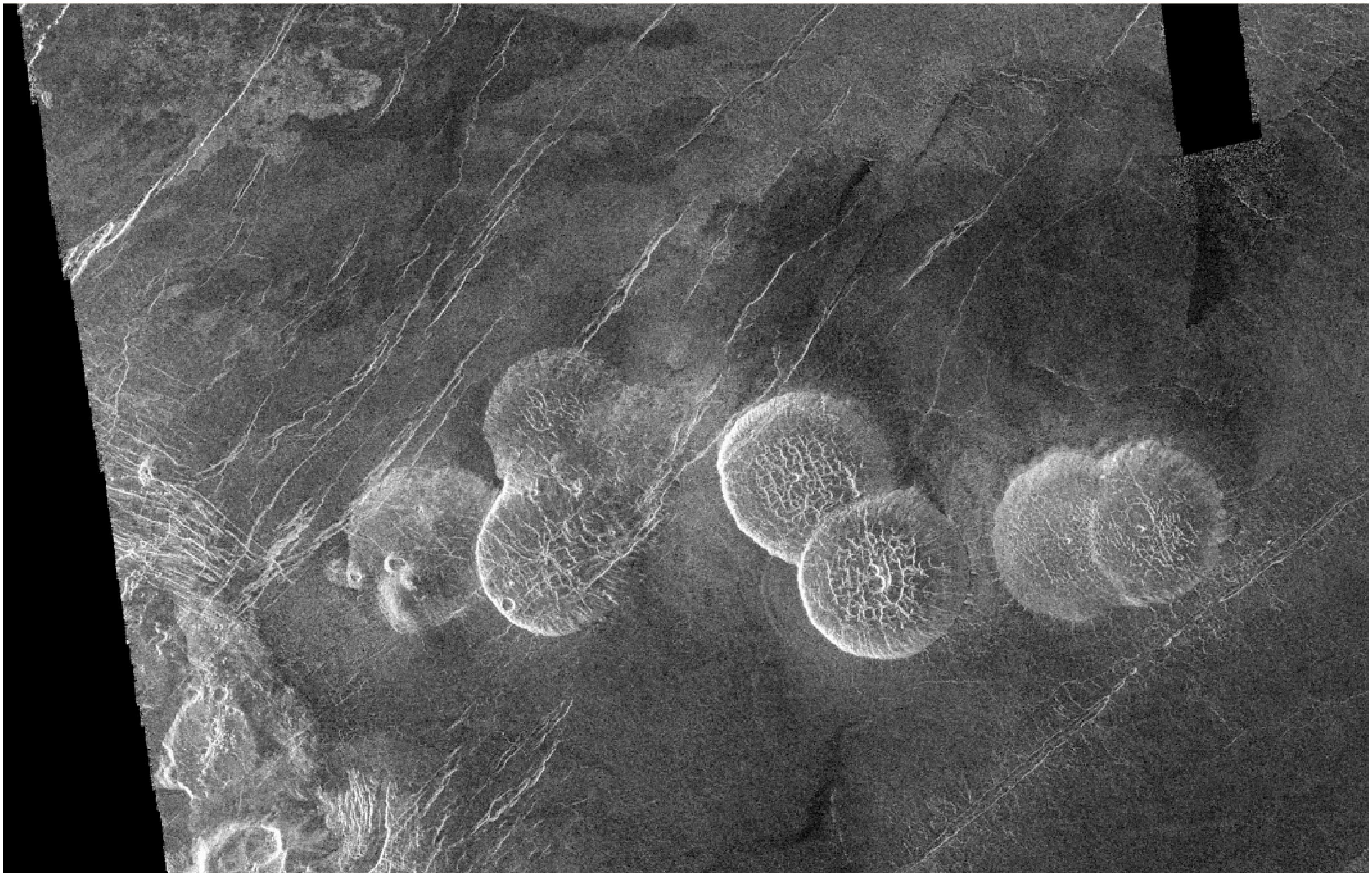


Figure 8: Radar image of Venusian pancake domes around the region of Alpha Regio—volcanic features characterized by their circular shape and steep edges.

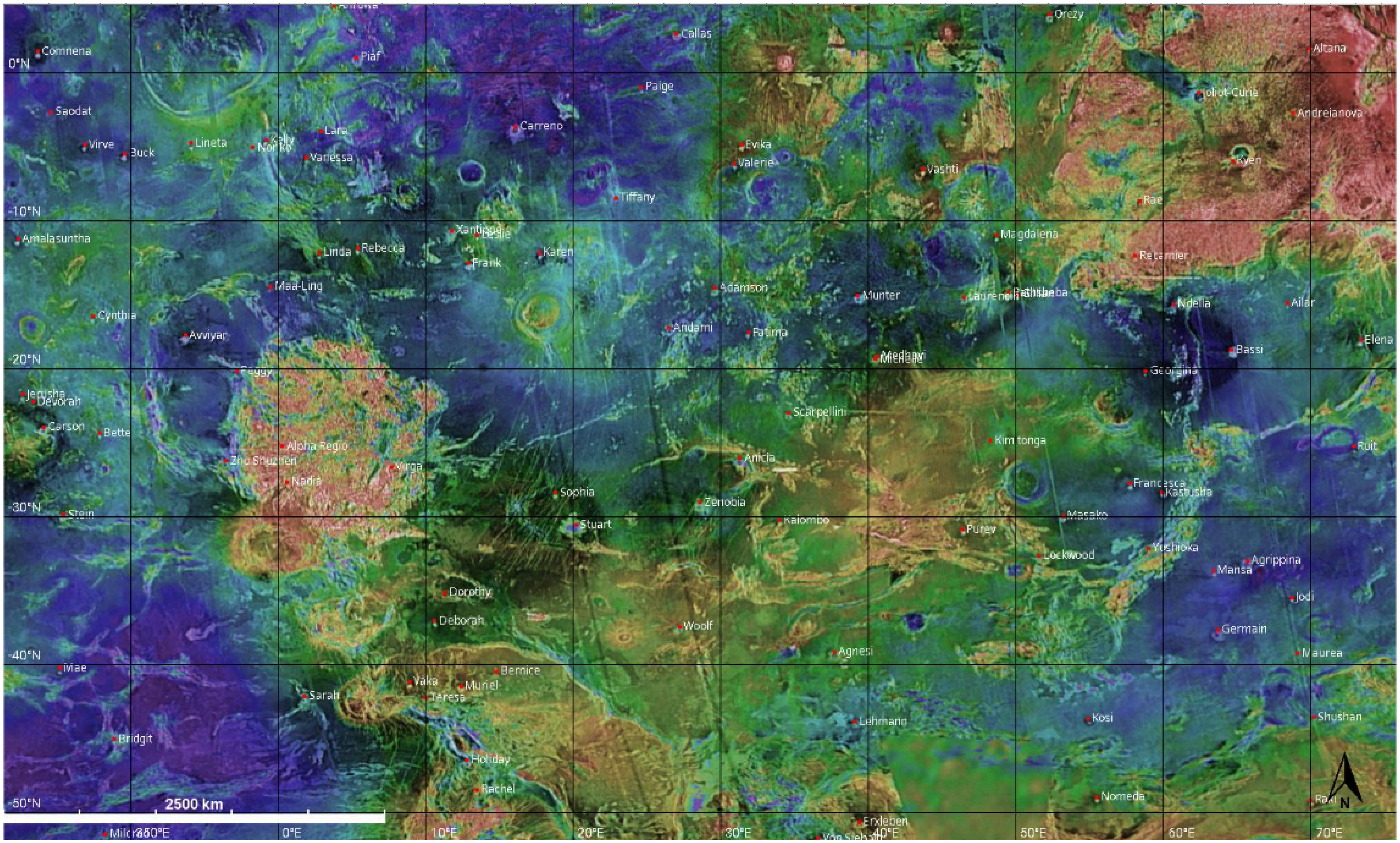


Figure 9: False-color topographic map of Venus highlighting key geological features, including craters, highlands, and volcanic regions around Alpha Regio.

The extensive analysis and visual evidence presented in this document provide compelling support for the selection of Idunn Mons as the prime candidate for future Venus exploration. The stability of the local atmosphere at Idunn Mons ensures that the UV/Vis spectrometer can operate with minimal interference, achieving the high SNR necessary for accurate SO_2 quantification. Moreover, the clear thermal signatures revealed by infrared measurements are indicative of recent volcanic activity, thereby fulfilling a key scientific objective.

Although Artemis Corona and Alpha Regio offer unique scientific insights, their operational challenges,such as elevated turbulence and high particulate concentrations, pose significant risks that could compromise the overall data quality. In contrast, Idunn Mons exhibits a harmonious balance between a stable atmospheric environment and well-defined surface features, making it an ideal target for the integrated instrument suite.

The chosen multidisciplinary approach encompassing high-resolution imagery, rigorous performance simulations, and advanced environmental modeling ensures that every aspect of the mission is optimized. The integration of quantitative data with qualitative observations has led to a robust site selection process, one that not only meets but exceeds the stringent requirements set forth by the latest planetary science directives.

1.4 Mission Requirements

The mission carries many requirements that ensure specific details and constraints to drive the project forward, ultimately reaching the desired outputs. These requirements not only serve as contractual obligations but also provide clarity on the mission's purpose, scope, and the constraints that the team must navigate. The constraints, both customer given and internally developed, define the limits within which the project must operate.

Following a vast amount of requirements, constraints are placed and if not followed the mission may be deemed cancelled as a failure for not following all procedures. These constraints are created by the descent subsystem, NASA, customers, and the system workers as well. The science and engineering team must adhere to the $200 million budget as well as the payload constraints for consideration of the descent subsystem and for the allowance the team was given. Any delays in development may result in having a new launch date or cancellation of the entire mission.

A 1m^3 constraint allows only vital components on the aerobot and its structure may be altered to be more aerodynamic or be beneficial when in Venus' atmosphere. A budget of $200 million according to NASA (2025), “Explorers Program” means by definition, data, and operations the mission is characterized as a medium class explorer (MIDEX). A prohibition of radioisotope thermoelectric generators or any radioactive materials may be on the spacecraft due to a high risk of nuclear leakage and can cause a cancellation of the mission. This is also a given constraint the mission was given and to use new technology or previously used that is capable of accomplishing the mission task without a high risk factor. The constraint of containing 5g or less of any radioactive material on the vehicle is due to the high risk factor, especially involving the Venusian environment.

The team must adhere to an readiness integration and launch date or the mission may be considered for cancellation due to missing its time window for launch. The requirements outlined here stem from both customer constraints and science goals, which were developed using the Science Traceability Matrix (STM). The mission's top level goal, along with two specific science objectives of determining the amount of outgassing that occurs from volcanic injections of sulfur dioxide and determining the amount of modern volcanic outgassing from the Venusian interior via thermal emission, are central to the mission's purpose. Table 3 includes detailed information on customer constraints, science goals, launch procedures, verification methods, and parent/child flow patterns, which ensure that the project remains aligned with its objectives throughout its development.

Table 3: Top-level Mission Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
MG-1.0	The mission shall measure atmospheric and geologic conditions of Venus' surface	Improve NASA's understanding of Venus' surface and atmospheric composition for the purposes of progressing science knowledge	Customer	MG-2.0 MG-3.0	Demonstration	Met
MG-2.0	The mission shall investigate the presence of key gases and how they correspond to atmospheric temperature and pressure	By understanding the quantities of key gases in Venus' atmosphere, correlations can be made to its atmospheric pressure and temperature. These correlations can further the research done on Venus' atmosphere and its effect on surface changes.	MG-1.0	-	Demonstration	Met
MG-3.0	The mission shall investigate Venus' surface features to understand geological processes and resurfacing rates	This requirement can help further the research done on Venus' surface and investigate questions relating to its ever-changing surface composition and topography when compared to Earth's surface.	MG-1.0	-	Demonstration	Met
PM-1.0	The mission shall follow all accepted given constraints listed by the customer	Addresses need for a cost-effective schedule that will meet the needs of the customer. It provides critical margins and constraints for scheduling and design processes.	Customer	PM-1.1 MCH-1.0 - 3.0	Inspection	Met
PM-1.1	The mission shall have a cost cap of $200M to expend	This requirement provides an understanding of budget constraints and allows for effective allocation of funds to where they are most needed and being mindful of what spending is potentially unnecessary to the success of the mission.	PM-1.0	-	Analysis	Met
MISS-1.0	The system shall be stored within dimensions of 1m x 1m x 1m	The aerobot system must be able to fit on the launch vehicle from which it is deploying and maintaining this size constraint allows for successful storage and launch procedures.	Customer	-	Inspection	Met
MISS-2.0	The system shall have a mass not exceeding 50kg	The primary spacecraft carrying the aerobot system has limited space and weight capacities so staying under the mass limit will ensure a successful launch	Customer	MISS-5.1	Inspection	Met

MISS-3.0	The mission shall utilize alternative power sources instead of a Radioisotope Thermoelectric Generator (RTG)	Because RTGs are a nuclear power source, there is a lot of risk with potential nuclear leakage and exposure if there is a launch accident. It is best to avoid this risk and use alternative power sources	Customer	-	Analysis	Met
MISS-4.0	The sum mass of any radioactive material used for other spacecraft systems shall be 5g or less	The mission should avoid potential dangerous radioactive exposure as possible	Customer	-	Inspection	Met
MISS-5.0	The aerobot system shall be ready to integrate with other systems by October 1, 2028 at Goddard Space Flight Facility (GSFF) in Greenbelt, MD	Launch timelines are very strict and in order to stay on schedule, the aerobot system must be fully functional and ready by a certain date to ensure launch can happen on time.	Customer	MISS-5.1 MCH-1.0 - 3.0	Inspection	Met
MISS-5.1	The system shall be ready to launch by March 1, 2029 at Cape Canaveral, FL	Launch timelines are very strict and in order to stay on schedule, the aerobot and all preceding systems must be fully integrated and ready by a certain date to ensure launch can happen on time.	Customer MISS-5.0	-	Demonstration	Met
MISS-6.0	The system shall gather all atmospheric and geologic data within a 48 hour duration	The balloon material that will suspend the aerobot system only lasts 48 hours and will start to degrade after that time so all data collected must occur within that time frame	Customer	SYS-1.0 - 5.0 CDH-1.0 PWR-6.0	Demonstration	Met
MISS-7.0	The system shall communicate with the primary spacecraft at least once every 90 minutes	Communication windows between the aerobot and the Primary Spacecraft should be expected to be every 90 minutes	Customer	SYS-1.0 SYS-3.0 CDH-1.0 - 3.0	Test	Met
MISS-8.0	The system shall obtain atmospheric and geologic data from 50-70 km in altitude	The team is able to control the altitude of the aerobot system between 50-70 km as desired but cannot stray outside that constraint	Customer	SYS-5.2	Analysis	Met
MISS-9.0	The system shall be used for a Discovery Program mission	The data collected according to the mission task document should be treated as a Discovery Program mission. This means the system will be used for scientific research and for future advancements	Customer	-	Demonstration	Met

1.5 Concept of Operations

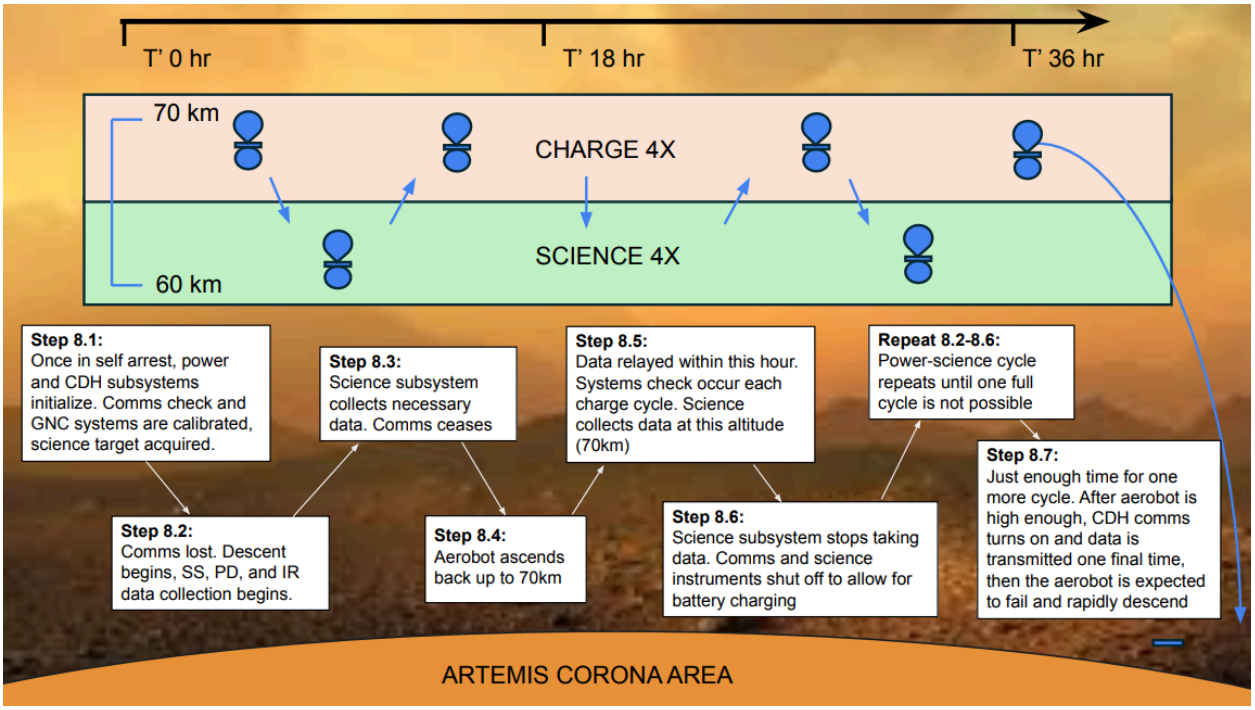


Figure 10: Concept of Operations

The mission follows a structured cyclic pattern that repeats science data collection and charging phases over a 36-hour period. The vehicle alternates between altitudes of 70 km (charge mode) and 60 km (science mode), leveraging aerobot mobility to collect atmospheric data over the Artemis Corona Area. This section outlines the sequence of operational steps (labeled 8.1 through 8.7) as depicted in the mission diagram.

Step 8.1 – Initialization and Target Acquisition:

At the beginning of the mission, the aerobot enters self-arrest at 70 km altitude. During this phase, the power and Command & Data Handling (CDH) subsystems are initialized. A communications check is conducted, and the Guidance, Navigation, and Control (GNC) systems are calibrated. Once complete, the science target is identified and locked.

Step 8.2 – Descent and Science Activation:

With communications intentionally shut off to conserve power and reduce interference, the aerobot begins its descent to 60 km. As it descends, science sensors—including the science suite (SS), pressure and density (PD), and infrared (IR) instruments—begin collecting data.

Step 8.3 – Data Collection at Low Altitude:

At 60 km, the science subsystem operates autonomously to collect the necessary atmospheric and surface data. During this time, communications remain inactive.

Step 8.4 – Ascent to Transmission Altitude:

After completing data collection, the aerobot initiates an ascent back to 70 km. This allows it to reach an altitude suitable for data relay and system recharging.

Step 8.5 – Data Transmission and System Check:

Within the hour at 70 km, data is relayed back to Earth or a relay station. The system performs health checks and confirms readiness for another cycle. Additional science data may also be gathered at this altitude.

Step 8.6 – Recharge Phase:

The science instruments are powered down to conserve energy and recharge onboard batteries. Communications and data collection systems remain offline during this phase.

Repeat Steps 8.2–8.6 – Science/Power Cycles:

This sequence of descent, data collection, ascent, transmission, and recharging repeats three times over an 18-hour mission window. Cycles continue until the aerobot can no longer complete a full sequence.

Step 8.7 – Final Cycle and Mission End:

In the final hours of the mission, the aerobot completes one last ascent and data transmission. The CDH system is reactivated for a final communication burst. After this, the aerobot is expected to lose altitude rapidly due to energy depletion and mission lifetime constraints.

Table 4: Detailed Concept of Operations Outline

Time (T')	Step	Cycle	Procedures	Contact	Altitude
0					
0.5					
1	8.1	Initialization / Charge	1. Self arrest 2. Power initialization 3. Comms check, system check 4. GNC Orientiation, science target acquisition		70 km
1.5					
2	8.2	Descent	DSS begins descent		~ 60 km
2.5					
3	8.3	Science			60 km

3.5 4	8.4	Ascent			~ 60 km
4.5 5 5.5	8.5	Science data collection and data transmission	Science subsystems collects data and CDH transmits stored data from 60km as well as data collected now		
6 6.5 7 7.5 8 8.5 9	8.6	Battery Charging	1. Battery charging		70 km
9.5 10	8.2	Descent	DSS begins descent		~ 60 km
10.5 11	8.3	Science			60 km
11.5 12	8.4	Ascent			~ 60 km
12.5 13 13.5	8.5	Science data collection and data transmission	Science subsystems collects data and CDH transmits stored data from 60km as well as data collected now		
14 14.5	8.6	Battery Charging	1. Battery charging		70 km

15					
15.5					
16					
16.5					
17					
17.5					
18	8.2	Descent	DSS begins descent		~ 60 km
18.5					
19	8.3	Science			60 km
19.5					
20	8.4	Ascent			~ 60 km
20.5					
21					
21.5	8.5	Science data collection and data transmission	Science subsystems collects data and CDH transmits stored data from 60km as well as data collected now		
22					
22.5					
23					
23.5					
24					
24.5					
25	8.6	Battery Charging	1. Battery charging		70 km

25.5					
26	8.2	Descent	DSS begins descent		~ 60 km
26.5					
27	8.3	Science			60 km
27.5					
28	8.4	Ascent			~ 60 km
28.5					
29					
29.5	8.5	Science data collection and data transmission	Science subsystems collects data and CDH transmits stored data from 60km as well as data collected now		
30					
30.5					
31					
31.5					
32					
32.5					
33	8.6	Battery Charging	1. Battery charging		70 km
33.5					
34	8.2	Descent	DSS begins descent		~ 60 km
34.5					
35	8.3	Science			60 km
35.5					
	8.7	Ascent	Final Data transmission before rapid descent		70 km

36					
AEROBOT DECOMMISSIONED					

The Concept of Operations is a well structured and repetitive cycle, that shall ensure mission success through data collection, system integrity, and optimized battery usage. The final phase of this mission shall ensure all data is collected from the aerobot and transported to the orbiter to further decommission the system.

1.6 Vehicle Design Summary

The V.E.L.A.Z.Q.U.E.Z system has focused on developing a state-of-the-art design to survive the Venusian atmosphere and collect as much scientific information as possible, despite a mission descope halfway through. The mechanical subsystem has developed a spherical chassis with a 5.5 mm thickness, made of Magnesium AZ31B, with a mass of 15.038 kg and an internal volume of 0.187 m^3 (106,247,797 mm^3). This chassis is tethered to the descent subsystem via Inconel cables weighing 1.82 kg and spanning a total volume of 492,773,779 mm^3. It contains internal fastening components totaling 0.95 kg to support sub-assemblies.

Some sub-assemblies will be mounted on the exterior of the 721 mm diameter spherical chassis, such as cables, surface coatings, and external instrumentation. These coatings include chromate conversion (volume: 10,000 mm^3), copper-gold multi-layer insulation (MLI, volume: 2.613 mm^3), and flat black paint (volume: 1.633 mm^3). Though negligible in mass, each plays a key role in thermoregulation and environmental protection. Chromate conversion is applied to all electronics for corrosion resistance and operational reliability.

The payload subsystem houses three key instruments:

- A UV/VIS spectrometer (mass: 3.1 kg, volume: 18,180,000 mm^3, power: 12 W) mounted at the bottom, following the heritage of the SPICAV/SOIR, aiming directly downward to Venus.
- An infrared radiometer/spectrometer (mass: 5.9 kg, volume: 7,500,000 mm^3, power: 15 W) oriented toward the horizon.
- The Mars Environmental Dynamics Analyzer (MEDA) (mass: 5.5 kg, volume: 2,528,114.3 mm^3, power: 17 W) mounted on the side of the chassis to capture environmental conditions.

These instruments are mounted using miscellaneous mechanical ports to take into account forces acting upon the aerobot, as the UV/VIS spectrometer will use a sapphire window. The sapphire window itself weighs 1.0985 kg and occupies 275,000 mm^3, ensuring maximum optical clarity for data collection.

The power subsystem includes a 4 kg lithium-ion battery (volume: 2,000,376 mm^3), a 1.5 kg gallium arsenide solar panel (volume: 8,036,000 mm^3), and 2 kg of power distribution hardware (volume: 2,500,000 mm^3). The subsystem draws a total of 522.54 watts, and overall accounts for 6.5 kg and 8,045,000 mm^3, about 4% of the chassis's internal volume.

The command and data handling (CDH) processing unit consists of:

- The BAE Systems RAD5545 Onboard Computer (mass: 0.8 kg, volume: 336.6 cm^3, power: 35 W),
- The Mercury RH3440 Data Recorder (mass: 0.62 kg, volume: 240 cm^3, power: 14 W),
- The JHU/APL Frontier Radio Lite Transceiver (mass: 0.4 kg, volume: 1,459 mm^3, power: 2 W),
- and runs NASA's core Flight System software.

Thermal regulation includes eight elements:

- Two passive: MLI and black paint,
- Three 100W heating strips (each set: 0.0294 kg, 25,806.4 mm^3, total: 300 W),
- Two 20W heating strips (each set: 0.0588 kg, 51,612.8 mm^3, total: 40 W),
- and one thermal sensor (mass: 0.06 kg, volume: 2,827.43 mm^3, power: 0.00025 W).

The total heating capacity is 340 watts, controlled via the CDH unit.

The communications subsystem includes:

- The ISARA reflectarray antenna (mass: 0.5 kg, volume: 200 mm^3, power: 0.2 W), installed on the chassis exterior,
- SpaceWire protocol (mass: 0.0435 kg, volume: 39 mm^3, power: 0.1 W), running along Inconel cables,
- A redundant quadrifilar helix antenna (mass: 0.27 kg, volume: 1,349 mm^3, power: 10 W), deployed from the sphere top.

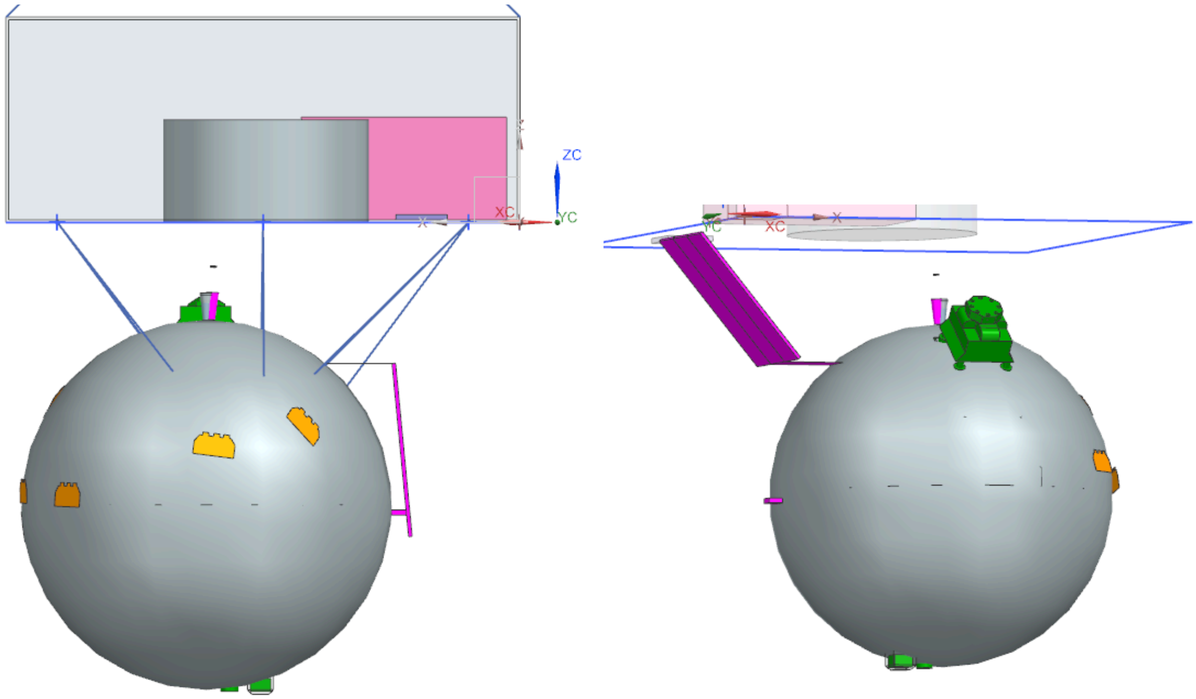


Figure 11: CAD Images of the V.E.L.A.Z.Q.U.E.Z Aerobot

1.7 Science Instrumentation Summary

The aerobot mission uses three unique instruments in order to achieve the science objectives. The first instrument is a UV/Visible Spectrometer, which measures 170-320 nm spectra of scattered sunlight. The UV/Vis spectrometer is able to quantify sulfur-dioxide abundance and other ultraviolet absorbers in order to trace active volcanic outgassing and atmospheric chemistry dynamics.

The next instrument being used is an Infrared Radiometer/Spectrometer. This instrument measures 0.1 μm-2 mm of thermal emission and 8-12 μm of broadband emission plus narrow near-IR windows. It can help achieve the main science goals by mapping surfaces and cloud-top brightness temperatures in order to locate the thermal hot spots. It can also infer fresh lava flows and derive lower-atmosphere temperature structure.

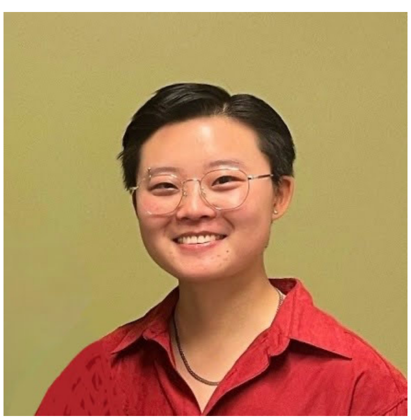
The final instrument that is being used is the MEDA Dust and Radiance Tool. This instrument measures multi-band photometry (~170-900 nm) and has sensors for dust/particle flux. This instrument accomplishes the main science goals by measuring aerosol optical depth, dust grain fluxes, and local radiative environment to characterize near-surface atmospheric dynamics and their coupling to volcanic activity.

By using these three instruments, the team can collect a wide range of data and gain broad insights into the atmospheric and geologic makeup of Venus.

1.8 Programmatic Summary

1.8.1 Team Introduction

Shehan Rajapakse
University of Colorado Boulder, Boulder, CO
Junior Aerospace Engineering student with minors in Music and Creative Technology & Design. Serves as project manager, overseeing scheduling, deliverables, and technical coordination across a multidisciplinary team. Systems engineer on the Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX), a multi-institution CubeSat mission investigating upper-atmosphere phenomena and demonstrating hybrid formation flying with cold-gas propulsion and differential drag. Experience includes developing interface control documentation, supporting integration planning, and contributing to mission architecture design. Additional technical background includes MATLAB-based modeling and simulation, propulsion system analysis, orbital mechanics, and uncertainty quantification for experimental calibration. Combines systems thinking with hands-on engineering skills in support of aerospace research and development.



Grace Kirk
Colorado State University, Fort Collins Colorado.
Senior dual majoring in Biomedical and Mechanical Engineering. Experienced in time management, team organization, and mentoring within fast-paced engineering

environments. Demonstrated expertise across the full system product lifecycle, from concept development through testing and validation. Skilled in technical writing for reports, procedures, and documentation. Strong foundation in mechanical systems and integration, with a focus on cross-functional collaboration and design optimization.

Angel Guerrero
Arizona State University, Tempe, Arizona
Senior majoring in Earth and Space Exploration. Currently awaiting to begin a post baccalaureate program at Oklahoma State University working with microbiota known as facilitators of adaptation to environmental change. Several semesters and capstone work utilizing NASA's life cycle and documentation, working alongside many aeronautical professionals.

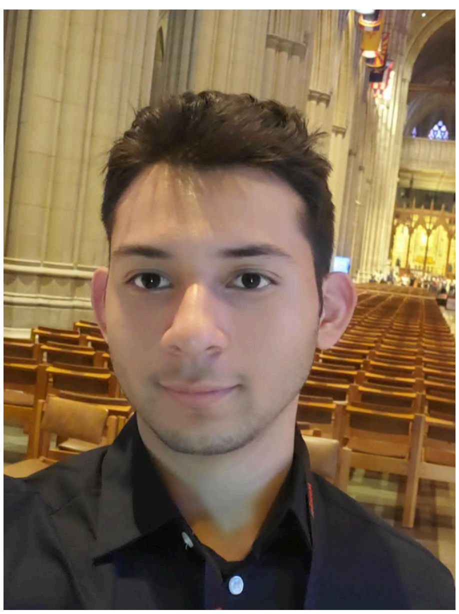
Daxx Delucchi
Arizona State University, Tempe, Arizona
Freshman Astrophysicist-Engineer and Chief Scientist of NASA's L'SPACE Mission Concept Academy, concurrently completing dual B.S. degrees in Astrophysics and Mechanical Engineering at Arizona State University Tempe. Author of two foundational manuscripts under submission to arXiv—"On a Classical Derivation of the Born Rule for Photons" and "The Ergodic Emergence of Quantum Mechanics from General Relativity"—demonstrating expertise in classical relativistic field theory, ergodic phase dynamics, and the emergence of quantum statistics. Skilled in CAD (Siemens NX), MATLAB/Simulink, orbital mechanics, and CubeSat subsystem design, with a track record of leading multidisciplinary teams in lunar and deep-space small-sat mission concept development. Founder & CEO of deep-tech ventures, recognized for resilience, clear technical communication, and innovative problem-solving. Committed to

integrating rigorous theoretical insights with practical aerospace engineering to advance humanity's exploration of space.

Carter Garrett
Brigham Young University, Provo, Utah
Rising Senior in Astrophysics and Philosophy. Currently working as the BYU Hybrid Rocketry Propulsion Research Team as Data Analytics Lead. Also working in variable star astroseismology as a Research Assistant to Dr. Eric Hintz. He has experience developing complex engineering space systems and instrumentation, as well as scientifically detecting and diagnosing intricate astrophysical phenomena.

Briseyda Loescher
Arizona State University Polytech, Phoenix, Arizona
Dual majoring in Aerospace and Mechanical engineering student with a passion for space exploration. Gained valuable experience in aerospace systems, research, and mission development through NASA's ASCEND, NCAS, and the L'SPACE Mission Concept Academy. Brings strong communication, resilience, initiative, and out-of-the-box thinking to every project. Driven by curiosity and committed to pushing the boundaries of space exploration, whether collaborating with diverse teams or tackling complex challenges.

Ethan Thai
The University of Utah, Salt Lake City, Utah.
Junior in Electrical Engineering, minor in Computer Science. Substantial coursework experience in applied electromagnetics and signal processing, at both the undergraduate and graduate level. Focused study in antenna systems and wireless communications. Foundational research in underpinnings of neural populations. Driven by the intellectual pursuit of languages in models and analogies; as teacher, student, researcher, and engineer.



Eduardo Beltran
Arizona State University; Tempe, Arizona.
Sophomore majoring in Mechanical Engineering with a personal interest in Astronautics. Currently employed as a Fulton Undergraduate Research Institute (FURI) research assistant for 1 year. Simulated extreme conditions of space and radiation across various semiconducting perovskite materials with the goal of enhancing the

structural and compositional stability of perovskites, while also gaining a greater understanding of the radiation effects on semiconducting devices.

Emily Castro Jimenez
Arizona State University; Tempe, Arizona
Senior majoring in Biological Sciences and Physical Geography with a focus on climatology/meteorology. Previously positioned as a Weather Observer at ASU's Weather Station taking weekly weather measurements with meteorological instruments for the National Weather Service.

James Rivera
Arizona State University; Tempe, Arizona
James Rivera is a sophomore at Arizona State University in Tempe, AZ, pursuing a degree in Mechanical Engineering. With a strong passion for aerospace and technology, James is actively involved in leadership at ASU as a senator for the Tempe Undergraduate Student Government and as a section leader, helping guide and mentor peers in engineering coursework. James is also an engaged member of Sigma Nu

fraternity, taking on leadership roles in academic and community service initiatives.

Luis Castaneda-Marquez
Arizona State University; Tempe, Arizona
Junior pursuing aerospace engineering at Arizona State University, Tempe, Arizona. Member of the SEDS Rocketry club at ASU. Contributing in this mission on scheduling the mission and bringing team-oriented expertise to the team.

Matthew Zhu
Arizona State University, Tempe, Arizona.
Senior majoring in Computer Systems Engineering with an interest in space avionics. Have been with ASU's Interplanetary Lab Initiative working on DORA and Coconut Cubesats and gained experience in testing CubeSat power hardware and PCB Design.

1.8.2 Team Management Overview

Team Organization:

The MCA team follows a structured hierarchy to ensure efficiency, communication, and mission success. At the top, the **Project Manager (PM)** oversees all activities, acting as the main point of contact between mentors and the team while ensuring that tasks are completed, meetings are scheduled, and documentation remains consistent.

Supporting the PM are key leadership roles, including:

- **Deputy Project Manager of Resources (DPMR)** – Manages programmatic aspects, including cost tracking, risk management, and schedule monitoring.
- **Chief Scientist (CS)** – Leads the Science Subteam, ensuring instrumentation and landing site selections align with mission objectives.
- **Lead Systems Engineer (LSE)** – Heads the Engineering Subteam, overseeing vehicle hardware, subsystem integration, and technical requirements.

The team is divided into three primary subteams, each specializing in a critical aspect of the mission:

- **Engineering Subteam** – Comprising Mechanical, Electrical, Thermal, and Computer Hardware Engineers, responsible for designing and integrating the mission vehicle's systems.
- **Science Subteam** – Includes Atmospheric and General scientists, responsible for defining science objectives and selecting instrumentation.
- **Programmatic Subteam** – Includes Program Analysts, Mission Assurance Specialists, and Outreach Officers, responsible for cost analysis, risk tracking, and public engagement.

The team follows an organizational chart that clarifies roles and reporting structures, ensuring seamless collaboration between subteams and leadership.

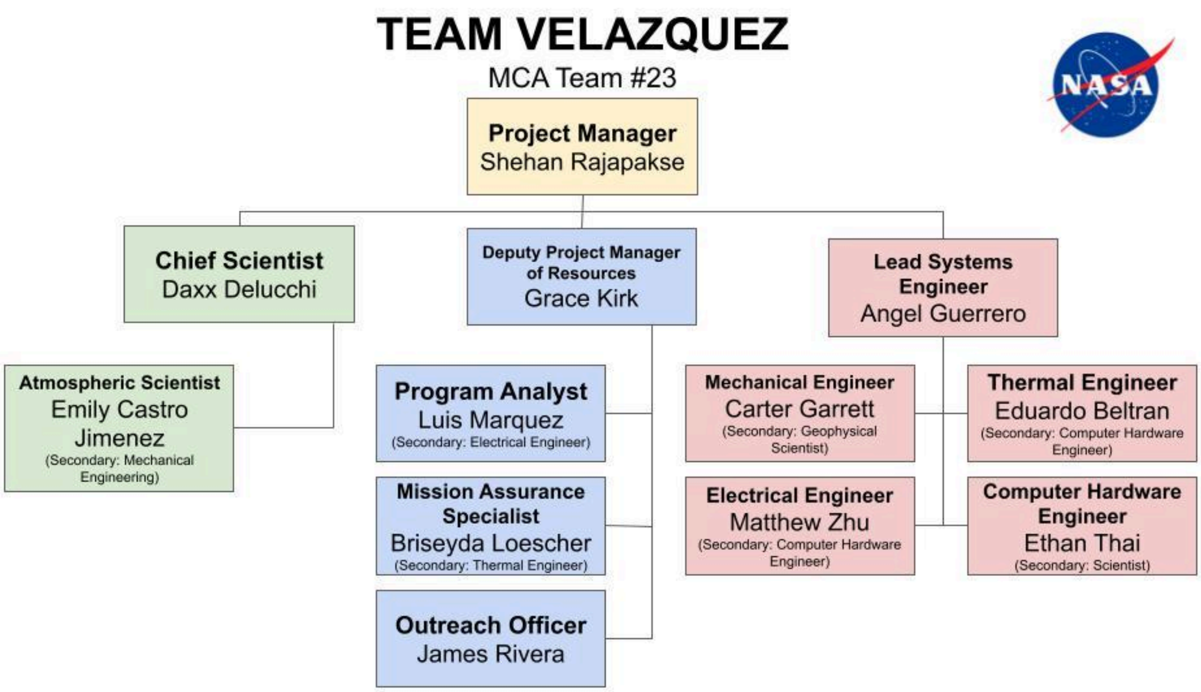


Figure 12: Team Organizational Chart

Workload Management:

Work is distributed based on expertise and interest, ensuring members contribute effectively to their respective subteams. Each role has defined responsibilities, and collaboration is encouraged across disciplines.

To ensure timely completion of tasks, the team employs:

- **Biweekly Check-ins** – Progress updates to address any roadblocks.
- **Task Assignments with Deadlines** – Clearly outlined deliverables to maintain steady workflow.
- **Role Flexibility** – Members can support secondary responsibilities to maintain balance.

Decision-Making Approach:

The team employs a hybrid decision-making approach that adapts to the situation:

- **Trade Studies** – Used for major technical decisions requiring in-depth evaluation (e.g., selecting power sources, material choices for thermal insulation).
- **Consultative Decision-Making** – Applied to time-sensitive choices where input from key experts leads to a quick consensus (e.g., modifying testing schedules due to unexpected delays).

A recent example involved selecting a communication system. Given tight deadlines, the team opted for a consultative approach, gathering rapid feedback from engineers and scientists to make an informed choice without delay.

Challenges and Solutions:

The team has faced several challenges and addressed them as follows:

- **Communication Barriers** – Initial difficulties in cross-team coordination were resolved by implementing shared documentation and increasing cross-functional meetings.
- **Workload Disparities** – Some members were overwhelmed, leading to a reassessment of task distribution and better delegation strategies.
- **Technical Uncertainty** – Unclear data for design decisions was mitigated by refining trade study methodologies and consulting external sources.

Recommendations for Future Improvement:

To enhance effectiveness, the team proposes:

1. **More Cross-Team Meetings** – Strengthening integration across subteams.
2. **Clearer Role Definitions** – Reducing overlap and ensuring accountability.
3. **Enhanced Time Management Tools** – Introducing structured task-tracking systems to better monitor deadlines.

By refining the organizational structure, workload management, and decision-making processes, the team aims to improve overall team efficiency and mission success.

1.8.3 Schedule Overview

Table 5: Schedule Overview

Schedule Overview			
Phase	Major milestone	Tasks	Timeframe
Phase C	CDR	Finalized detailed system design	7/29/26 - 9/30/26
		CDR APPROVAL	10/1/26 - 10/15/26
	PRR	Prep for fabrication and software	10/16/26 - 2/28/27
		Production & assembly prep	3/1/27 - 6/30/27
Phase D	SIR	Integration & operational planning	7/1/27 - 9/30/27
		Final system integration	7/14/28 - 8/8/28
		Subsystem integration	8/9/28 - 9/8/28
	ORR	Full system testing	9/9/28 - 9/23/28
		Test results analysis	10/2/28 - 10/10/28
		ORR action items resolution	10/24/28 - 10/31/28
	MRR	Pre-launch checkouts/reviews	11/1/28 - 11/30/28
		Launch approval	2/28/29 - 2/28/29
Phase E	LRD	Launch readiness date	03/01/2029
	PLAR	Post-launch assesment review	4/1/29 - 4/12/29
		Cruise phase monitoring	3/2/29 - 9/16/29
		System health checks	3/2/29 - 9/16/29
	CERR	Critical event readiness review	9/13/29 - 9/16/29
		Mission operations	9/17/29 - 10/5/29
Phase F	DRR	Decomissioning	10/22/29 - 11/4/29
		Final mission report	12/5/29 - 12/20/29
		Closeout	12/21/29 - 12/31/29

The overview of the mission here is used to briefly showcase how the mission will undergo over the customer constraints which will explain more in detail on the 5.2.2 Mission Schedule. The brief overview takes some of the dates from the Gantt chart provided in the appendix with some of the most important dates needed to understand how the mission will be undertaken. The schedule overview goes over phases C through F - final design fabrication through closeout of the mission. Within these phases there are several major milestones including the customer's constraints: SIR and LRD.

1.8.4 Cost Overview

The aerobot mission's cost plan has been structured to deliver maximum scientific return within the $200 million MIDEX-class cap, while providing adequate reserve and margin against technical, schedule, and programmatic risk. The program is organized into four sequential phases, C (Year 1), D (Year 2), E (Year 3), and F (Year 4), each with specific objectives, deliverables, and resource requirements.

Phase C, encompassing final design maturation, hardware fabrication, and subsystem verification, carries a total estimated outlay of $47.44 million. Of this, $17.94 million (38%) supports core personnel: systems engineers, payload scientists, mission assurance specialists, and integration technicians whose expertise is essential to translate conceptual designs into flight-ready hardware. Direct costs of $28.88 million (61%) fund procurement of specialty materials, precision machining, sapphire windows for the UV/VIS spectrometer, and custom gallium arsenide solar panels—investments that anchor our high-fidelity test campaigns. A modest $0.07 million (0.1%) in travel enables key subsystem teams to conduct on-site testing at partner facilities, while $0.55 million (1.2%) underwrites strategic outreach, public engagement, and stakeholder briefings to ensure sustained program visibility and stakeholder alignment.

During Phase D, which spans mission integration, system-level testing, and launch readiness activities, the total planned expenditure rises slightly to $50.12 million. Personnel costs decrease to $6.21 million as the bulk of design staffing transitions to operations support, yet remain crucial for test directors, flight software engineers, and launch-support liaisons. Direct costs peak at $43.32 million (86% of Phase D), reflecting the culmination of large-format structural tests, thermal-vacuum chamber campaigns simulating Venusian conditions, and final assembly of the aerobot-orbiter interface. Travel and outreach allocations remain tightly controlled at $23 thousand and $0.57 million, respectively, to facilitate only the most mission-critical exchanges with NASA centers and external partners.

Phases E and F, covering pre-launch operations, mission execution support, data downlink validation, and post-mission closeout, are comparatively lean, with combined totals of $4.60 million and $4.81 million. In these years, personnel efforts focus on flight operations analysts, data processing specialists, and instrument calibration teams, accounting for $4.33 million and $4.54 million, respectively. Travel budgets of $23 thousand per year sustain essential real-time support at mission control, while outreach funds ($0.24 million in Phase E and $0.25 million in Phase F) enable scientific workshops, peer-review publications, and public engagement events that disseminate our findings to the planetary science community and broader public. Direct hardware procurement is not required in these phases, reflecting a completion of flight hardware deliverables.

Across all four years, the team allocated $33.03 million to personnel, $72.20 million to direct mission hardware and test activities, $1.60 million to outreach and engagement, and $0.14 million to critical travel. The resulting total mission cost of $106.97 million represents only 53.5% of our $200 million cap, yielding a healthy 46.5% contingency buffer. This margin accommodates up to 20% technical reserves for unforeseen engineering challenges, 10 % schedule slack to absorb delays, and a further 16.5 % for scope adjustments or emergent science opportunities.

By front-loading investment in Phase C and Phase D, where technical risk and hardware complexity are greatest, and tapering resources appropriately in later phases, we achieve an efficient allocation of funds. Personnel budgets are tightly scaled to evolving mission needs, direct costs are matched to discrete procurement and test events, and outreach and travel remain lean yet sufficient to maintain mission momentum and stakeholder engagement. This disciplined programmatic approach ensures that the aerobot delivers its ambitious science objectives on Venus within both budgetary and schedule constraints, upholding NASA's rigorous standards for cost, schedule, and performance.

Table 6: Cost Overview

Mission Phase	C	D	E	F	
Year	1	2	3	4	Total
Cost Breakdown					
Personnel	$17,942,293	$6,213,242	$4,333,985	$4,540,526	$33,030,046
Travel	$69,600	$23,200	$23,200	$23,200	$139,200
Outreach	$550,000	$565,634	$240,592	$247,185	$1,603,412
Direct Costs	$28,880,000	$43,320,000	-	-	$72,200,000
Total Estimated Cost	$47,441,893	$50,122,076	$4,597,777	$4,810,911	$106,972,658

2 Overall Vehicle and System Design

2.1 Spacecraft Overview

Table 7: Top-level Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
SYS-1.0	The Aerobot system shall autonomously collect, process, and transmit science data from the Venusian atmosphere to the orbiter.	This requirement sets a basis for the mission goals and scientific objectives. This ensures the system can operate on Venus without human help	MISS-6.0 MISS-7.0	CDH-- MCH-- TMS-- PAYL--	Test	Met
SYS-2.0	The Aerobot system shall operate within a temperature range of 200 K to 350 K ±25 K.	The system must be able to handle the extreme temperature conditions of Venus to ensure proper functioning of the equipment.	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-3.0	The mission shall have an operational Command & Data Handling (CDH) subsystem that processes all data for transmission with a latency of 1 second.	The CDH subsystem ensures that all collected data is processed and transmitted back to the Primary Spacecraft for analysis.	MISS-6.0 MISS-7.0	CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-4.0	The Aerobot shall include a mounting structure/plate with threaded holes to integrate with the DSS.	A secure interface is needed for proper integration with the Deployment Support System (DSS), enabling proper deployment and operation.	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Inspection	Met
SYS-5.0	The Aerobot system shall include redundant systems to ensure mission continuity in case of primary system failure.	Redundant systems ensure that the mission can continue in the event of a failure, enhancing mission reliability.	MISS-6.0	SYS-5.1 SYS-5.2 CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-5.1	The system shall undergo testing of 0-737K and 1 atm testing to simulate Venus' extreme temperature and pressure conditions.	Environmental testing verifies the system's ability to function within Venus' harsh conditions.	SYS-5.1 MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-6.0	The Aerobot shall maintain consistent communication with the orbiter throughout the mission with a data rate	Matches frequent data relay and data throughput	MISS-6.0	CDH-- MCH-- TMS--	Inspection	Met

	of 1 Mbps.			PAYL--		
SYS-7.0	The Aerobot shall be designed to have an operational lifespan of 36 hours.	36-hour balloon lifetime constraint is set on the mission, so the system shall push to the constraint and more	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-8.0	The Aerobot system shall be designed to minimize contamination of the Venusian atmosphere.	As many other Discovery missions, the system shall be as uncontaminated as possible to make all discoveries as pure as possible	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-9.0	The Aerobot system shall be designed to maintain its designated altitude range (60-70 km) with a precision of ± .1 km.	The systems will be able to fly within the main cloud layers lying in the Venusian Atmosphere	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Analysis	Met
SYS-10.0	The Aerobot system shall be designed to hold a defined volume of 0.18716 m^3 to meet launch vehicle and deployment constraints.	Due to the confined space of the 710 shell diameter of the chassis, we are confined to a volume of .18716m^3 to use for interior instruments	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Inspection	Met
SYS-11.0	The Aerobot system shall be designed to survive the shock and vibration loads involved with launch, deployment, and entry into the Venusian atmosphere.	The system shall be able to accommodate all instruments whether they be interior or exterior with withstanding forces not within the missions control	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Demonstration	Met
SYS-12.0	The Aerobot shall be designed to operate within a 445 power budget to ensure sufficient energy for the operation of the mission.	A formidable power budget shall be supplied whether that be from solar panels or a larger battery to support the rising and lowering of the aerobot as well as its instruments	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Inspection	Met
SYS-13.0	The Aerobot shall be designed for autonomous fault detection, isolation, and recovery to ensure mission longevity.	The aerobot shall have parameters within itself to improve reliability over the missions duration	MISS-6.0	CDH-- MCH-- TMS-- PAYL--	Demonstration	Met

The system comprises 4 subsystems that will drive the mission forward, driven by various subassemblies that will push the mission forward to its final goal. The system contains requirements for all systems to meet as these are contractual statements between the mission team and the customers, meaning the mission shall accomplish previous mission requirements and meet standards for a robotic mission that will be going to Venus. The system should contain necessary capabilities to work autonomously in the Venusian atmosphere as it is labeled a robotic-Discovery mission. Given this requirement, the system shall be capable of withstanding temperatures and forces that can not be helped in person. This means surviving 200 K to 350 K with a ± 25 K as a margin.

A command and data handling unit shall be installed on an autonomous aerobot that will be transmitting and receiving information, with a transmission latency of at least 1 Mbps for on-board processing as well. The aerobot shall also be capable of being integrated with the descent subsystem to make the mission possible and travel to Venus with the EDI system instead of spending millions of dollars more into a spacecraft mission and going through a londer LCR's. To maintain the system within an operational temperature range, a thermal subsystem shall be integrated within the aerobot and undergo testing as well as the mechanical subsystem for shock and vibrational forces.

The lifetime of the aerobot should last a total of 36 hours after a descope and weight 45 kilograms, with its last subsystem supplying at least 445 watts in total as the total system's instrumentation draws 445 watts. The aerobot system shall also fit within the constraints given by the mission of a 1m^3 and will be in a spherical chassis with a volume which in turn shall limit and provide a volume of 0.18716 m³ for all interior instrumentation to fit within.

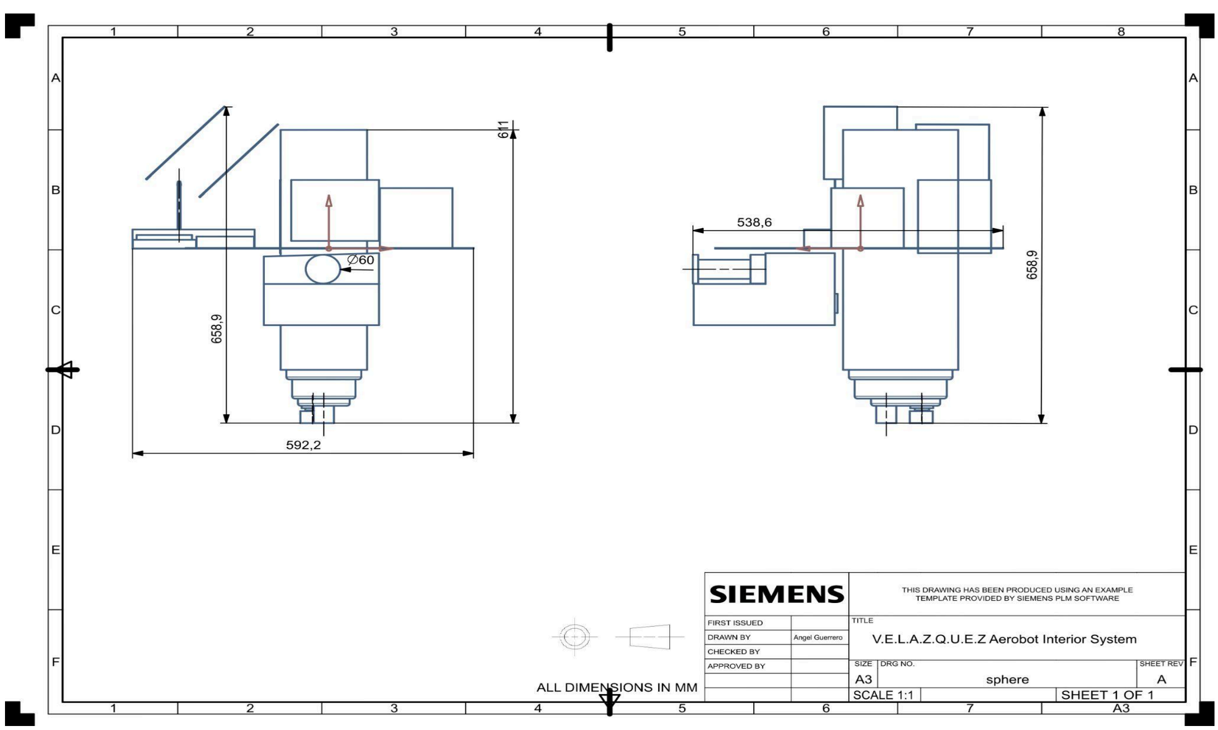


Figure 13: NX Drawing Showing Interior System of Aerobot

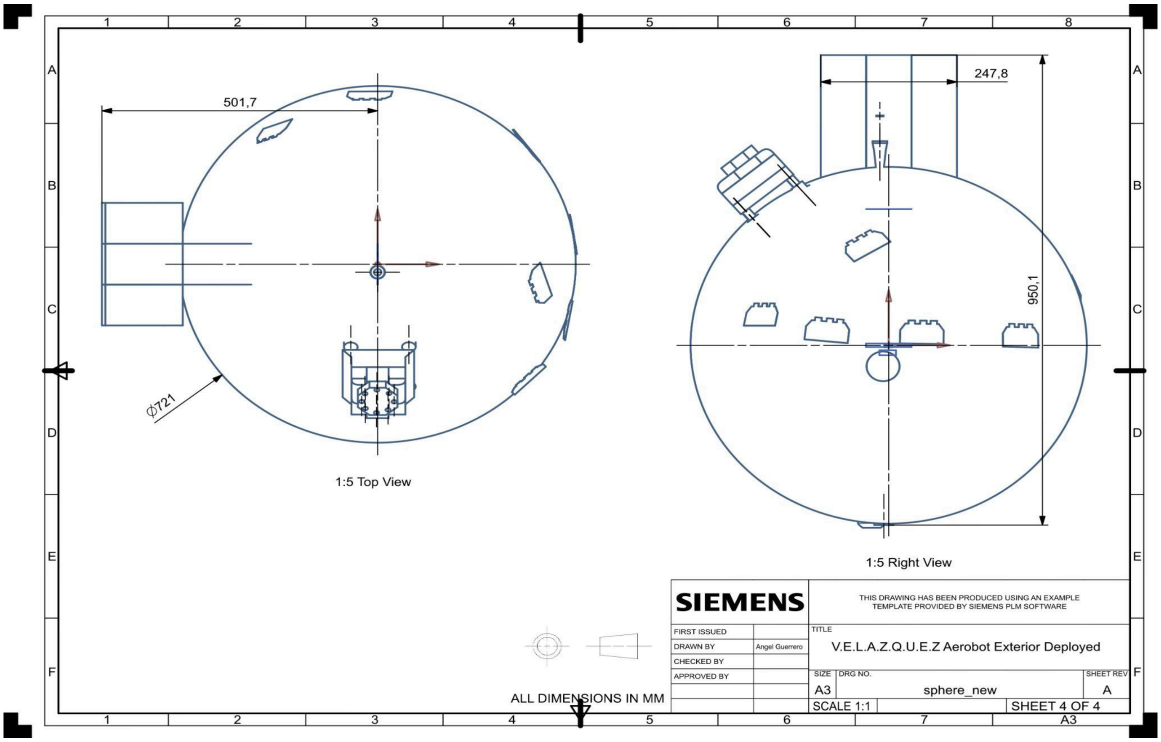


Figure 14: 1:5 Top and Right View of Exterior Deployed Aerobot

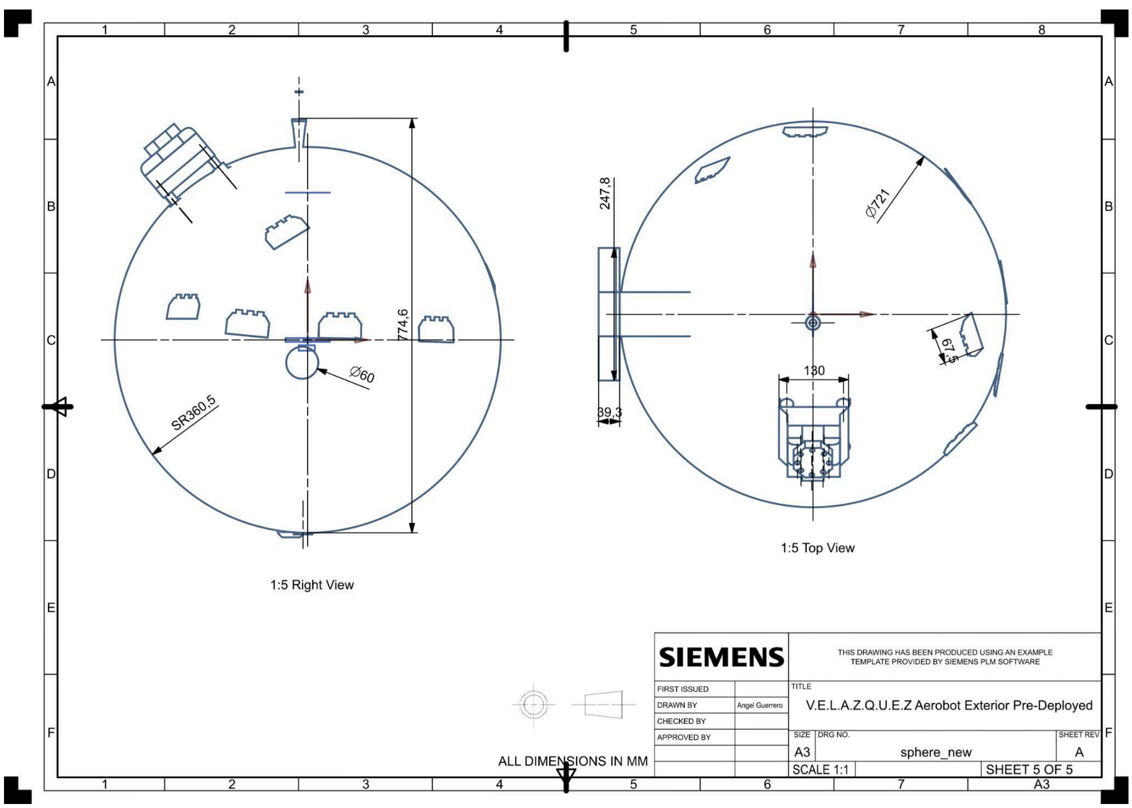


Figure 15: Undeployed Aerobot with a 1:5 Right and Top View

Table 8: SWaP Chart Displaying Mass, Dimensions, and Power Draw

WBS	System / Subsystem	Description	Selected component	Mass (kg)	Total Dimensions m^3	Power (W)
1.0	**Spacecraft**	**Entire spacecraft with all systems**	**Name of the component**	**43.8059**	**0.6403220685**	**66.73975**
1.1	**Science Instrument**					
1.1.1	UV/VIS Spectrometer	Captures ultraviolet and visible spectra	Instrument	3.1000	18180000	-12
1.1.2	Infrared Radiometer/ Spectrometer	Measures infrared spectral radiation	Instrument	5.9000	7500000	-15
1.1.3	MEDA Dust and Radiance Tool	Analyzes dust and solar radiance	Instrument	5.5000	2528114.3	-17
1.2	**Mechanical Structure**					
1.2.1	Chassis	Main structural support frame	Magnesium AZ31B	15.0380	106247797	0
1.2.3	Cables	Tethering cables to DSS	Inconel Cable	1.8200	492773779	0
1.2.4	Coating*	Protective surface treatment layer	Chromate Conversion	< 0.0001	10000	0
1.2.5	Assembly*	Integrated internal mechanical assembly	DSS, Internal , Electronics	0.9500	87530	0
1.2.6	Sapphire Window	Optical window for instruments	Sapphire	1.0985	275000	0
1.3	**Power**					
1.3.1	Battery	Stores electrical energy onboard	Lithium ion battery	4.0000	2000376	0

1.3.2	Solar Panel	Generates power from sunlight	Gallium Arsenide Multijunction cells	1.5000	8036000	522.54
1.3.3	Power Distribution	Puts power across subsystems	Power Distribution Board	2.0000	2500000	0
1.4	**Thermal**					
1.4.1	TurboFlex Heaters	Heating strip for thermal control	Set of 3 PN 220206 (ASRBQF), Polyimide, 5x6 in., 100W	0.0294	25806.4	-100
1.4.2	TurboFlex Heaters	Heating strip for thermal control	Set of 3 PN 220206 (ASRBQF), Polyimide, 5x6 in., 100W	0.0294	25806.4	-100
1.4.2	TurboFlex Heaters	Heating strip for thermal control	Set of 3 PN 220206 (ASRBQF), Polyimide, 5x6 in., 100W	0.0294	25806.4	-100
1.4.3	TurboFlex Heaters	Heating strip for thermal control	Set of 2 PN 220210 (ATABQN), Polyimide, 5x8 in., 20W	0.0588	51612.8	-20
1.4.4	TurboFlex Heaters	Heating strip for thermal control	Set of 2 PN 220210 (ATABQN), Polyimide, 5x8 in., 20W	0.0588	51612.8	-20
1.4.5	ST-100: Thermistor Temperature Sensor	Thermal Sensor to detect internal system temperature	Thermal Sensor	0.0600	2827.43	-0.00025
1.4.6	Copper Gold MLI	e = 0.01	MLI	0.0000	0.000000002 613	0
1.4.7	Flat Black Paint Coating	a=0.99	Coating	0.0000	0.000000001 633	0

1.5	**Comms**					
1.5.1	Orbiter Primary Comms	Solar powered directional reflectarray antenna	Integrated Solar Array and Reflectarray Antenna (ISARA)	0.5000	0.0002	-0.2
1.5.2	DSS Primary Comms	High speed onboard data protocol	Spacewire	0.0435	0.000039	-0.1
1.5.3	Redundant Comms	Omnidirectional backup helix antenna	Quadrifilar Helix Antenna	0.2700	0.001349	-10
1.6	**CDH**					
1.6.1	Onboard Computer	CPU is able to process and execute commands and manage data	BAE Systems RAD5545 Multicore Onboard Computer	0.8000	0.0003366	-35
1.6.2	Filight Control Software	Controls and manages flight operations	NASA core Flight System	0.0000	0	0
1.6.3	Storage	Stores mission and sensor data	Mercury RH3440 Data Recorder	0.6200	0.00024	-14
1.6.4	Transceiver	Sends and receives spacecraft signals	JHU Frontier Radio Lite Transceiver	0.4000	0.001459	-2
Descent Subsystem						
						-10.5

2.1.1 Mechanical Subsystem Overview

This section will provide an overall description of how the mechanical subsystems will combine and function. The Mechanical Subsystem contains the spherical chassis, aperture window, anticorrosive coatings, internal fastening components, external fastening components, and primary DSS connectives. Overall, the subsystems will successfully sustain operability during flight cycles in the Venusian atmosphere between 50 and 70 km above the planet surface.

The chassis houses the science payload, data configurations, power units, and thermal regulators. The chassis is a Magnesium AZ31B spherical shell, with an outer diameter of 0.721 meters and an inner diameter of 0.710 meters. The spherical shell itself has a mass of 15 kilograms. 8 steel alloy cables will be used to connect the chassis to the DSS. Each will run from the screwheads on the DSS interface to the chassis. The short cables are 0.177 + 0.2m, and the long cables are 0.31 +0.2 m. The alloy cables are fitted with stops which will be threaded through bores on the surface of the chassis. Smaller bores will be located adjacent to the cables, which will feed SpaceWire to the DSS mainframe. The Spacewire will wrap along the cables, and connect to the entry ports on the DSS.

The mechanical subsystems also will include specific coatings to inhibit chemical and radiative degradation. The electronics will have mechanical coverings as well as a Silicon-Carbon composite protective powder coating to prevent sulfur dioxide reactions and electrical interference from the Venusian atmosphere. The exterior of the chassis and cables will be treated with aluminum - chromate conversion coatings to mitigate reaction and radiation damage as well.

Located on the bottom face of the chassis is the Synthetic Sapphire window for the spectrometer aperture. The dimensions are 5 cm x 5 cm x 11 cm, and have been selected to maximize protection and simultaneously permitting maximum light through the window. The edges of the window opening will be beveled flush with the chassis window opening, such that space - grade epoxy can be applied and cured.

Internal fastening components will consist of Inconel Bored Couplings, Aluminum 6061 Tangs, and EpoTek 353 ND SpaceGrade Epoxy. These components will secure the power units, thermal regulators, computer configurations, and science payload to protect against the kinematic strain of launch and operation. All components of the chassis can sustain temperature fluctuations of 200 degrees Kelvin during each science and recharge cycle. Moreover, the coatings and protective components of the chassis will successfully mitigate corrosion and chemical damage to all of the aerobot subassemblies.

Table 9: Mechanical Subsystem Mass, Dimensions, and Max Power Draw

Mechanical Subassembly	**Mass (kg)**	**Dimensions**	**Max Power Draw (W)**
Chassis	15 kg	r = 721 mm	0
Anti Corrosive Treatments	< 0.0001 kg	$6.53e^6$ mm^3	0
Fastening Components - DSS	0.07 kg	5 mm ∅ x 50 mm	0
Fastening Components- Internal	0.1 kg	5 mm ∅ x 25 mm	0
Sapphire Window	1.0985 kg	50 x 50 x 110 mm	0
Steel Alloy Cables	1.82375 kg	0.635 cm ∅, 177 mm and 310 mm (Short and Long lengths)	0
Electronics Protection	.< 0.01 kg	x	0

*Note that the electronics protection forms a thin powder coating on the exterior of the electronics subassembly. It forms a layer on the order of microns, which is a negligible overall volume.

2.1.1.1 Mechanical Subsystem Requirements

The Mechanical subsystem includes 14 core requirements involving the protection, framework, organization, and flight control of the Aerobot system (Table 10).

The core requirements related to protection include the resistance towards stress/vibrations (MCH-1.0), extreme temperatures (MCH-2.0), corrosion/chemical reactivity (MCH-3.0), and Venus' external applied forces (MCH-13.0). These are essential so that the Aerobot system does not collapse before it can collect any data pertaining to the mission goals. It is crucial for the exterior of the system to remain insusceptible to the environment/forces Venus has, so that the interior (containing the DSS, instrumentation, and circuitry) remains unharmed and fully functional.

The core requirements related to the framework of the Aerobot system include the rigidity of an internal frame (MCH-8.0) and screws/nuts and bolts/welding (MCH-8.1). In addition, the framework will require shielding properties such as diverse materials for chemical resistance (MCH-8.2), redundant materials (MCH-12.0), and materials to shield instrumentation (MCH-14.2). Simultaneously, the framework shall not use materials that interfere with radio frequencies and other forms of communication (MCH-5.2).

The framework requirements will influence the safety of the Aerobot system's safety from possible environmental/force impacts. Thus, it is crucial that the components of the Aerobot system remain rigid and shielded so that the interior is undamaged, while using the appropriate materials.

The core requirements related to the organization of the Aerobot system include the designated slots for the DSS subsystem (MCH-4.0), power and communication wiring for the DSS (MCH-4.1), the power source (MCH-9.0), and sensors and scientific instruments (MCH-10.0). Moreover, the Aerobot system will be designed in a way that does not obstruct camera/sensor views (MCH-5.1), and does not obstruct the effectiveness of the system's circuitry (MCH-5.3 & MCH-5.4). These requirements regarding organization make it possible for the system's components to run with full functionality and efficiency. The organization as well allows for easy inspection to find any errors within the system.

The core requirements related to the flight control of the Aerobot system include the steadiness of the Aerobot system's positioning and descent (MCH-7.0), and its oscillation (MCH-7.1). Flight control is essential to record data at desired targeted positions, as well as promoting the safety of the system from environmental hazards. This will mainly be handled by the DSS.

In addition to the core requirements related to protection, framework, organization, and flight control of the Aerobot system, there are basic mission requirements. These mission requirements include the dimension and weight of the Aerobot system, such as having 1x1x1 m (MCH-1.3) dimensions and having a weight no more than 50kg (MCH-1.2). Within the 50kg weight requirement, it is necessary to have at least 18 kg designated for scientific instrumentation (MCH-14.1). These requirements are inserted into the Mechanical subsystem requirements because of default conditions held by the mission task. Though they also influence organization and flight control for the system, as well as budgeting for mission's given cost constraints.

Table 10: Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
MCH-1.0	The Aerobot system shall withstand mechanical and environmental stresses during launch, deployment, and operation	The ability to withstand such forces allows the instruments to reach the Venusian environment and collect data and still have the Aerobot sustain harsh forces	MISS-1.0	MCH-1.1 MCH-1.2 MCH-1.3	Test	Met
MCH-1.1	The Aerobot system shall be able to withstand 800kN of drag force from the Venusian winds and dust in atmosphere	Set number of force from Venusian atmosphere promtos suspension preparedness	MCH-1.0	-	Test	Met
MCH-1.2	The Aerobot system shall have a mass no more than 50kg	Specified weight to limit the cost of manufacturing	MISS-2.0	-	Inspection	Met
MCH-1.3	The Aerobot system shall be constrained to dimensions of 1x1x1 m	Specified dimensions to limit the cost of manufacturing and encourage material organization	MISS-1.0	-	Inspection	Met
MCH-2.0	The Aerobot system shall withstand temperature fluctuations of ~200 K to 400 K in each ascent cycle	The material of the Aerobot system will expand or contract, depending on the temperature fluctuations in the space and Venus environment	TMS-1.0	MCH-2.1	Test	Met
MCH-2.1	The Aerobot system chassis shall operate nominally in a maximum temperature environment of 500 K	The chassis will expand or contract depending on temperature environment	MCH-2.0		Demonstration	Met
MCH-3.0	The Aerobot system shall be resistant to corrosion and chemical degradation within the interior and exterior of the system	Many materials degrade over time due to chemical reactivities (e.g. degradation of aluminum with gamma radiation)	MCH-1.0	MCH-3.1 MCH-3.2	Analysis	Met
MCH-3.1	The Aerobot system shall use shielding materials to prevent degradation from gamma and other types of radiation	Lead is a material that is resistant to the effects of radiation, and can be used to shield materials that are not resistant	MCH-3.0	-	Analysis	Met
MCH-3.2	The shielding materials shall not inhibit the communication, GDC, or science instrumentation or *deflect radio waves.*	While protective components are necessary, shielding components should not debilitate the aerobot's capacity to relay key science data or receive command instruction.	MCH-3.1	-	Analysis	Met

MCH-4.0	The Aerobot system shall have designated slots in the mechanical interface with the Descent Subsystem (DSS) for successful deployment	To ensure other subsystems do not interfere with the success of deployment	MCH-6.0	MCH-4.1 MCH-4.1	Inspection	Met
MCH-4.1	The Aerobot system shall have designated slots in the mechanical interface for power and communication wiring to the DSS	Allows for easy inspection and reduces risk of frequency interference	MCH-4.0	-	Inspection	Met
MCH-5.0	The Aerobot system shall keep all materials rigid to prevent internal damage due to Venusian winds	Venus' atmosphere and strong winds will shake/vibrate the system--materials must be kept rigid to prevent internal system damage	MCH-1.0	MCH-5.1 MCH-5.2 MCH-5.3 MCH-5.4	Analysis	Met
MCH-5.1	The Aerobot shall prevent materials from obstructing camera and sensor views	Clear sensor and camera views are necessary to collect data and pinpoint the targeted location(s)	MG-1.0	-	Inspection	Met
MCH-5.2	The Aerobot system shall include materials that do not contaminate electromagnetic communication or scientific frequency ranges.	Highly conductive materials block radio frequencies, which would cause issues with radars and forms of communication	CDH-3.0	-	Analysis	Met
MCH-5.3	The Aerobot system shall separate internal circuitry from scientific instruments	Instruments, such as radars, may signal radio frequencies that may lead to circuit degradation and data loss	MCH-3.0	-	Inspection	Met
MCH-5.4	The Aerobot system shall implement non-magnetic materials near circuit boards to prevent damage	Magnets may create small voltages that can travel through the circuits and damage them	MCH-5.3	-	Analysis	Met
MCH-5.5	The aerobot system shall include a window with a high-transmittance material for the spectrometer.	The window cannot cause chromatic or spherical aberrations. It also must not thermally radiate and transmit source light successfully to the spectrometer while maintaining thermal isolation of the system	MCH-5.0	-	Analysis	Met
MCH-6.0	The Aerobot system shall deploy successfully	To allow successful data collection with provided instruments	MCH-1.0	MCH-7.0	Demonstration	Met
MCH-7.0	The Aerobot system shall maintain stable descent and positioning within the Venusian atmosphere	Allows instruments to accurately collect data and mitigates risk of exterior damage	MCH-6.0	MCH-7.1	Demonstration	Met

MCH-7.1	The Aerobot system shall be designed to minimize unwanted oscillations during flight	Allows instruments to record accurate data and reduces drag	CDH-1.0	-	Analysis	Met
MCH-8.0	The Aerobot system shall have an internal frame to provide structural integrity	Keeps the exterior of the system rigid, despite harsh forces acting on the system	MCH-1.0	MCH-8.1 MCH-8.2	Analysis	Met
MCH-8.1	The Aerobot system shall use screws, hinges, nuts, bolts, or welding for secure fastening of components	Ensures rigidness of specifically positioned materials, components, and instruments	MCH-8.0	-	Analysis	Met
MCH-8.2	The Aerobot system shall use various materials to explore the mission goal	Diverse materials increases efficiency of Aerobot system through increased safety, data collection, and communication	MISS-1.0	-	Inspection	Met
MCH-9.0	The Aerobot system shall have a defined power source location	Mitigates risk of damage on a critical component	MCH-4.1	-	Inspection	Met
MCH-10.0	The Aerobot system shall have areas designated for sensors and scientific instruments	Decreases risk of frequency interference and data collection, and fosters system orientation	MCH-5.1	-	Inspection	Met
MCH-11.0	The Aerobot system shall be designed to permit communication signals without interference.	Aluminum and copper materials are highly conductive materials that may block radio frequencies	MCH-5.2	-	Analysis	Met
MCH-12.0	The Aerobot system shall incorporate safety factor dimensions for critical components	To mitigate risk of damage on critical Aerobot system components	MCH-8.2	-	Analysis	Met
MCH-13.0	The Aerobot system shall be able to withstand forces applied from external and internal forces	To ensure the exterior and interior of the system does not get damaged	MCH-1.0	MCH-13.1 MCH-13.2	Analysis	Met
MCH-13.1	The Aerobot system shall avoid malfunction due to atmospheric granule infiltration or impact with seals and hard materials	Set number of wind speed resistance promotes suspension preparedness	MCH-13.0	-	Demonstration	Not Met
MCH 14.0	The Aerobot system shall have sufficient instrument housing capacity to conduct science optimally.	Ensure functionality of instruments within the aerobot system	MISS-2.0	MCH-14.1 MCH-14.2 MCH-14.3	Analysis	Met
MCH-14.1	The aerobot chassis shall support at least 20 kg of scientific instrumentation.	The aerobot will be unable to fulfill mission objectives if it cannot support	MCH-14.0	-	Analysis	Met

		the mass of the onboard instruments.				
MCH-14.2	The aerobot shall include protective aperture coatings and lenses for the photodiodes of the optical sensors	Ensures safety of imaging / sensor systems included in the photodiode system.	MCH-14.0	-	Analysis	Met

2.1.1.2 Mechanical Sub-Assembly Overview

A presentation of the mechanical subsystems is given in this section. The main lower level assemblies include the chassis design, solar arrays, apertures, anticorrosive coatings, fastening components, and protective materials for electronics. As a preliminary note, the implementation of actuators for the aerobot subassemblies has become unnecessary. Since the SRR, improved designs have reduced mass and simultaneously eliminated the need for collapsible and deployable substructures– hence actuators have been removed from trade studies and overviews in these sections.

The main chassis structure shall be of a spherical-shell form factor. The result of the trade study indicated that this structure will perform optimally in the Venusian environment. Relevant publications and research studies are included in the citations.The outer diameter of the shell Chassis is 0.721 m, and the inner diameter is 710 m. 710 m is the optimal inner radius to simultaneously maximize internal volume for payload and minimize mass. The thickness of the shell is 0.11 m, or 110 millimeters. This includes a safety factor of 2. The minimum required thickness to support the entire system is much lower. The material selected for the chassis is Magnesium AZ31B (Mg AZ31B). Magnesium is routinely employed in various different aerospace applications, but has yet to be applied in this kind of context (Aroh 2017). In fact, NASA is currently developing Magnesium alloy solutions for space applications (Aroh 2017). It boasts high mechanical strength properties and is among the lightest metal alloys of its kind. It has a density of 1.7 g/cm^3, a tensile strength of 260 MPa, a yield strength of 200 MPa, and an 88 on the Vickers hardness scale (AZO Materials, 2012.). The chassis will need to be anodized to reduce reactivity and improve chemical resistance, which will be done by the supplier. Thermally, it is incredibly inert, with an expansion coefficient of 26 1/C^{o} (AZo Materials, 2012). The chassis will be bored to drill and connect components to the interior and exterior of the surface.

Figure 16: Sketch of Aerobot Mechanical

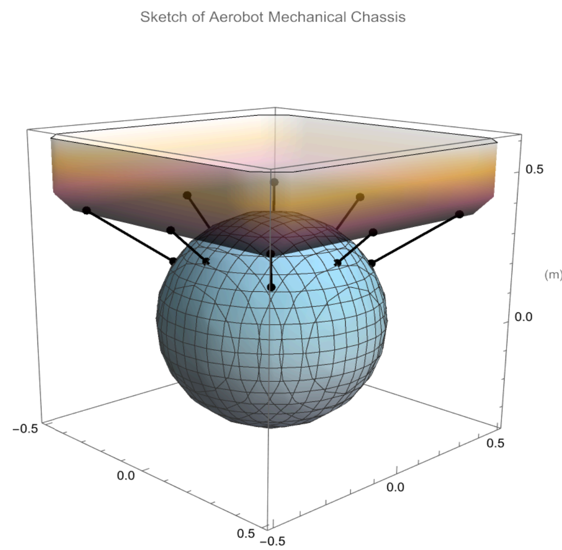
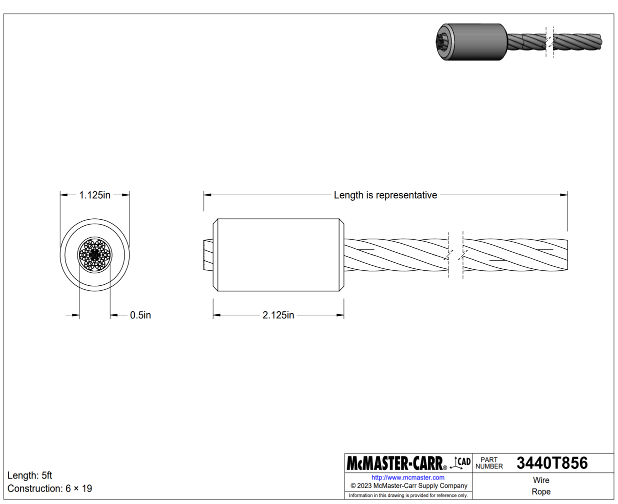


Figure 17: CAD for Fastening Components



The spherical design minimizes the effects of drag on the aerobot body (NASA Glenn Research Center, 2023). The chassis will sustain the vibration environment of launch and deployment. The chassis shall meet all the relevant requirements outlined in 1.5.2.2. The chassis TRL is 4. The spherical chassis design has been incorporated in planetary exploration missions as well as in missions like Sputnik (Li et al., 2023). Though these designs have included much different instrumentation and scopes, the spherical chassis itself obtains a 4.

The chassis mainframe hemispheres shall be anodized to mitigate any chemical reactions that may occur on the surface. (Blawert et al, 2006). The treatment is not expected to interfere with other mechanical, electrical, or scientific subassemblies (Salman and Okido 2013). The treatment adds negligible mass and thickness to the shell. The total mass of the coating will be less than 0.01 kg. The TRL of anodization for this component in the Venusian environment is a 4. Anodization has been used in some aerospace applications prior to this (Yang et al. 2024).

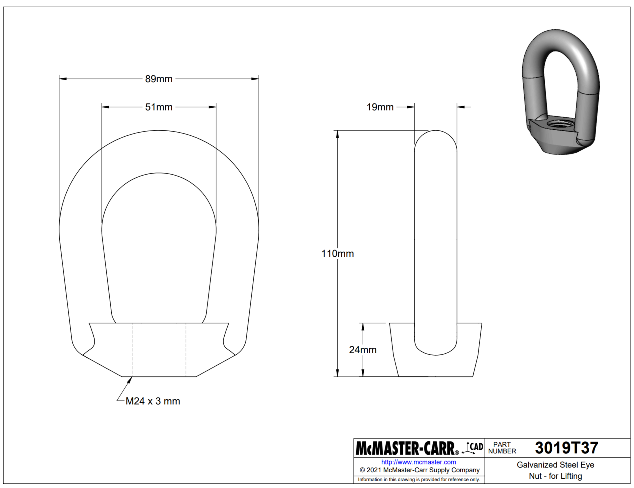


Figure 18: CAD for Fasteners for IWRC Cables

Fastening components used to secure the chassis to the DSS are 8 alloy steel socket head screws, which are 5 mm diameter screws with a depth of 50 mm. These screws have been selected by the DSS construction and assembly team. The heads of the screws will be located in the interior of the DSS, with the threads extending downwards towards the DSS (Interface Control Document, 2025). These will be connected to the cable subassemblies, which connect to the chassis. The threaded end will be fitted with custom ordered eye nuts from Clarendon Aerospace Fasteners.

The eye nuts will be very similar to the ones available on McMaster-Carr, however the thread size selected by the DSS Assembly is incompatible. Hence, eye nuts with a thread size of 5 mm will be required. Clarendon Aerospace Specialty Fasteners will manufacture these pieces. They will be similar to the eye nuts in Figure 18, but with an eye diameter of ½ in and a thread size of 5 mm.

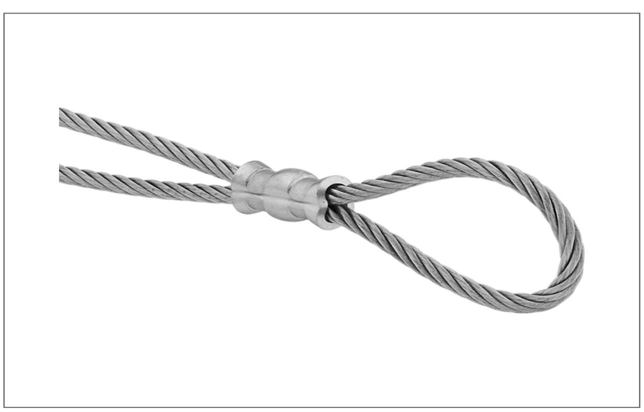
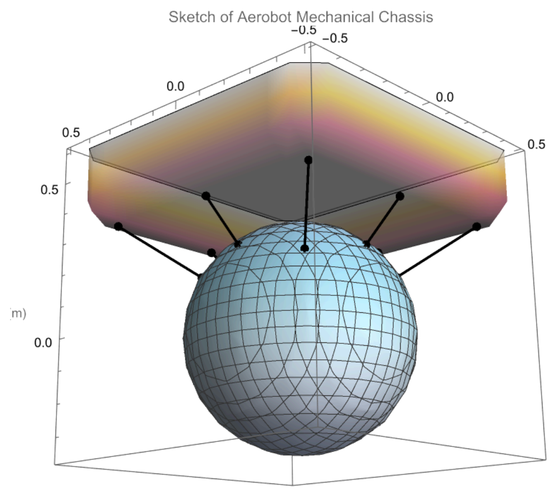


Figure 19: Image of IWRC Cables

The cables that connect to the chassis are McMaster-Carr steel alloy IWRC cables with stops. They are ½ in in diameter. These have a load capacity of over 5000 pounds (“McMaster-Carr 2019”), and are rated for lifting. CAD for the wire rope The stops will be threaded through bores on the surface of the chassis surface. The end that connects to the eye nut will be lined through the eye, and then fitted with a compression sleeve to secure the end. 10 lengths of 5 foot cable will be purchased, however the cable lengths will be 1.77798 + 0.2 m and 0.310291 + 0.2m. The factor of 0.2 m includes the loop to be compressed for attachment. The cables will be fastened such that the aerobot chassis is secure, with marginal oscillatory motion. The cables will simultaneously serve as a kind of damped shock absorber, while simultaneously securing the chassis against motion.

Figure 20: Simulation of Cables Attached to Chassis



The compression sleeves will be attached after securing the stopped end through the aerobot chassis. The ½ in diameter sleeves are rated for loads of their parent component- in this case, the steel alloy cables are capable of loads much heavier than the aerobot chassis and payload (“McMaster-Carr 2019”). Thermally, the steel is extremely inert.

The steel alloy to be used will have a yield strength of approximately 220 MPa in the target environment temperatures and conditions (AMeS, n.d.). On Venus, the gravitational force of the aerobot will be 443.5 N. This would correspond to which would correspond to 0.87 MPa through one wire. Each cable will therefore be subject to only 0.05% of its maximum bearing capacity (see Supplemental Calculations). The TRL of the steel alloy cables is 5. These cables have been used in aerospace systems and performed optimally and are manufactured for aerospace purposes. The TRL of the custom eye nuts is 3 (Moore et al., n.d.). Clarendon has manufactured similar fasteners for aerospace applications (Wayken 2023). They are expected to operate normally in the Venus environment.

The solar sub assembly will consist of a series of small CAVU Aerospace Triple Junction 30 GaAs Solar panels. Each panel is 30.15 cm^2, and has a mass of 0.125 g/cm3 (CAVU Aerospace, n.d.). 340 panels can be employed within the mass constraint. The panels will be attached by small bored couplings, through which electrical transport wires will connect to the panels. The panels will be distributed evenly across the upper hemisphere of the chassis mainframe. The TRL of the solar sub assembly is 4. The panels have been employed extensively in space satellite missions (CAVU Aerospace, n.d.). They theoretically can operate in the Venus environment, but the inclusion of other sub components in the solar array brings the TRL down to 4. The solar array in this new capacity has yet to be tested in the target environment.

The aerobot shall also include an electronics protection subassembly. This will include SiC powder coatings. These are anticorrosive materials and will protect the wirings and electrical subassemblies. The mass density of SiC powder is 3.2 g/cm3. The total mass of required coating will be less than 0.01 kg. SiC has been tested in high temperature environments with similar chemical abundances as the Venusian environments, specifically for in situ missions (Lukco et. al., 2018). The TRL for this technology is 5. In 2017, Lukco et al tested various materials in a chamber specifically designed to simulate the Venus atmospheric environment. Chemical abundances of sulfur, chlorine, carbon dioxide, fluorine, and others were all matched to the Venusian conditions. SiC among other materials for electronics protection were tested. SiC formed no compounds and showed no evidence of reactivity. Therefore, it was chosen for the aerobot design.

Internally, components will be fastened by welded housing (done in-house), screws through the bored couplings, and EpoTek 353ND Space-grade epoxy. The EpoTek 353ND epoxy is one of the most trusted bonding adhesives for space grade applications, and NASA standards that require epoxies to meet outgassing limits while in extreme environments (EpoTek, n.d.). The epoxy will secure internal components and also be used to reinforce and hermetically seal the cable stops from the interior. The TRL of the 353ND epoxy is a 3.

Table 11: Refractive Index of Sapphire

Refractive Index of Sapphire									
Wavelength	Refractive Index	Wavelength	Refractive Index	Wavelength	Refractive Index	Wavelength	Refractive Index	Wavelength	Refractive Index
0.200	1.912709	0.381	1.790112	0.725	1.762358	1.380	1.749084	2.627	1.722923
0.207	1.899888	0.393	1.787723	0.749	1.761606	1.425	1.748325	2.712	1.720615
0.213	1.888224	0.406	1.785513	0.773	1.760880	1.471	1.747543	2.801	1.718115
0.220	1.877745	0.419	1.783438	0.798	1.760178	1.520	1.746702	2.893	1.715438
0.228	1.868299	0.433	1.781503	0.824	1.759497	1.569	1.745850	2.987	1.712605
0.235	1.859757	0.447	1.779688	0.851	1.758835	1.621	1.744932	3.085	1.709544
0.243	1.851917	0.462	1.777995	0.879	1.758185	1.674	1.743980	3.186	1.706271
0.251	1.844804	0.477	1.776397	0.908	1.757549	1.728	1.742992	3.290	1.702774
0.259	1.838259	0.493	1.774907	0.938	1.756918	1.785	1.741927	3.398	1.699002
0.267	1.832235	0.509	1.773508	0.968	1.756297	1.843	1.740820	3.509	1.694975
0.276	1.826748	0.525	1.772195	1.000	1.755678	1.904	1.739626	3.624	1.690637
0.285	1.821634	0.543	1.770953	1.033	1.755055	1.966	1.738383	3.742	1.686006
0.294	1.816969	0.560	1.769787	1.066	1.754449	2.030	1.737065	3.865	1.680981
0.304	1.812662	0.579	1.768678	1.101	1.753823	2.097	1.735647	3.991	1.675619
0.314	1.808647	0.598	1.767635	1.137	1.753192	2.165	1.734167	4.122	1.669806
0.324	1.804975	0.617	1.766647	1.175	1.752536	2.236	1.732576	4.257	1.663556
0.335	1.801549	0.637	1.765706	1.213	1.751890	2.309	1.730889	4.396	1.656835
0.346	1.798355	0.658	1.764808	1.253	1.751215	2.385	1.729078	4.540	1.649558
0.357	1.795405	0.680	1.763956	1.294	1.750526	2.463	1.727160	4.688	1.641733
0.369	1.792655	0.702	1.763141	1.336	1.749823	2.543	1.725128	4.842	1.633206
								5.000	1.624032

The aerobot shall also include a small aperture window of 5 x 5 cm^3 for the spectrometer instrument. The window shall be made of synthetic sapphire (Analytical Components International, 2023). Synthetic sapphire has high thermal resistance and high transmittance in the desired wavelengths for science key objectives, from the near ultraviolet into the mid infrared ranges (Boullot, 2023). A table of predicted refraction indices from Meller Optics can be viewed in Table 11. Low refraction is expected in the target wavelengths of data collection. Synthetic sapphire has extremely high scratch resistance and is sufficiently chemically inert. The impact residual strength is also incredibly high for synthetic sapphire, which makes it a very reliable optical element in the Venusian atmosphere (Luxium Solutions, n.d.). The material will be fastened using the 353ND epoxy. The TRL of synthetic sapphire for this mission is 4. It has been deployed and tested in space environments and can operate in predicted temperature environments of this mission without issue. Meller optics produces custom synthetic sapphire elements for space applications which have operated successfully. It fails to reach 6 since the specific morphology of optic required for this mission has not been tested, but can easily be manufactured.

The lowest TRL value for the assembly is a 4. It is acknowledged that the solar panels themselves have a high TRL and have been tested and implemented extensively in space environments. It is the mere mechanical integration with the couplings that brings the TRL down. The mechanical integration is not expected to reduce the efficiency or operability of the panels. Although the aerobot system does not attain TRL levels as high as 6, it noted that this is not a Flagship mission. Therefore, the lower TRL values are justified in this mission context.Therefore, the TRL of the mechanical subsystem is a 4.

Cables

```
In[ ]:= Clear["`*"]

In[440]:=
(*diameter of .0.721, let x= 0 be the center of the aerobot.*)

locations = {
   {-.4, 0,  z},
   {-.4, .4, z},
   {0, .4, z},
   {.4, .4, z},
   {.4, 0, z},
   {.4, -.4, z},
   {0, -.4, z},
   {-.4, -.4, z}
  } /. z → .721 / 2

Out[440]=
{{-0.4, 0, 0.3605}, {-0.4, 0.4, 0.3605}, {0, 0.4, 0.3605}, {0.4, 0.4, 0.3605},
 {0.4, 0, 0.3605}, {0.4, -0.4, 0.3605}, {0, -0.4, 0.3605}, {-0.4, -0.4, 0.3605}}

In[519]:=
sphere = RegionPlot3D[x^2 + y^2 + z^2 ≤ (.721/2)^2,
   {x, -.6, .6}, {y, -.6, .6}, {z, -.6, .6}, ColorFunction → "Aquamarine"];

points = Table[Point[locations[[n]]], {n, 1, Length[locations]}];
screws = Graphics3D[{PointSize[Large], points}];

lines = Table[Line[{{0, 0, 0}, locations[[n]]}], {n , 1, Length[locations]}];
cables = Graphics3D[{Thick, lines}];

planeq = {z ≥ (0.721 / 2) && Abs[x] ≤ .5 && Abs[y] ≤ .5};
plane = RegionPlot3D[ planeq, {x, -.6, .6}, {y, -.6, .6}, {z, -.6, .6},
   PlotStyle → Opacity[.5], ColorFunction → "SunsetColors", Mesh → None];
```

2 | *chassis.nb*

```
(*to find points on spherical surface, and minimum cable lengths*)

cablelengths = Table[Norm[locations[[n]]] - (.721 / 2), {n, 1, Length[locations]}]

4 * cablelengths[[1]]
4 * cablelengths[[2]]

Out[531]=
{0.17798, 0.310291, 0.17798, 0.310291, 0.17798, 0.310291, 0.17798, 0.310291}

Out[532]=
0.711918

Out[533]=
1.24116
```

In[514]:=
```
lineeqns = Table[t locations⟦n⟧, {n, 1, Length[locations]}];
tvals = Table[
   NSolve[lineeqns⟦n, 1⟧^2 + lineeqns⟦n, 2⟧^2 + lineeqns⟦n, 3⟧^2 == (0.721 / 2)^2, t],
   {n, 1, Length[lineeqns]}];
surfacevals = Point[{lineeqns⟦1⟧ /. tvals⟦1, 2, 1⟧,
    lineeqns⟦2⟧ /. tvals⟦2, 2, 1⟧,
    lineeqns⟦3⟧ /. tvals⟦3, 2, 1⟧,
    lineeqns⟦4⟧ /. tvals⟦4, 2, 1⟧,
    lineeqns⟦5⟧ /. tvals⟦5, 2, 1⟧,
    lineeqns⟦6⟧ /. tvals⟦6, 2, 1⟧,
    lineeqns⟦7⟧ /. tvals⟦7, 2, 1⟧,
    lineeqns⟦8⟧ /. tvals⟦8, 2, 1⟧}];
attach = Graphics3D[{PointSize[Large], surfacevals}];

Show[cables, sphere, plane, screws, attach, Axes → True,
 PlotLabel → "Sketch of Aerobot Mechanical Chassis", AxesLabel → "(m)"]
```
Out[518]=

In[591]:=
```
totalcablelength = Total[cablelengths] m ;
UnitConvert[totalcablelength, "cm"];
% (2.54/4)^2 cm^2 * π;

totalcablmemass = UnitConvert[% * 7.8 g/cm^3 , "kg"]
```
Out[594]=
```
1.9298 kg
```

Figure 21: Computation on Cables and Location

2.1.1.3 Mechanical Subsystem Recovery and Redundancy Plans

Here it is emphasized that actuators have been removed from the mechanical sub assembly design, and have been reconsolidated to the power recovery and redundancy plan. The majority of the mechanical subsystems are static and structural in nature, such as the chassis, the DSS attachment interfaces, the optical window, cables, and fasteners.

Redundancy

Each steel alloyed cable that connects the DSS to the aerobot is an SPF item. Failure is highly unlikely for any failure mode, given that the ultimate strength of the alloy is at least 203 MPa on the low end. On Venus, the gravitational force of the aerobot will be 443.5 N, which corresponds to 0.8 MPa altogether. Each cable will therefore be subject to only 0.05% of its minimum bearing capacity. The maximum operating temperatures are 73 K to 1800 K, which easily encompass temperatures of space and the Venusian atmosphere. Moreover, the anti-corrosive coatings will mitigate any corrosion or oxidation of the materials. But in the case that any of the cables fail due to thermal, kinematic, or chemical fatigue, the aerobot can remain stable and oriented correctly.

The main chassis airframe is a SPF item. The failure of the chassis could prove catastrophic to mission success, depending on the severity of damage incurred or failure mode. However, it is unreasonable to include redundancies for the chassis mainframe. The structural integrity thresholds exceed the maximum stresses and strains of launch, travel, descent, entry, and the Venusian atmosphere. The chassis itself has an Ultimate Bearing Strength of 55800 psi. All interior component melting points exceed 700 K, far beyond the temperatures of the Venus atmosphere and other environments. Thus, the team has elected to neglect redundancies for the chassis mainframe.

Each solar array is a redundancy for itself. While separate redundancies for the solar arrays are unlikely employable, the four panels serve as redundant systems anyway. Should a number of panels fail, charge and descent cycles can be extended and shortened respectively to return to nominal operating status. Expected operating temperatures are within the CAVU Triple Junction solar cell tolerances, and no chemical interaction is expected to occur.

Redundancies for mechanical components shall include reinforcing shafts and extra fastening components. Cable stoppers, which fix the cable to the surface of the aerobot, shall be reinforced with medium, space - grade epoxy from Epotek. Multiple redundant screws and bored couplings can be fastened as precautionary measures, without adding considerable mass to the aerobot.

Recovery

Very few mechanical subsystems will require specific recovery mechanisms or additional systems. For the chassis, cables, and internal fastening components, should the temperatures impose fatigue and/or unsustainable strain, the aerobot can be returned to the upper atmosphere to cool and settle at optimal temperatures.

The solar arrays, should photovoltaic cells fail, cannot be recovered. However, the operating temperatures are well within expected temperatures of the Venusian environment. The four panels can provide power sufficiently, and operating cycles can be adjusted to meet charge time requirements. The panels can be operated if deployment fails, but with suboptimal efficiency– locks can be released to drop the solar arrays without dynamic control if necessary.

2.1.1.4 Mechanical Subsystem Manufacturing and Procurement Plans

This section provides an overview of the procurement procedures and development of the mechanical assemblies.

Chassis

The chassis will be manufactured custom by AT CNC Machining, which is a contractor. There are little to no existing products that can meet the chassis mission requirements, which meant contractors would be required. The organization has years of experience manufacturing custom, complex magnesium parts. They have a variety of magnesium alloys available for production, including Mg Alloy AZ31B (AT Machining, n.d.). Due to the material’s excellent machinability and weldability, AT Machining is capable of producing magnesium structures with tolerances down to 0.005 in (0.127 mm). The sphere diameter falls within the maximum volume producible in their machine shop (2000 x 800 x 1000 mm). The lead time for a custom part is typically 7 days for their standard products, which is incredibly quick for the ISO9001 - certified production plant. AT Machining offers a variety of support structures during production and is able to provide expert insight and guidance during the production process to improve quality of the product.

Should AT CNC Machining fail or become unavailable, an alternative supplier is A.R. Machining. The contractor also specializes in custom magnesium machined parts for aircraft and aerospace applications (A.R. Machining Inc, 2018). Their in-house manufacturing shop is both ITAR and ISO9001 certified, and are also able to apply zinc-phosphate coatings to finished products to boost corrosion resistance. The generous lead time estimate from A.R. Inc. Machining is 30 days.

Connection Cables

The cables will be ordered from McMaster-Carr. These are steel alloy cables of ½ inch diameter IWRC cores, and stoppers at the end for connecting the aerobot to the DSS (McMaster-Carr 2019). These are easily ordered and already manufactured. The product is an over the shelf option since the component itself requires little to no customization. McMaster is a trusted metal part producer and manufacturer, the lead times and systems integration times are incredibly low. A lead time of 1 - 2 weeks is listed for the product by the manufacturer. McMaster also manufactures numerous additional aerospace interface assembly pieces, which greatly increases ease of integration in the case that some components prove inadequate.

Should McMaster - Carr be unavailable to supply ½ inch steel alloy rope, US Cargo Control is able to supply EIPS - IWRC galvanized steel alloy ropes that meet the same requirements (USCC 2025). It is also rated for overhead lifting and can be implemented in the same fashion. Estimated lead times from USCC are on the order of one week. The cable costs very little per foot, and can also be ordered with additional customization options.

Compression Sleeves

The compression sleeves for creating loops will also be ordered from McMaster-Carr. These lead times are on the order of one week. The sleeves will be pressed and clamped during the assembly process once the payload has been fitted and the chassis sealed.These have been ordered off the shelf because little customization is required for this component of the mechanical subassembly (McMaster-Carr 2019). For orders within the U.S., lead times are anywhere between 1 to 5 days.The sleeves will be crimped in house using standard in-house toolsets.

Should McMaster - Carr be unable to supply the compression sleeves, Huyett Industrial Distribution can supply the very same component (Huyett 2025). The component is in stock and can be delivered anywhere from 1 to 5 days. The component meets the same specifications, including RoHS compliance.

Joiners

The eye nuts, which will connect the DSS interface screws to the cables, will be produced by Clarendon Specialty Fasteners. Clarendon is a high - level and experienced spacecraft assembly part manufacturer. The DSS manufacturer selected screws of 5 mm thread diameter. Unfortunately, very few eye-nut fasteners exist with thread diameters of 5 mm. Given that Clarendon offers a wide range of possible engineered products, eye nuts of part number 3019T31 will be designed, save a thread diameter of 5mm and an inner eye diameter of at least 0.313 inches (Clarendon SF 2025). Lead times are estimated to be about 30 days.

Should Clarendon be unable to manufacture the part, MS Aerospace is a viable alternate supplier. The organization also boasts an extensive background in space-based airframes and mechanical structures. They are capable of producing the same eye nuts to meet system requirements as described above (MS Aerospace 2020). Lead times are estimated to be about 30 days.

Synthetic Sapphire Window

The aperture for the synthetic sapphire window will be manufactured by Meller Optics, a contractor. The specificity required for the component is very high, and Meller Optics is able to produce synthetic sapphire lenses and windows for space-based applications (Meller Optics 2016). According to Meller Optics, manufacturing lead time is around 2 to 3 weeks, which makes total lead time about 30 days.

Should Meller be unable to produce the required optical window, Guild Optics is capable of producing an identical custom synthetic sapphire window for space based applications (Guild Optics 2024). The current typical lead time is about 7 weeks after order placement, as per a notice the company published concerning low supply chain stocks.

Internal Fastening Components

EpoTek provides a space-grade epoxy with high thermal resistance and a near-hermetic seal. It passes NASA low outgassing standards (ASTM 595) for adhesives in space applications The product can be ordered and stored at room temperature for 1 year (EpoTek n.d.). The lead times for EpoTek epoxies vary on large timescales due to their high environmental sensitivity before curing. According to HISCO, the maximum lead time when EpoTek products are not in stock is approximately 50 days.

Should EpoTek be unable to supply the required space-grade epoxies, MasterBond produces similar, equally viable epoxies that can be used in the optical element application. Lead times are on average 3 - 5 days after the date of order placement (MasterBond 2025).

2.1.1.5 Mechanical Subsystem Verification Plans

The Mechanical verification plans include testing, analysis, demonstration, and inspection. For the majority of mechanical sub components, inspection and analysis suffice. Demonstrations are necessary for performance based requirements. These verification methods shall determine whether the system is being built correctly.

The testing phases target the structural integrity of the aerobot mainframe. These tests will determine whether the aerobot is structurally sound and structurally isolated.

Structural isolation refers to the aerobot's capacity to prevent infiltration from the Venusian atmosphere. Structural soundness refers to the aerobot's resistance against disintegration. The tests shall confirm the aerobot's ability to maintain operation in high wind and high pressure environments, as well as highly granular atmospheres.

Demonstrations will occur in-house. Demonstrations primarily confirm the aerobot's ability to operate CDH, power, and thermal systems along with the mechanical subsystems. Analyses of aerobot mechanical subsystems mainly determine whether or not the aerobot is compatible with science payloads and contractor-provided requirements. Inspections will be performed both during and before the assembly process to ensure that the aerobot is meeting the top-level parent requirements, for those that do not require more rigorous verification methods.

Table 12: Mechanical Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MCH-1.0	The Aerobot system shall withstand mechanical stresses and vibrations during launch, deployment, and operation	Test	The system needs to be able to mechanically sustain itself for the duration of operation. Utmost assurance that the aerobot system will survive launch, deployment, and operation is required for a successful mission.	Vibration test laboratory. at the Kennedy Space Center to ensure structural integrity during launch and atmospheric stresses during deployment and operation.
MCH-1.1	The Aerobot system shall be able to withstand 800kN of drag force from the Venusian winds and dust in atmosphere	Test	The system must be able to operate in the Venusian atmosphere. It will be subject to drag forces from the wind. Testing is required to evaluate aerodynamic profiles and system stability.	Wind and aerodynamics testing at Basic Aerodynamic Research Tunnel (BART)
MCH-1.2	The Aerobot system shall have a mass no more than 50kg	Inspection	This requirement can be met by weighing the mass of the entire aerobot system.	Take mass values of components before assemblies, ensure that mass requirements will be met.
MCH-1.3	The Aerobot system shall be constrained to dimensions of 1x1x1 m	Inspection	This requirement can be met by measuring the entire aerobot system, to ensure it meets volume requirements.	Verify that subassemblies fit within internal volume of the chassis. Take measurements of all external sub assemblies, including chassis. Verify that the aerobot can meet volume requirements at assembly house.
MCH-2.0	The Aerobot system shall withstand temperature fluctuations of ~200 K to 400 K in each ascent cycle	Test	The mechanical system cannot incur thermal fatigue during operation. It is mission critical that the mechanical subassembly can undergo thermal fluctuations of 200 K in magnitude without failure.	This can be done conjointly with TMS - 1.0 testing plan. Use a thermal vacuum chamber to test structural and operational integrity of the mechanical subsystem for anticipated science/charge time cycles.
MCH-2.1	The Aerobot system chassis shall operate nominally in a maximum temperature environment of 500 K	Test	The mechanical system cannot incur thermal fatigue during operation. It is mission critical that the mechanical subassembly can endure temperatures of up to 500 K without failure.	This can be done conjointly with TMS - 1.0 / MCH- 2.0testing plan. Use a thermal vacuum chamber to test structural and operational integrity of the mechanical subsystem at maximum anticipated temperature.
MCH-3.0	The Aerobot system shall be resistant to corrosion and chemical degradation (due to sulfuric acide and carbon dioxide) within the	Analysis	The chassis will be anodized to resist chemical reactions with chemical compounds in the Venusian atmosphere. The anodization bath needs to meet standard voltage and electrolyte values to	Ensure the chassis is clean and degreased before anodization. Before, during, and after anodization process, ensure that correct voltage will be applied for the correct electrolyte solution. This can be inspected

	interior and exterior of the system		be successful.	with multimeters.
MCH-3.1	The Aerobot system shall use shielding materials to prevent degradation from gamma and other types of radiation	Inspection	Anti corrosive coatings can be inspected for correct application and functionality. Chassis materials can be inspected for electromagnetic radiation resistant properties	Ensure that anticorrosive coatings have been applied, and determine radiative resistivity of chassis material using EMF or Gauss meters.
MCH-3.2	The shielding materials shall not inhibit the communication, GDC, or science instrumentation or *deflect radio waves.*	Demonstration	The functionality of comms and GDC can be determined in-house without testing facilities.	Attempt to operate communication and data relay sub assemblies while positioned in the aerobot, on-site during assembly process.
MCH-4.0	The Aerobot system shall have designated integration subassemblies for successful integration with the Descent Subsystem (DSS).	Inspection	No tests or formal demonstrations are required.	Ensure that integration subassemblies are present during the aerobot assembly process.
MCH-4.1	The Aerobot system shall have designated slots in the mechanical interface for power and communication wiring to the DSS	Inspection	No tests or formal demonstrations are required.	Ensure by inspection that there are internal fastening components and slots present for securing and housing internal subassemblies.
MCH-5.0	The Aerobot system shall keep all materials rigid to prevent internal damage due to Venusian winds	Analysis	Results of tests for MCH-1.0 will provide insight and results for MCH-5.0, but analysis of rigidity can be performed in-house during assembly.	Analyze the rigidity of internal components during MCH-1.0 test and also on-site with available mechanical tools
MCH-5.1	The Aerobot shall prevent materials from obstructing camera and sensor views	Inspection	No tests or formal demonstrations are required.	Ensure by inspection on-site that no internal components or external components inhibit the spectrometer field-of-view.
MCH-5.2	The Aerobot system shall include materials that do not contaminate electromagnetic communication or scientific frequency ranges.	Analysis	No tests or formal demonstrations are required. In fact, spectral data can be somewhat corrected for thermal noise in the near-IR and visual ranges.	Ensure on-site that coatings, materials, and sub assemblies do not emit electromagnetic noise in the target frequency ranges. Can be analyzed in later phases of assembly, when comms and science instruments can be operated within the entire assembly.

MCH-5.3	The Aerobot system shall separate internal circuitry from scientific instruments	Inspection	No tests or formal demonstrations are required.	Ensure by inspection that circuitry for science instrumentation and operational wiring are spatially separated by at least 4 cm.
MCH-5.4	The Aerobot system shall implement non-magnetic materials near circuit boards to prevent damage	Analysis	No tests or formal demonstrations are required.	Ensure on-site using magnometers that materials employed do not generate unsustainable magnetic interference.
MCH-5.5	The aerobot system shall include a window with a high-transmittance material for the spectrometer.	Inspection	No tests or formal demonstrations are required.	Ensure by inspection during the assembly process that synthetic sapphire window is present in the construction.
MCH-6.0	The Aerobot mechanical system shall deploy successfully	Demonstration	The aerobot deployment from the ESI, after being integrated and attached to the DSS cannot be demonstrated until mission	The aerobot's ability to deploy and maintain structural integrity in a space environment will be done as part of the mission.
MCH-7.0	The Aerobot mechanical system shall maintain stable descent and positioning within the Venusian atmosphere	Demonstration	The aerobot deployment from the ESI, after being integrated and attached to the DSS cannot be demonstrated until mission	The aerobot's ability to deploy and maintain structural integrity in a space environment will be done as part of the mission.
MCH-7.1	The Aerobot system shall be designed to minimize unwanted oscillations during flight	Analysis	No tests or formal demonstrations are required. Stabilizing and fastening components can be analyzed.	Following testing, ensure that components are successfully secured.
MCH-8.0	The Aerobot system shall have an internal frame to provide structural integrity	Inspection	No tests or formal demonstrations are required. A simple inspection will suffice.	During assembly, ensure that internal support structures are present.
MCH-8.1	The Aerobot system shall use screws, hinges, nuts, bolts, or welding for secure fastening of components	Inspection	No tests or formal demonstrations are required. Ensure that components will be welded, bolted, and fastened.	During assembly, ensure that internal fastening components are present.
MCH-8.2	The Aerobot system shall use various materials to explore the mission goal	Inspection	No tests or formal demonstrations are required. Ensure that optimal materials for each requirement are implemented.	During assembly, inspect the system for various materials and best-suit applications of materials.
MCH-9.0	The Aerobot system shall have a defined power source location	Inspection	No tests or formal demonstrations are required. Locate the interior volume where power components will be placed.	Before assembly, ensure that power assemblies are accounted for with designated locations.

MCH-10.0	The Aerobot system shall have areas designated for sensors and scientific instruments	Inspection	No tests or formal demonstrations are required. Locate the interior volume where science instruments will be placed.	Before assembly, ensure that science instruments are accounted for with designated interior locations.
MCH-11.0	The Aerobot system shall be designed to permit communication signals without interference.	Demonstration	Communicative compatibility with mechanical materials can be thoroughly demonstrated to show that materials do not inhibit key data relays.	During assembly, demonstrate that required volume of data and communications can be achieved with the integrated mechanical subsystem.
MCH-12.0	The Aerobot system shall incorporate safety factor dimensions for critical components	Inspection	No tests or formal demonstrations are required. For critical components, ensure that safety factors are present in design.	During design, ensure that assembly components have included safety factors in dimensional allocations.
MCH-13.0	The Aerobot system shall be able to withstand forces applied from external and internal forces	Test	Needs to be fulfilled with tests. Internal forces and pressures that may cause structural failure can be demonstrated during assembly, external force resistance can be tested for in the wind tunnel from the test of MCH-1.1	See plan for MCH 1.0, MCH 1.1
MCH-13.1	The Aerobot system shall avoid malfunction due to atmospheric granule infiltration or impact with seals and hard materials	Test	Select materials that have high hardness and resistance. Use welding and or epoxies to seal. Testing for earlier requirements will also meet this requirement satisfactorily.	See plan for MCH 1.0, MCH 1.1
MCH 14.0	The Aerobot system shall have sufficient instrument housing capacity to conduct science optimally.	Analysis	No tests or formal demonstrations required. Volume and housing for instruments can be accounted for during design.	During design, ensure that housing and structural support for science payload is present.
MCH-14.1	The aerobot chassis shall support at least 20 kg of scientific instrumentation.	Demonstration	Ensure that the structure of the chassis can support the science payload both in design and during assembly. Since analysis will not guarantee this requirement is met, demonstrations will suffice.	Ensure that materials with proper tensile and load strengths are selected. During design, demonstrate that science payload can be supported.
MCH-14.2	The aerobot shall include protective aperture coatings and lenses for the photodiodes of the optical sensors	Analysis	During design, analysis of aperture windows can be done to confirm high photometric transmittance.	Analyze transmittance and reflectance coefficients of apertures, as well as other relevant optical properties.

2.1.2 Power Subsystem Overview

The power subsystem consists of three main subassemblies: the gallium arsenide solar panels, the lithium ion battery, and the power distribution board. The solar panel is the main source of power for the aerobot the majority of the time when it's higher in the atmosphere due to its high sunlight radiance which is almost twice that of Earth's (Grandidier 2023). When the aerobot descends, the battery will take over as the main source of power since very little sunlight is able to propagate through the thick atmosphere of Venus. Both of these sources of power attach to the power distribution board, which will step down or up the input voltage and deliver the appropriate amount of power to each subsystem. When looking at the max power draw of other subsystems, the following wattages were obtained:

Table 13: Maximum power consumption of each subsystem

Subsystem	**Max power draw**
Command and data handling	61.3W
Thermal control	340W
Science instruments	44W
Descent subsystem	10.5W
Total	**455.8W**

The maximum power that can be drawn at one time is 455.8W. Sufficient power management will be necessary to ensure that the science subsystem is able to accomplish their goals without significantly straining the power subsystem of the aerobot. To achieve this, the aerobot will follow a power-science cycle, which follows this general cycle: the aerobot will descend to a lower altitude, gather data as necessary, ascend back, transmit data gathered, recharge the battery, and restart the cycle again. With a very limited amount of battery capacity and limited leftover power to charge the battery, it's necessary to follow this power-science cycle to efficiently allocate power while still achieving the mission goals.

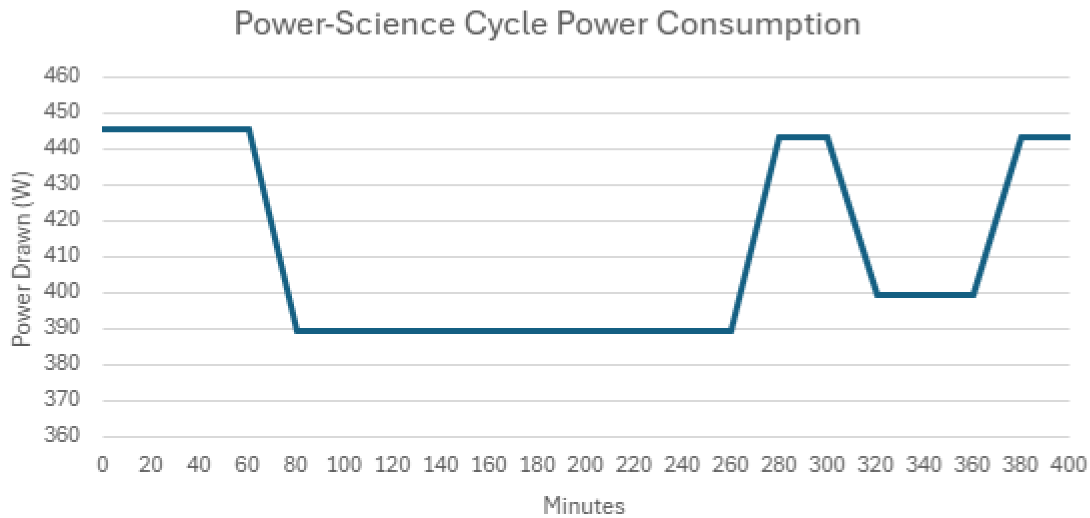


Figure 22: Graph of the power draw of a single power-science cycle

Note that the battery has a capacity of 800Whr and uses the power leftover from the aerobot at 70km. At that altitude, it takes around to charge the battery back to maximum capacity with the science and CDH subsystems turned off. During the descent, scene and CDH communications remain turned off to conserve power while the descent subsystem will draw an additional power to change altitude. Since the battery has a very limited capacity, the aerobot can only descend down to 60km. Data is expected to be stored during the time that the aerobot is lower in the atmosphere and transmitted when it's higher. This is to maintain signal integrity as the thick atmosphere also prevents radio signals from propagating from the high signal attenuation of the atmosphere. After science data has been gathered at 60km, the aerobot ascends and the cycle repeats again. This cycle aims to maximize the quality, quantity, and variety of data from the altitudes obtained in Venus' atmosphere.

2.1.2.2 Power Subsystem Requirements

Table 14: Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
PWR-1.0	The mission shall operate using a power source that is both efficient and lightweight	To meet the mission constraints (less than 50kg) and last the entire time that the mission is expected to take place	SYS-1.0	PWR-1.1 PWR-1.2 PWR-1.3	Inspection	Met
PWR-1.1	The power source shall achieve at least a 85% power efficiency when distributing power to subsystems	Ensures that most power is actually being used by the subsystems rather than wasted. Lithium ion batteries have a round-trip efficiency of around 85%-98%. As a conservative estimate, we assume the lowest part of this range	PWR-1.0	-	Test	Met
PWR-1.2	The battery shall have a mass less or equal to 5kg	Ensures that the power subsystems meets mission requirements to be less than 50kg	PWR-1.0	-	Analysis	Met
PWR-1.3	The power distribution board shall not exceed 0.5m x 0.5m	Ensures that the power subsystem fits inside of the Aerobot for room for other subsystems.	PWR-1.0	-	Analysis	Met
PWR-2.0	The power source shall last the entire expected duration that the system is in the air	To ensure that the Aerobot is powered if it lasts the entire mission duration	MISS-6.0	PWR-2.1 PWR-2.2	Demonstration	Met
PWR-2.1	The mission shall include a component to store at least 800 watt-hours	System must be able to power all components for the mission duration, which was found to require this many watts	PWR-2.0	-	Test	Met
PWR-2.2	The power source shall supply a peak of 250 watts	System must be able to power components as they are simultaneously running	PWR-2.0	PWR-2.2.1 PWR-2.2.2	Analysis	Met
PWR-2.2.1	The power source shall power the descent subsystem at a maximum of 10.5W at one time	10.5 watts is the max power that the descent subsystem will draw. Important for controlling the altitude	PWR-2.0	-	Analysis	Met
PWR-2.2.2	The power source shall power the thermal subsystem at a maximum of 50W at one time	50 watts is the max power that the thermal subsystem will draw. Important for ensuring that all electrical components stay within the operational temperature	PWR-2.0	-	Analysis	Met
PWR-3.0	The power source shall withstand	Aerobot should work even when exposed to	MG-1.0	-	Test	Met

	the atmosphere conditions of Venus	the harshness of Venus' environment				
PWR-4.0	The power subsystem shall include protections to protect the instruments and other components onboard	Improves the reliability of the whole system and ensures the instruments work	MG-1.0	PWR-4.1 PWR-4.2 PWR-4.3 PWR-4.4 PWR-4.5	Analysis	Met
PWR-4.1	In the event overvoltage or overcurrent, the power distribution system shall include current and voltage limiting circuits to protect other subsystems	Protect the components and instruments to ensure that the mission can persist	PWR-4.0	-	Test	Met
PWR-4.2	In the event of electromagnetic interference, the power source shall prevent sudden voltage or current spikes or dips to protect components	Protect system against electromagnetic interference	PWR-4.0	-	Analysis	Met
PWR-4.3	The mission shall include at least one other power source as redundancy	If the main power system fails, have a backup so that the mission can still carry on	PWR-4.0	-	Demonstration	Met
PWR-4.4	The power source shall remain above it's minimum depths of discharge to prevent capacity degradation	To ensure that the battery is in good condition and can still maintain capacity and provide nominal voltage	PWR-4.0	-	Inspection	Met
PWR-4.5	In the event of a voltage dangerously close to its minimum depth of charge, the power system shall enter a low power safe mode that preserves critical systems until the battery is charged	To protect the health of the battery and subsequently the instruments connected to it	PWR-4.0	-	Demonstration	Met
PWR-5.0	The power subsystem shall not cost more than 20M$ in total, which includes the cost of materials and any cost associated to integrate the power subsystems onto the Aerobot	To ensure that the cost to make the Aerobot meets mission requirements (<200M$)	PWR-4.0	-	Analysis	Met

These requirements outline the power requirements to ensure that all other subsystems obtain the necessary amount of power to operate and perform essential functions. Requirements PWR-1.X mainly focus on the high level overview of the dimension, mass, and efficiency requirements of the power subsystem. PWR-2.X requirements specify the necessary capacity of the battery and max outputs to ensure that the subsystem is able to provide that is needed for other subsystems. PWR-3.0 is in place to ensure that the power system can withstand the Venusian environment. PWR-4.X defines requirements to protect the battery and other subsystems from unpredictable electrical events. PWR-5.0 defines the max budget allocated to the power subsystem

2.1.2.2 Power Subassembly Overview

The power subsystem for the aerobot will be designed to provide a reliable and efficient power source to support all other subsystems, especially command and data handling components, science instruments, and the descent subsystem. Three subassemblies will be considered for the power system: solar panels for power generation, a lithium ion battery for energy storage and redundancy, and a power distribution board to ensure that all components obtain appropriate power and voltage levels. All three major subassemblies work to drive the power-science cycle and deliver the necessary power to all other subsystems.

2.1.2.2.1 Power generation through solar panels

The solar panel will be the main source of power for all subsystems while the aerobot is in the upper ranges of the atmosphere. After being released from the EDI system, the solar panels will deploy and immediately start generating power to supply the science instruments as well as recharging the battery if it is not at full capacity. The battery will be especially important when the aerobot is lower in the atmosphere, where sunlight is not as available as in high altitudes.

When the aerobot is at the higher altitude range the solar panels are expected to deliver 632.11 watts assuming optimal daylight conditions and considering an approximately 30% efficiency in power conversion; however, when the aerobot is lower in the atmosphere, the sunlight reaching Venus has a significantly higher diffuse horizontal irradiance (Geoffrey et al., 2013), preventing a significant amount of power generation from the solar cells. Since the aerobot is expected to maintain an altitude of around 50-70km another power source is necessary when the aerobot descends to the lower ranges since significantly less sunlight reaches this low. A lithium ion battery will be used when sunlight is not as available at lower altitudes and will also act as redundancy if the solar panel cannot provide sufficient power necessary. This will ensure that all science and data handling subsystems obtain sufficient power at all times during the 36 hour mission duration. Solar power will mainly be used when the aerobot is higher in the atmosphere and battery power will take over when the aerobot is lower.

For solar cell chemistry, multi-junction gallium arsenide solar panels will be used for their high efficiency and radiation-resistant properties which are ideal for Venus' low light environment and radioactivity from cosmic rays and other sources (Papez et al. 2021). Gallium arsenide solar cells in particular have been used in a multitude of space missions such as the International Space Station, the Hubble Space Telescope, and the Spirit and Opportunity rovers. Since they have been used in previous space missions, they have a high technology readiness level up to 9; however, for our specific implementation, the TRL will go down to 6 since it has been operated in a relevant environment, but has not been specifically implemented on our instrument yet in Venus' atmosphere.

Mechanically, since the solar panels will deploy from the aerobot; however, with the extremely high winds of up to 220 mph, it is necessary to ensure that the solar panels remain in operational condition to power all subsystems. Wind will introduce significant vibration and structural stress upon the solar panels, and a strong mounting system will be necessary to reduce the risk of mechanical failure and prevent potential electrical failures as well.

2.1.2.2.2 Lithium ion battery

The lithium ion battery will act as an energy reserve to store excess power from the solar panel and an additional battery will act as redundancy when solar power is not available or insufficient enough to power the other subsystems. At an altitude of 50 km or 60 km, a significant amount of sunlight is reflected or absorbed in the atmosphere and is a cause for concern since the solar panels are potentially unable to generate enough power for all subsystems; therefore, it is necessary to have a secondary power source to provide power at the lower altitude ranges to ensure that the science subsystem is able to perform its duties.

After an initial trade study, lithium ion batteries were determined to be the most suitable battery chemistry for its high specific energy, low self-discharge, operational temperature, and efficiency (Clean Energy Institute 2010). The high specific energy allows for a large amount of energy to be stored within a smaller mass, making it optimal to meet the 50kg max mission requirement. Additionally, low self-discharging is important to ensure that the battery does not use a significant amount of energy while not in use or discharge below its minimum depth of discharge, which is particularly important on the journey to Venus which will likely take several months. Furthermore, Venus is known for its high temperatures of up to around 464C (NASA) . With the thermal regulation system, lithium ion batteries will be able to operate within -20-50C ensuring that the battery remains operational. Lastly, lithium ion batteries have a high efficiency, meaning most power is delivered to the subassemblies instead of being wasted. This makes lithium ion batteries the optimal battery chemistry for this mission.

Lithium ion batteries are used extensively in space hardware such as probes, rovers, and especially cube satellites. For this reason, it has a high TRL -likely a 9; however, with TRLs being implementation specific, the TRL for our battery subassembly drops down to a 6. Again, while lithium ion batteries have been widely used in a variety of environments and launched space instruments, they have not been utilized in our specific aerobot implementation.

2.1.2.2.3 Power distribution

For the power distribution board, a custom board will be made to produce an electronic power system to convert solar power into usable electrical power. This board is mainly responsible for converting solar power to electrical power and also ensuring that the max efficiency is achieved while doing so.

To touch on the specific components likely onboard the electronic power system, several major components will likely be used. A maximum power point tracker is a major component on the board that will ensure the maximum power output from the solar panels by continuously adjusting the operating point such that the voltage and the current return the maximum output power. This will also ensure that no matter the altitude or weather, the solar panel is still able to maximize the power output. Maximizing the power generated saves valuable time. With only a 36 hour window, the aerobot must gather as much data as possible. Spending less time charging the battery so that the aerobot can descend into necessary altitude will help maximize the data collected.

DC-DC converters will also be used to step down or step up the voltage required for all subsystems. 28V, 12V, 5V, and 3.3V lines are likely to be included since these particular voltages are common for powering space instruments and microcontroller logic (for the lower voltages). Switching regulators (or buck/boost converters) will be used since they are the most efficient type of DC-DC converters. Low-dropout regulators will be avoided because of their high inefficiencies and additional heat generation. In general, electrical components that generate an excessive amount of each should be avoided as not only does that stress the thermal subsystem, but heat reduces the conductivity of PCB traces, which can affect the processing speed of the onboard computer and any other micro processing units. In addition to main power components, protections are needed to protect the health of the battery, the power subsystem itself, and other subsystems. External short protections, undervoltage, overvoltage, and overcurrent events are relatively likely to happen and is a significant risk that needs to be addressed to protect the science and CDH subsystems, especially including the battery, which is critical to the power-science cycle of the mission. A number of side-effects to the battery can happen, but the decrease in battery capacity is most likely and concerning since less time is allocated to the science and can potentially not allow the aerobot to descend or ascend to the necessary altitude to perform science missions. Additionally, catastrophic battery damage can result in the battery generating even more heat, swelling, and at the worst case, a fire hazard or explosion. Because of this, it is imperative that these protections are in place to maintain the health of the battery.

Most if not all types of components used in power distribution boards have been used in countless space instruments. Again, since they have not been used in our specific implementation but have been tested in various relevant environments, the components for the power distribution board will have a TRL of 6.

Table 15: Mass, dimensions, and power supplied/drawn for each subassembly

Subassembly	**Mass**	**Dimensions**	**Power draw/supply**
Solar panels	1.5kg	0.98m x 0.82m	522.54W
Battery	4kg	12.6cm x 12.6cm x	800W

		12.6cm	
Power distribution board	2kg	0.5mx0.5m	0W
Total	7.5kg		1332.54W

2.1.2.2.4 The Power-Science Cycle

To efficiently manage power while completing the science objectives, the aerobot will operate on a repeating power-science cycle to maximize the variety and quantity of data collected. It will follow a pattern of remaining in the higher ranges of the altitude range to charge the battery and power the subsystems and descending to the lower range as necessary for gathering science data to which the battery will take over as the sole power source. This cycle is necessary because of Venus' thick atmosphere, which prevents the solar panels from being able to operate at all altitude ranges, with the lower ranges having an insufficient amount of sunlight to power all subsystems from the solar panel alone. The lithium ion battery is necessary to ensure that the science subsystem can accomplish their science goals regardless of altitude. This cycle assumes that the science subsystem needs to go down to the lowest altitude range to perform its duties.

It is important to note that the average rate of altitude change achieved by the descent subsystem is 5m/s, meaning that to traverse the 20 km difference from the upper to lower bound of the altitude range (or vice versa) will take around an hour and seven minutes. The aerobot also needs to ascend high enough such that the solar panels are able to recharge the battery with two hours being the round trip time to go down and back up; however, the battery does not have enough capacity to down to the lowest 50 km altitude, so 60km will be minimum altitude the aerobot can descend before risking losing the aerobot entirely; however, with a capacity of 800Whr, the battery is expected to last the entire duration of this cycle.

Initially at the start of the cycle and assuming a fully charged battery, the aerobot will descend downwards to 60km, which will take around 30 minutes. After that, the science subsystem will be turned on to collect data at 60km for a little less than an hour. Then the aerobot will rise back up to 70 km. After the ascent all subsystems, except for the descent subsystem, will be on. Science will collect data at 70 km and CDH will transmit that data as well as the stored data from 60 km for an hour. Generally, while the aerobot is near the upper ranges of the atmosphere, the solar panel will act as the primary power source which will power all other subsystems for the time that the aerobot is in the upper atmosphere while also recharging the battery. With a capacity of 800Whr, the solar panel generating 632.11W per hour, and 242.61W left after powering all other subsystems, the battery will fully charge to its max capacity after around 3 hours and 20 minutes assuming optimal sunlight conditions. After that hour of collecting and sending data at the start, the CDH communications and science subsystems will be shutdown to speed up the process of charging the battery, to which the cycle starts over again with another descent. This means that the entire power-science cycle takes 6 hours and 40 minutes, meaning around 4 cycles for the entire expected 36 hour mission.

This structured cycle ensures that the aerobot can sustainably achieve its science objectives while efficiently maintaining effective power usage. This cycle also assumes that the aerobot will descend to the lowest available altitude as a conservative estimate for the expected duration of the power cycle; however, descending to such a range is not necessary. A higher minimum descend means that the power-science cycle can be lengthened, with the aerobot staying at the predetermined lower range even longer along with a shorter round-trip time for collecting data

2.1.2.2.5 Subassembly integration

The lithium ion battery, the solar panels, and the power distribution board all come together to make the power subsystem to generate, manage, and effectively deliver electrical energy to the entire system. The solar panels and batteries are connected to the power distribution board, to which the board also provides output connections to power all other subsystems while stepping down or up the voltages as necessary. The power distribution also ensures that the maximum power is outputted from the solar panels and distributes that power while also charging the battery as necessary. The board should also ensure that it's able to charge the battery as fast as possible without damaging the health of the battery to allow maximum data collection from the science team during the power-science cycle. Additionally, when the battery takes over as the main power source when the aerobot is at a lower altitude, the power distribution must be able to allow both power sources to power the subsystems, either one or both at a time. All three subassemblies come together to form the power subsystem and ensure that the aerobot can meet all its requirements.

2.1.2.3 Power Subsystem Recovery and Redundancy Plans

Redundancy and recovery plays a crucial role in this aerobot by ensuring reliability in that if a particular component or subassembly fails, the aerobot can still operate and complete its mission. Several plans are in place for the aerobot which include separating solar panels, having redundant battery packs, voltage protections, and a lower power mode.

Solar panels are one out of the two main power sources for the aerobot, and it is necessary to have a system to ensure that the aerobot still works even if a solar panel were to fail. Venus has very harsh winds and solar panels are directly exposed to winds as well as the chemical elements of Venus. Separating each solar panel and putting them in parallel with each other with their own maximum power point tracking and battery charging circuitry would help in recovery. This is in place so that if a specific section of solar panels fail, the other solar panels attached can still work and power the system. A series connection with the solar panels should be avoided since one non-working solar panel could potentially compromise the whole solar panel array. Maximum power point tracking circuitry will also be put on every solar panel string such that a failure in one string won’t affect the ability of the other solar panels to generate power.

In the same vein concerning power, a low power mode will be in place as recovery. The battery and solar panels are the main power sources of the aerobot; however, if for some reason, the power drops down to a level that is concerning such that the aerobot may be lost, a low power mode state will be induced. The low power mode can operate differently based on altitude and status of the other power subassemblies. For example, if the aerobot is at a low altitude with potentially not enough power to ascend normally, the aerobot will shut off power to all other subsystems and power only the descent subsystem. This is so that the aerobot can rise to an altitude with more sunlight so that the solar panels can recharge the battery and power all other subsystems. In the absolute, worst case scenario, where the battery and solar panels have completely failed, the aerobot will use the last of its power to ascend as high as it can go to avoid transmission issues with the thick atmosphere and send all of the data onboard before attempting recovery again. This is to ensure that all data is offloaded and that it's not lost when the aerobot potentially experiences a complete failure.

Voltage protections will also be in place on the power distribution board to both protect the battery as well as other subsystems in the event of a potential overvoltage or overcurrent occurrence. Protecting the battery is especially important because that subassembly component is what allows the aerobot to descend to the lower ranges of the available altitude range, which also returns valuable science data for the science subsystem. Typically, lithium ion battery cells have a minimum and maximum voltage of 3.0V and 4.2V respectively, with a 3.7V nominal voltage. Overvoltage and undervoltage protections will be put in place such that each cell will always be within that 3.0V to 4.2V range. Not putting these protections in place has harmful effects for the health of the battery. Charging the battery above its maximum voltage rating can potentially cause thermal runaway, potential fires or explosions, or severe electrolyte breakdown, which would not only generate more, but also affect the rest of the subsystems to function. On the other hand, letting the battery discharge below its minimum safe voltage can cause permanent capacity loss and make the battery completely unrecoverable, with no way to recharging the battery. These events make it necessary to have under and overvoltage redundancy systems to maintain the health of the battery so that the aerobot can perform its science mission.

2.1.2.4 Power System Manufacturing and Procurement Plans

The primary supplier for the system's solar cells will be CAVU Aerospace, providing their 32% Efficiency Triple Junction GaAs Solar Cells. They have proven flight heritage, which ensures that they meet the mission's power needs. All power calculations were done assuming around a third of the power generated is converted to actual, usable power, and these solar panels provide the closest estimate to that calculation. Additionally, these solar cells are chosen for their radiation tolerance and thermal stability, making them a good fit for the aerobot missions in the Venusian atmosphere. The high temperatures in the Venusian atmosphere pose a significant threat against the efficiency of the solar panels. While not necessarily catastrophic, this would severely limit the amount of data collected within the expected 36 hour time frame, so having a high thermal stability greatly preserves the efficiency and allows for the most data to be gathered. The lead time for these primary solar cells from CAVU Aerospace is approximately 12-16 weeks due to the manufacturing and testing process with a need for quotes as well.

However, in the event that CAVU Aerospace's solar cells become unavailable, Redhawk Aerospace's rigid solar arrays will serve as the backup. Redhawk Aerospace's solar arrays also have a proven heritage and provide good thermal stability as well. The backup rigid solar arrays from Redhawk Aerospace have a shorter lead time of around 4-6 weeks, as they involve custom manufacturing but require less extensive testing.

For the secondary power source, EnerSys' ABSL space batteries have been chosen for their space proven design, having been used in the James Webb Space Telescope and the recent Europa Clipper Mission, which are relevant since they demonstrate that these solar panels will work in a variety of environments. EnerSys specialize in energy systems for instruments and have a proven track record with other NASA missions, meaning that they have a high TRL for our mission. A commercial off-the-shelf battery was chosen instead of an in-house option since lithium ion batteries in particular have a wide range of quality options available for specific power requirements and extensively used in space with the ability to resist the harsh environments of Venus. These batteries have the necessary specific energy to deliver enough power while maintaining a relatively mass, perfect for meeting mission requirements. An expected 4-6 weeks is estimated as the turnaround time for these batteries.

For power distribution, the board (or some other power distribution unit) will have to be made in-house. This Aerobot has a very unique selection of instruments, all with different power requirements that an off-the-shelf PCB or other power distribution module will not meet. Additionally, a custom PCB will provide the best optimization of efficiency since components and circuitry can be made to maximize efficiency for our unique power requirements. Because of this, it's necessary to make a custom, in-house power distribution module for the Aerobot. Since this in-house design will be complex since it needs to meet the power requirements of all instruments and provide battery charging capabilities, it's likely to take 4-6 months to develop.

For secondary suppliers, several companies who also have a history of working with NASA were chosen as reliable backups in the event that the primary supplier is unable to deliver. Rocket Labs (another secondary), GS Yuasa, and Minco were chosen as solar panel, battery, and power distribution backups respectively. These companies are expected to have around the same turnaround time as the primary suppliers.

Rocket Labs' Z4J+ 4 Junction Solar Cells were chosen as another backup for the primary solar panels. They have an efficiency of 31.3%, which while it is slightly lower than the primary solar cells, it's of a reasonably low difference such that the mission, nor the power-science cycle of the power system would be significantly affected by this lowered efficiency. They offer a radiation hardened design with a good thermal operating range suitable for the aerobot.

GS Yuasa is a Japanese company specialized in lithium-ion batteries, which have been used in previous NASA missions. These batteries are able to meet the requirements of the aerobot, with a good specific energy to keep the lithium ion batteries relatively low mass while maintaining enough capacity to supply the other subsystems.

If the power distribution board cannot be made in-house for whatever reason, Minco Products will be contracted to make the PCB. Minco has worked with NASA in the past, specifically on its Voyager program, making their PCBs highly reliable in a space environment. Additionally, besides PCB design, they offer flexible boards with heaters and electronic components, which may be used in the final aerobot electrical design. Since the power distribution module will not be made in-house, it's expected to take slightly longer for the company to develop and then ship the module, which will likely add an additional 4 weeks on top of the expected in-house development time.

2.1.2.5 Power Subsystem Verification Plans

To meet the power requirements, a variety of verification plans will be implemented to ensure that the power subsystems meet all requirements. These include extensive electrical data gathering to verify that the power subassemblies are up to the task, basic inspection of dimensions and mass, analysis of electrical characteristics, and demonstrations of components ability to deliver power to all other subsystems. Each specific power requirement section is addressed using specific procedures to ensure that power subsystems deliver power and operate as expected even in the harshest of Venusian conditions.

For PWR-1.0 requirements, which are mass and efficiency requirements, a combination of analysis, inspection, and testing will be used. Inspections will be used to verify the dimensions of particular power subassemblies and to ensure that it is within the aerobots internal structure. Measurement tools and CAD models will be used to ensure that all power subassemblies will fit within the aerobot.

Analysis will be used for verification of the overall mass of the power subsystem using a combination of CAD and materials analysis to ensure that the final mass is as accurate to the expected mass of the system. These will not only include the subassemblies, but also include components such as wires, individual components, and mounting hardware so that the power subsystem as a whole is meeting the mass requirements of the power subsystem. Testing will be performed on the battery to ensure that it has at least a 85% round-trip efficiency rate using a charge and discharge efficiency test, which will utilize an electronic load and power supply to charge the battery and discharge through the load in a controlled discharge cycle using various discharge rates. Periodic timing data The results of this verification should ensure that the battery will not generate excessive heat or waste a significant amount of power.

Requirements for PWR-2.0 involve ensuring that the power subsystem is able to last the entire duration of the mission. All four verification methods are employed to ensure that the power system is able to provide enough power. A battery discharge test will be utilized on the battery to ensure that the actual capacity of the battery is enough to service the power-science cycle and to verify that the capacity is at least 800Whrs. In addition, an analysis of the maximum discharge rate will be done on the battery to ensure that it's able to meet the 250W maximum discharge rate, which in turn should also verify the sub requirements to power the thermal and descent subsystems. The discharge rate should simulate the expected draw to mimic the environment that the battery will be in to effectively measure the battery's performance.

PWR-3.0 specifies the requirements for withstanding the Venusian environment. Testing is necessary, which is likely to be done in a thermal and vacuum chamber to ensure that the aerobot is able to operate even while under high thermal and atmospheric conditions. These tests will expose the components to temperature ranges between 253.15 to 323.15 K, which is the expected temperature range that the thermal subsystem is expected to keep electronics within. Additionally, corrosion resistance tests may also be considered since Venus' has a high amount of sulfuric acid clouds.

Protections for the subsystem are especially important to have and act as a recovery for the power subsystem. PWR-4.0 requirements specify the necessary protections needed on the power distribution board. Tests, such as electromagnetic interference tests will be performed on the board and the wire harnesses to ensure that the system is able to resist ambient noise without malfunctioning or causing harm to other subsystems. Additionally, radiation tolerance testing will be done on critical board components such as the maximum power point tracker and other integrated circuits that transmit electrical data. Demonstrations will also be used to ensure that protection circuitry works in protecting the battery and other subsystems.

Lastly, PWR-5.0 specifies the maximum budget of the power subsystem. A budgetary analysis will be performed to ensure that the total cost, including parts and time of personnel, are within the maximum 20 million dollar cost allocated to the power subsystem.

Each subassembly within the power subsystem is expected to survive the Venusian weather conditions and reliability deliver power to the rest of the aerobot subsystems. Rigorous verifications processes on electrical and some mechanical aspects of the subsystem will be performed to verify that the subsystem meets each requirement listed in 2.1.2.1. Electrical simulations, analytical CAD modeling, and real Vensian environment simulations will be performed to provide an accurate assessment of how the subsystems will meet the requirements to ensure reliability in all phases of the mission.

2.1.3 CDH Subsystem Overview

The Command and Data Handling (CDH) subsystem is responsible for all collection, flow, and communication of data in the Aerobot. Each subassembly of the CDH Subsystem contributes a vital function toward the operation of the CDH Subsystem and the Aerobot as a whole. These subassemblies have been broken up into Processing, Storage, Communications (Antenna), Data Transfer (Transceiver), and Data Interfacing Subassemblies, respectively. Further detail into each subassembly's individual components will be covered under the subassembly overview.

The Processing subassembly interprets and executes all internal Aerobot commands. For instance, a low-power warning issued by the Power Subsystem will be handled promptly by CDH Processing, responding with the execution of low-power operation across the Aerobot. These commands are issued by the On-board Computer through the flight control software package.

Every 8.6 minutes (Appendix C), Processing facilitates a discrete data log to Data Storage using flight control software capabilities. The Storage subassembly is responsible for transferring data locally to the Data Transfer (Transceiver) subassembly, where the signal can be processed and determined where to be sent thereafter ("9.0 Communications - NASA," 2025).

As mentioned, the transceiver in the Data Transfer Subassembly is responsible for all flow of data that enters or exits the Aerobot to or from the Descent Subsystem or the Primary Spacecraft Orbiter. It takes input from Storage, processes the signal for transmission, and depending on execution commands from Processing, sends out the signal via antenna (to the orbiter) or via SpaceWire (to the DSS). If processing executes a command for receiving, the transceiver expects to receive a signal and will conduct appropriate signal processing on the received signal before passing it along to Processing.

Communications consist of the physical devices used to transmit data outside the Aerobot, for which the mission will utilize two main types: Radio Frequency (RF) and SpaceWire. RF, which represents the transmission of Ka-Band radio frequency signals (Baldwin et al. 2018), will be used to transmit data to the primary spacecraft orbiting Venus, where communication windows are short and far between, and speed, precision, and range is required for effective data communication. SpaceWire will primarily be used for intercommunication with the DSS, where a consistent data rate of 5 Mbps is required over a much shorter distance of ~0.25m, well under SpaceWire's constraints (STAR-Dundee 2020).

Lastly, Data Interfacing includes how data flows across subsystems. This is done through either electrical current, RF radiation, or digital commands (through SpaceWire). Digital commands are the main focus of logic and data interfacing of the CDH Subsystem, because of the subsystem's main responsibility of handling digital data.

After mission initialization from T=0 to T=1 (Step 8.1 of the Concept of Operations (ConOps)) (Section 1.5), the Aerobot begins its first descent down to an altitude of 50 km before collecting Payload data. This begins a periodic cycle where the Aerobot descends, collects science, transmits any stored data, and ascends to charge (where the solar panels offer higher efficiency at higher altitudes). This cycle is repeated until the end of the 36 hours at ConOps Step 8.6, where the CDH engages in a mode of continuous transmission to get as much data as possible to the orbiter and consequently back to Earth. The pseudocode presented under the Flight Control Software Sub-assembly goes into greater detail how these functions may be implemented.

The SAFC (figure 23) illustrates the above function and interaction within the CDH Subsystem. In addition, it details the flow of data within all subsystems of the Aerobot and the central role CDH plays in the flow of data around the system. CDH's Processing Sub-assembly serves as the main interface between inter-subsystem communication, with the flight software handling all execution of outbound commands, and the Onboard computer mainly handling the interpretation of inbound inputs from other subsystems. All commands, designated by black lines on the SAFC, will be facilitated through SpaceWire as a transmission medium, seeing as each subsystem is nearby and housed within the same chassis (with the exception of the DSS, which is still in contact with the Aerobot's chassis). Each subsystem's interaction with CDH is outlined below:

The Payload Subsystem is the most important in terms of data, taking all science and instrument data vital to the mission. Data from the payload is either continuously or discretely streamed to the Onboard Computer depending on the setting of measurement the instruments in the Payload Subsystem will be on (PAYL-6.0).

The Power Subsystem is heavily integrated with the CDH Subsystem as well, with the CDH constantly regulating power delivery via Pulse Width Modulation (PWM) commands based on power level readings reported by the Power Subsystem ("Microelectronics Evaluation. Pulse Width Modulator and Power Driver" 1967). In addition to the regulation of power delivery, the Power Subsystem is also responsible for providing modulated current to the current-dependent components within other subsystems; like resistive heaters that provide variable heat based on current. This modulated current is delivered based on executed commands by CDH.

The Thermal Subsystem requires less interaction with command and data handling, which is reflected by its fewer connections with the CDH Subsystem in the SAFC. The thermal sensors deliver a constant update of system and subsystem temperatures to the CDH in order for proper thermal monitoring. In addition, it includes the use of active resistive heaters, requiring modulated current delivered by electric cables routing from the Power subsystem to provide active and variable heating.

The Mechanical Subsystem consists only of passive components and requires no integration with commands and data handling.

Finally, the SAFC documents how CDH handles external communications beyond the Aerobot System; as mentioned in the overview of the CDH's Communication Subassembly, communication with the Descent Subsystem (DSS) and primary spacecraft orbiting Venus is required. This is achieved through constant transmission with SpaceWire for the DSS and a high-gain data transmission every 3 hours minutes when the primary orbiter makes a communications pass. The transmission signal encodes important science data as a log for easy access and retrieval by the primary spacecraft.

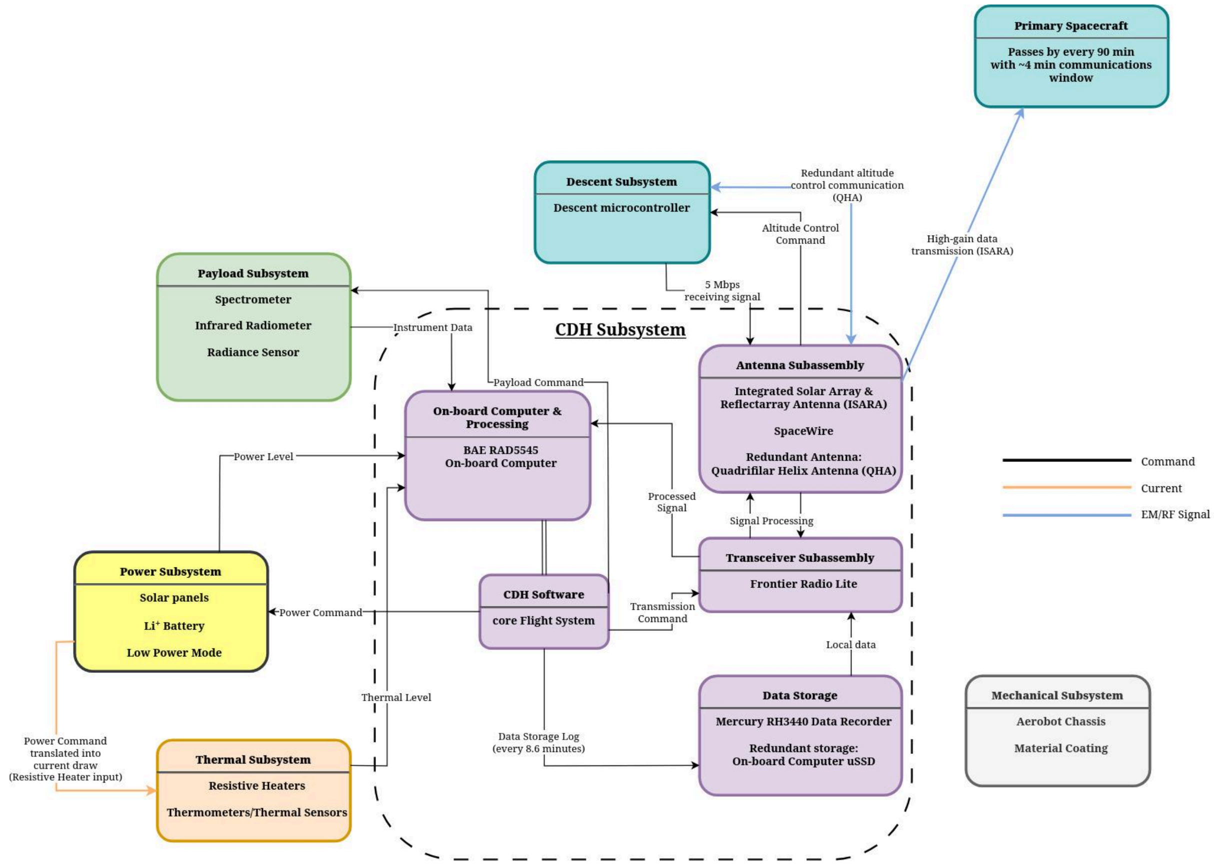


Figure 23: Software Architecture Flowchart

A summary of the Mass, volume, and Power of each subassembly in the CDH Subsystem has been included below.

Table 16: CDH Subsystem MVP table

CDH Subassembly	Mass (kg)	Dimensions	Max Power Draw (W)
On-board Computer	0.8	(170 × 110 × 18) mm³	35
Storage Device	0.62	(160 × 100 × 15) mm³	14
Communications	0.75	ISARA: (339 × 82.6 × 7) mm³ (stowed) SpaceWire: negligible QHA: (110mm diameter, 142mm height)	0.2 + 3 + 0.5

Data Transfer (Transceiver)	0.4	(152 × 96 × 10) mm^3	2

2.1.3.1 CDH Subsystem Requirements

The Command and Data Handling (CDH) subsystem is designed to ensure real-time data processing, secure communication, and efficient power management in Venus' harsh environment. Requirements are derived from mission constraints and validated through rigorous testing (Table 17). For instance, the Onboard Computer (OBC) must maintain a memory bandwidth of 100 MBps and an input-output bandwidth of 80 MBps, based on continuous data collection needs from spectrometers and imaging systems. Validation includes functional testing and performance benchmarking under simulated operational conditions.

Radiation hardening requirements, such as a Total Ionizing Dose (TID) of 5k rad[Si] and a Single Event Effect (SEE) rate under 1e-10 upsets/bit-day, are informed by models like SPENVIS (SPace ENVironment Information System) and OMERE (Outil de Modélisation de l'Environnement Radiatif Externe), with component selection verified through radiation exposure testing. Communication requirements, including a transmission antenna gain of 8-12 dBi and a 5 Mbps data reception rate, are based on link budget calculations using parameters such as orbiter altitude and X-band frequency, validated through signal testing and environmental simulations. Power constraints ensure a 55W average draw with a 30W low-power mode, tested through operational power profiling. These measures collectively ensure system resilience and mission success.

Additionally, recovery will be considered in the context of collected data. Data recovery protocols shall be included by the CDH Subsystem's requirements, which will be implemented in the form of logical data recovery protocols. This means that recovery protocols will be put in place to mitigate the effect of emergency or unforeseen events on software data. Further detail on recovery can be found in the Recovery and Redundancy subsection. On the other hand, physical recovery will not be implemented due to the mission's limited time of flight, as physical recovery can often take a duration on the order of weeks to months.

Table 17: CDH Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
CDH-1.0	The Aerobot's Command & Data Handling subsystem shall manage onboard command, execution, data storage, and mission control communication (internal and external) as close to real-time as possible	A capable CDH subsystem will be required to operate in the Venusian environment and send data through Venus' atmosphere	SYS-1.0	CDH-2.0 CDH-3.0 CDH-4.0 CDH-5.0 CDH-6.0 CDH-7.0 CDH-8.0 CDH-9.0 CDH-10.0 CDH-11.0 CDH-12.0 CDH-13.0	Demonstration	Met
CDH-2.0	The Command & Data Handling subsystem's Onboard Computer (OBC) shall be capable of real-time data processing and storage.	Many of the mission's payload instruments will record data continuously. The OBC must be able to facilitate processing the stream of input continuously as well.	CDH-1.0	CDH-2.1 CDH-2.2 CDH-2.3 CDH-2.4 CDH-2.5 CDH-2.6	Demonstration	Met
CDH-2.1	The On-Board Computer (OBC) shall execute software that is effective, efficient, and secure.	Software should be efficient and effective to best aid mission goals, while being secure from cyber risks.	CDH-2.0	-	Demonstration	Met
CDH-2.2	The On-Board Computer (OBC) shall be able to handle a Memory Bandwidth of 100 MBps and an Input-Output bandwidth of 80 MBps	This is the estimated bandwidth required from a continuous scan in two spectrometers and imaging systems.	CDH-2.0	-	Demonstration	Met
CDH-2.3	The On-Board Computer (OBC) shall include the use of a Real-Time Operating System (RTOS)	A real-time Operating System allows for real-time processing of all other subcomponents.	CDH-2.0	-	Inspection	Met
CDH-2.4	The On-Board Computer (OBC) shall allow for remote software updates.	This ensures the system can adapt to any unforeseen bugs and circumstances.	CDH-2.0	-	Demonstration	Met
CDH-2.5	The On-Board Computer (OBC) shall not weigh more than 1kg	The CDH Subsystem is allocated a total weight of 5kg to fit within costs and system integration. The OBC will be designated 20% of the weight, derived from baseline trade studies.	CDH-2.0	-	Inspection	Met

CDH-2.6	The On-Board Computer (OBC) shall not be larger than (200 × 150 × 25) mm^3	The Aerobot Chassis is determined as a sphere with radius 0.8m, and the CDH Subassemblies must fit within its designated constraints.	CDH-2.0	-	Inspection	Met
CDH-3.0	A transceiver shall facilitate inter-subsystem communication, accommodating appropriate transmit and receive rates while handling appropriate signal processing	The Command & Data Handling subsystems shall include suitable data interfacing to facilitate communication within the Aerobot's many subsystems.	CDH-1.0	-	Demonstration	Met
CDH-3.1	The transceiver components shall not weigh more than 1kg	The CDH Subsystem is allocated a total weight of 5kg to fit within costs and system integration. The transceiver will be designated 20% of the weight, derived from baseline trade studies	CDH-3.0	-	Inspection	Met
CDH-3.2	The transceiver shall not be larger than (175 × 100 × 20) mm^3	The Aerobot Chassis is determined as a sphere with radius 0.8m, and the CDH Subassemblies must fit within its designated constraints.	CDH-3.0	-	Inspection	Met
CDH-4.0	The Aerobot's Command & Data Handling System shall store data recorded from payloads in a storage device every 8.6 minutes.	This will store data over the 36 hours across 250 discrete logs, ensuring a balance between volume, processability, and redundancy (Appendix C).	CDH-1.0	CDH-4.1 CDH-4.2 CDH-4.3	Demonstration	Met
CDH-4.1	The Aerobot's Command & Data Handling System shall accommodate at least 2 GB of data from payloads	Data size calculated for each payload instrument using (16 bits/channel * (spectral range/spectral resolution) channels)	CDH-4.0	-	Demonstration	Met
CDH-4.2	The data storage system shall not weigh more than 1kg	The CDH Subsystem is allocated a total weight of 5kg to fit within costs and system integration. Storage will be designated 20% of the weight, derived from baseline trade studies	CDH-4.0	-	Inspection	Met
CDH-4.3	The data storage system shall not be larger than (200 × 100 × 20) mm^3	The Aerobot Chassis is determined as a sphere with radius 0.8m, and the CDH Subassemblies must fit within its designated constraints.	CDH-4.0	-	Inspection	Met

CDH-5.0	The Aerobot's Command & Data Handling subsystem shall communicate with the primary spacecraft orbiting Venus during the 36 hours of descent	The Aerobot will not be recoverable, so the data has to be transmitted during its window during the descent. A trade study will be conducted to decide between transponders and antennas for data interfacing.	CDH-1.0	CDH-5.1 CDH-5.2 CDH-5.3 CDH-5.4 CDH-5.5 CDH-5.6 CDH-5.7 CDH-5.8 CDH-5.9	Demonstration	Met
CDH-5.1	The Command & Data Handling's transmission antenna shall achieve a signal gain of 8-12 dBi	Gain is derived from orbiter altitude (200-300km), Aerobot operational altitude (50-70km), Frequency (Ka-Band), and an uplink rate of 5-10 kbps (Pasternack Link Budget Tool). Also see Appendix C.	CDH-5.0	-	Analysis	Met
CDH-5.2	The Aerobot’s Command & Data Handling receiving antenna shall achieve a signal gain of 3-6 dBi omnidirectionally	Low gain allows for a wider coverage, which would be ideal to account for motion handling and reliable communication with the DSS, which is relatively near to the Aerobot.	CDH-5.0	-	Analysis	Met
CDH-5.3	The CDH receiving System shall maintain minimal variation in signal gain within Venus' temperature extremes and TID and SEE ionization effects.	The hazards on Venus can greatly affect signal gain in the CDH's communication components.	CDH-5.0	-	Test	Met
CDH-5.4	The Aerobot’s Command & Data Handling's Receiving System shall be able to receive data at a rate of 5 Mbps or 625 ksps	The DSS will transmit data at a constant rate of 5 Mbps = 0.625 ksps; transceiver rates are reported in sps, so the conversion will prove convenient.	CDH-5.0	-	Demonstration	Met
CDH-5.5	During the 36 hours, the CDH subsystem shall transmit stored payload data to the primary spacecraft at intervals multiples of 90 minutes, within ±30 seconds interval variation	The ConOps details planning for communication windows every 3 hours (90 minutes multiplied by 2). Assuming the orbit is approx. 200km, the calculated window is 32 seconds (Appendix C).	CDH-5.0	-	Demonstration	Met
CDH-5.6	The Command & Data Handling subsystem shall not receive or transmit data while the descent system is changing altitude	The DSS requires that data is not sent during the process of altitude change.	CDH-5.0	-	Demonstration	Met
CDH-5.7	At the end of the 36 hours, the Aerobot shall transmit data one last time to the orbiter	To ensure all data is collected, one final transmission shall be sent	CDH-5.0	-	Demonstration	Met

CDH-5.8	The antennas combined shall not weigh more than 2kg	The CDH Subsystem is allocated a total weight of 5kg to fit within costs and system integration. The antennas will be designated 40% of the weight, derived from baseline trade studies	CDH-5.0	-	Inspection	Met
CDH-5.9	The antennas combined shall not be larger than (500 × 150 × 200) mm^3 before being deployed (in stowed form)	The Aerobot Chassis is determined as a sphere with radius 0.8m, and the CDH Subassemblies must fit within its designated constraints.	CDH-5.0	-	Inspection	Met
CDH-6.0	The Aerobot’s Command & Data Handling subsystem shall adjust its power consumption depending on operation.	Power draw is an important constraint of the mission, and the Command & Data Handling Subsystem needs to work well with the power subsystem to ensure efficient operation.	CDH-1.0	CDH-6.1 CDH-6.2 CDH-6.3	Demonstration	Met
CDH-6.1	The Aerobot’s Command & Data Handling subsystem shall not draw more than 70 Watts of power maximum	Max power constraint	CDH-6.0	-	Inspection	Met
CDH-6.2	The Aerobot’s Command & Data Handling subsystem shall not draw more than an average 55 Watts of power	Average power constraint	CDH-6.0	-	Inspection	Met
CDH-6.3	The Aerobot’s Command & Data Handling subsystem shall retain critical function while not drawing more than 30 Watts of power in the Aerobot's minimum power mode	The power subsystem includes a low-power mode in which the CDH subsystem must remain in control of critical functions in order to maintain the Aerobot's ecosystem.	CDH-6.0	-	Demonstration	Met
CDH-7.0	The Aerobot's Command & Data Handling System shall maintain a temperature of 308 K, with a fluctuation threshold of 35 K, regardless of external temperatures.	Computer hardware is extremely sensitive to temperature; the Aerobot's computer hardware systems need to withstand Venus' extreme temperature extremes ranging from as low as 165 K to as high as 400 K.	CDH-1.0	-	Analysis	Met
CDH-8.0	The Aerobot's Command & Data Handling System shall withstand the resonant vibration frequencies in the kHz range and shock events up to 50g.	Pyroshocks that arise from separation from the primary spacecraft can cause short, high-frequency, high-amplitude shockwave vibrations. It is vital that the onboard electronics can withstand these.	CDH-1.0	-	Test	Met

CDH-9.0	The Aerobot's Command & Data Handling System shall undergo Radiation Hardened Assurance (RHA) to ensure its components can withstand extreme radiation levels on Venus.	Solar and cosmic rays bombarding Venus' relatively weak atmosphere can penetrate the spacecraft's body, interfering with the CDH Subsystem. This is detrimental to all communication and electronic components on the Aerobot and must be accounted for thoroughly.	CDH-1.0	CDH-9.1	Analysis	Met
CDH-9.1	The Command & Data Handling Subsystem shall include an On-board Computer that is radiation hardened for a Total Ionizing Dose (TID) of 5k rad[Si] and Single Event Effects (SEE) and under 1e-10 upsets/bit-day. (Herbst et al. 2020)	Converting ion pair values into TID and SEE values using models like SPENVIS and OMERE, values for Venus' atmospheric radiation can help derive the required values for optimal operation under such radiation effects.	CDH-9.0	-	Test	Met
CDH-10.0	The CDH shall be capable of continuing data processing and communication during periods of Venusian dust storms, with minimal impact on the system's power consumption and communication latency	Dust winds have the potential to interfere with communication signals and increase latency. The CDH Subsystem shall mitigate this to best achieve mission goals.	CDH-1.0	-	Test	Met
CDH-11.0	The Aerobot's Command & Data Handling System shall withstand any electromagnetic storms in Venus' atmosphere	Electromagnetic storms occur at 40-60 km altitude in Venus' atmosphere; the electronic components in the CDH Subsystem must be able to withstand them should the Aerobot encounter one.	CDH-1.0	-	Test	Met
CDH-12.0	The CDH system shall include secondary communication and storage devices to ensure continuity in case of primary subassembly failure	Redundancy of these devices is important to ensure minimal data is lost in the case of loss of components.	CDH-1.0	-	Inspection	Met
CDH-13.0	The CDH Subsystem shall include logical data recovery protocols to preserve collected data. No physical data retrieval protocols shall be implemented.	Logical data recovery is vital to ensuring data makes it back to earth reliably in the case of unforeseen events. Physical recovery is beyond the scope of the mission's schedule.	CDH-1.0	-	Demonstration	Met

2.1.3.2 CDH Sub-Assembly Overview

Computing Subassembly: On-board Computer

The processing unit in the CDH Subsystem is handled entirely by BAE Systems' RAD5545, a radiation-hardened on-board computer with multiple processing units. The OBC handles simultaneous input from the Thermal, Power, Mechanical, and Payload Subsystems, as well as the Transceiver Subassembly and processing output through the computing software. The multiunit processor aboard the RAD5545 will take in all data input from other subsystems and process them into the necessary commands and directives for the control software to execute, as detailed in the block diagram in figure 24. Additionally, a thermal subassembly with cooling and heating capabilities will also be applied to keep the RAD5545 within the operationally defined 218-398 K range (BAE Systems 2019).

The OBC includes 12 SpaceWire links capable of 320 Mb/s each, as well multiple memory units facilitated by field programmable gate arrays (FPGAs) to facilitate logics in the OBC (BAE Systems 2019). The features of the RAD 5545 OBC offers a streamlined integration of the component with the CDH Subsystem as a whole.

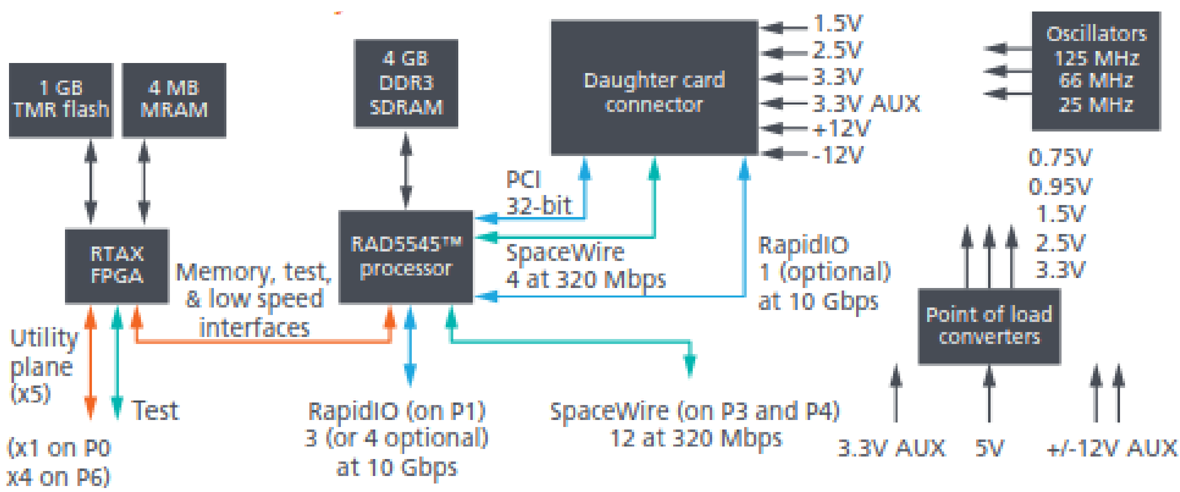


Figure 24: Hardware Block Diagram of the RAD 5545 (BAE Systems 2019)

The RAD 5545 is the multiunit successor of the RAD750, both OBCs having many considerations for spaceflight applications taken into consideration and developed from a history of applications in space missions. With a TID tolerance rating of 100 Krad (Si) and a SEE tolerance rating of 1e-3 upsets/card-day (BAE Systems 2019), it well exceeds radiation hazard requirements. Through its multi-core processor, studies have also shown its high performance of memory and I/O bandwidth parameters (**Fig []**), well exceeding computational requirements.

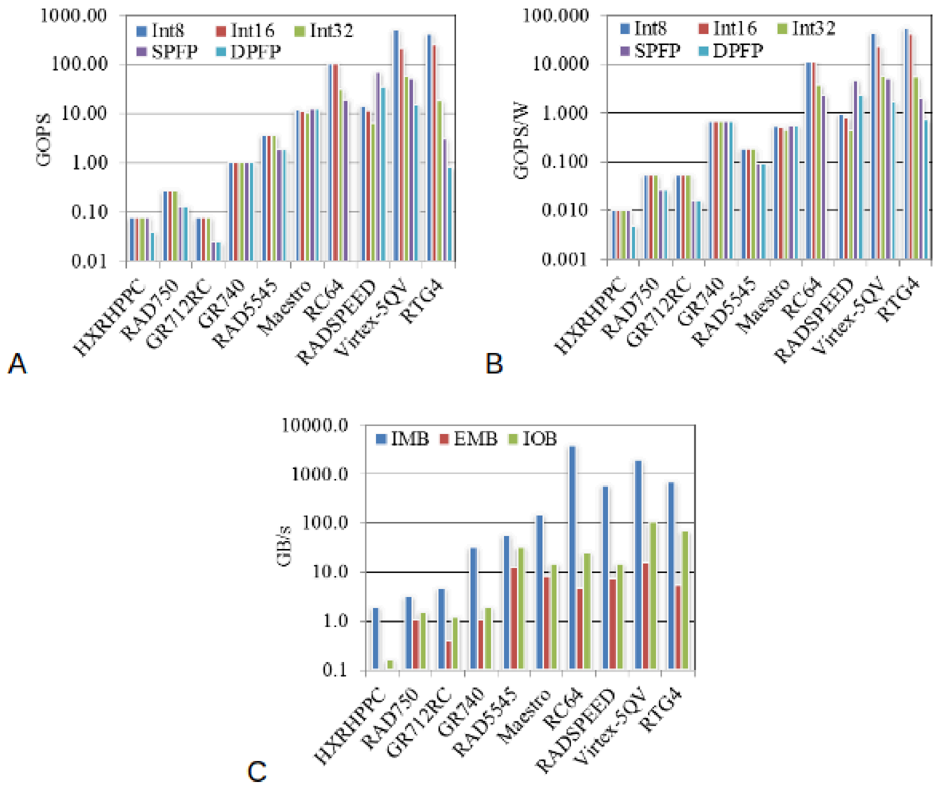


Figure 25: Comparative analysis of Computational Density (A), Computational Density per Watt (B), and Memory Bandwidths (C)

Figure 25 above describes how the RAD 5545 and its predecessor, the RAD 750, are compared side-by-side (Lovelly et al. 2017)

The combination of a well-established product framework in deep-space applications as well as its high performance across subsystem requirements (determined by baseline trade studies), the OBC yields a high TRL.

TRL: 5

Computing Subassembly: Flight Control Software

NASA's core Flight System (cFS) software will be used by the Aerobot to handle the execution of all outgoing commands to the Thermal, Power, Mechanical, and Payload Subsystems, as well as the Transceiver Subassembly. cFS will serve as the bundle for all other software required for interfacing with hardware, taking care of abstraction, platform support, and flight executives (NASA 2025). It will also be responsible for administering updates, both real-time and planned, to the mission during operational emergencies and failure, like switching over to redundant components. Below documents sample pseudocode for the core Flight System to execute to ensure that the Aerobot operates according to the mission's Concept of Operations (ConOps). Comments documenting the logic and flow of the pseudocode are denoted with a "#" at the beginning of the line.

```
### BEGIN PSEUDOCODE
# Initialization at mission commencement (ConOps Step 8.1)
read power draw levels (repeat forever)
read thermal sensor levels (repeat forever)

# Communication initialization
if altitude is changing according to DSS:
      pause all subsystem command execution until done
else:
      if comms with orbiter AND ISARA not broken/corrupt:
          use ISARA
      if comms with DSS AND SpaceWire not broken/corrupt:
          use SpaceWire
      else:
          use Quadrifilar Helix Antenna

# Payload initialization
Begin storing Payload data every 11.5 minutes

# Communication, Payload, and Power management
# Based on calculations done in the ConOps, if transmission happens 1 hour after
descent, the first transmission occurs at T=3hr in, making the 90 minute window.

if time elapsed since end of last descent >= 1 hour:
      Execute data transmission to orbiter

      if battery level < 10%:
          shut off power to transceiver, antennas

      begin recharge using solar panels
      pause payload measurement
      issue altitude change command to DSS to begin ascent to 70 km altitude

# With the descent and ascent taking 1hr each, every descend-measure-ascend-charge
cycle takes ~3 hours.
# 3 hours each cycle => 3 hours between orbiter transmissions meaning the
transmissions make the 90 minute windows for orbiter passes.
# More details can be found in the CDH Subsystem Overview.

if time since charge begin >= 1 hour:
      if antennas, transceiver off:
           restore power to transceiver, antennas
      issue altitude change command to DSS to begin descent to 50-60 km altitude
```

```
      resume spectrometer, photodiode, IR irradiance measurement

# Thermal management
if temperature sensed by thermal sensors < 290K:
      issue power command to activate a resistive heater
else if temperature sensed by thermal sensors > 310K:
      issue power command to shut off a resistive heater
else:
      maintain current in resistive heaters

# Final transmission (ConOps Step 8.6)
Final hour of mission:
      Execute continuous transmission of stored data

### END PSEUDOCODE
```

Figure 26: Pseudocode

The core Flight System has been used in multiple NASA missions like the Artemis Program and Project Morpheus (NASA 2012) while remaining extremely modular and mission-independent to allow for tailoring to different applications.

TRL: 7

Storage Subassembly

The Storage Subassembly is a vital part of this mission, as science data collected by the Payload will need to be stored before it can be transmitted at the right time during a comms pass. Storage on the Aerobot is handled by a primary Mercury RH3440 440 GB radiation hardened data recorder and a secondary, redundant 1 GB storage on board the CDH On-board Computer. The RH3440 is radiation hardened to protect itself from Venus' harsh environment and offers Error Correction Code (ECC) to mitigate data integrity being affected by radiation effects and events. Responsible for storing data every 8.6 minutes, the storage device will also uplink data to the transceiver every 3 hours during the orbiter's communication pass. A thermal subassembly with cooling and heating capabilities will also be applied to keep the RH3440 within the operationally defined 233-345 K range (Mercury Systems, Inc 2021).

The RH3440 has been specifically defined for harsh environments like Venus, with various applications in nuclear to LEO satellites. It is a strong choice with many built-in failsafes to mitigate hazardous effects.

TRL: 6

Communications: Antenna Subassembly

The Antenna Subassembly consists of two different antennas: a high-gain, highly directional antenna, and a low-gain, redundant, omnidirectional antenna. It also includes the use of SpaceWire for short-distance communications with the DSS.

For communications with the primary orbiter, the Integrated Solar Array and Reflectarray (ISARA) achieves a high gain of up to 33.5 dBi at 26 GHz and 100 Mbps uplink rate (Hodges et al. 2015). The ISARA is stowed as three flat panels folded onto each other with dimensions (339 × 82.6)mm^3 before unfurling after launch and deployment.

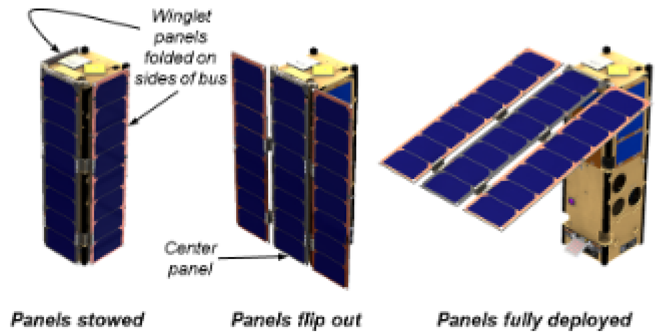


Figure 27: The deployment of the ISARA Reflectarray on a CubeSAT (Hodges et al. 2015).

The gain of ISARA is achieved by the panels that serve as solar arrays on one side and reflectarrays on the other. When unfurled, the solar arrays absorb solar energy to provide power for the Aerobot, while the reflectarray reflects RF signal onto or from a small panel feed (depending on reception or transmission), allowing it to achieve a very high gain without any substantial increase in weight (figure 27).

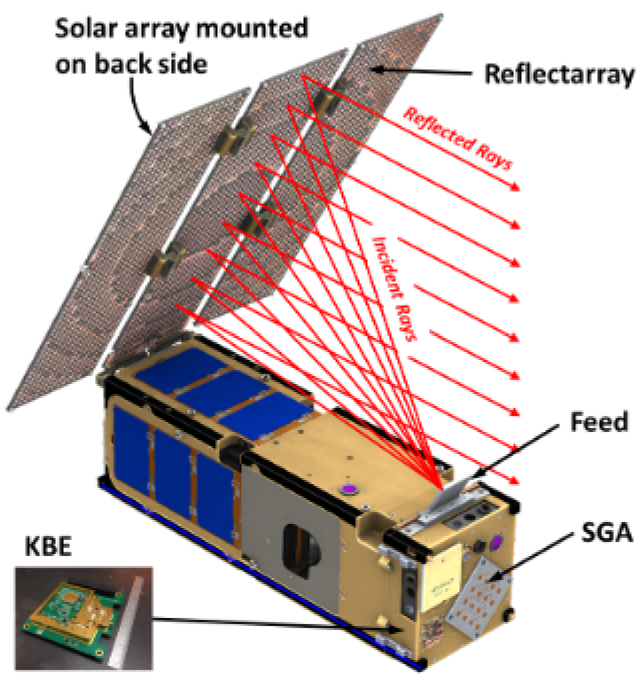


Figure 28: Feed and panel mount configuration of the ISARA on a CubeSAT (Hodges et al. 2015).

The ISARA has been used previously in multiple CubeSAT missions as well as the Cygnus resupply mission (NASA 2023), and is designed to integrate well into small form factors. However, it has not been previously tested for specific Venus environments and thus earns a TRL of 4.

TRL: 4

Communications with Aerobot's Descent Subsystem (DSS) does not require a dedicated antenna as due to its close proximity to the chassis that houses the CDH's transceiver (0.2 - 0.3 meters apart). SpaceWire routing from the DSS to the Aerobot will thus provide quick and efficient communication with the DSS. With data transfer capabilities of up to 400 Mbps (STAR-Dundee 2020), and interface integration support with the RAD 5545 OBC, SpaceWire far exceeds the DSS' requirement for a constant 5 Mbps data link rate.

The SpaceWire will be routed in the space between the Aerobot chassis and DSS, along the Inconel cables that hold the two together. This allows for use of redundant space inside the protective cable cladding, as well clever use of the already robust architecture of the Mechanical Subsystem to take advantage of SpaceWire's capabilities. Figure 29 shows said cables the SpaceWire will be routed along.

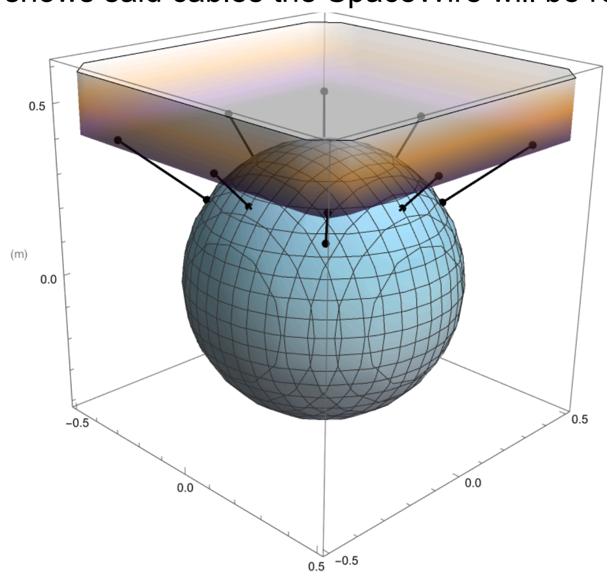


Figure 29: 3D sketch of the Aerobot's attachment with the DSS using Steel alloy cables (not to scale).

In Figure 29, the SpaceWire will be routed along these cables, under the protective cladding to serve as an interface between CDH and the DSS.

SpaceWire will also be used for data interfacing within the CDH Subsystem and between the different subsystems. A robust technology having been implemented in the SPRINT-A satellite mission to Venus' atmosphere (STAR-Dundee 2019), SpaceWire achieves a very high TRL.

TRL: 6

Being the most important subassembly to ensure collected data can make it back to the primary spacecraft, a lower gain, deployable Quadrifilar Helix Antenna (QHA) has been included for redundancy. It achieves a gain of ~4 dBi (Kim et al. 2016), allowing it to achieve operable communication with the primary spacecraft (provided some margin of error) while preserving DSS communications should the SpaceWire fail. Figure 30 shows the gain radiation pattern of a QHA designed with right-handed helices, providing optimal gain in transmitting right-hand circularly polarized fields (RHCP). NASA's transmission and receiving protocols typically define RHCP as a standard (Cermak 2025) and thus will serve as the foundation for the QHA's design. The QHA will therefore be mounted on the +Z face of the Aerobot facing the DSS and along the presumed direction of the primary spacecraft during communications windows. The QHA serves as a sufficient redundant component for communications with the primary orbiter because signal attenuation due to Venus' atmosphere is approximately 0.50 dB at S-Band frequency ranges (Du Toit et al. 2019), for which the QHA is fully capable of achieving (Figure 30).

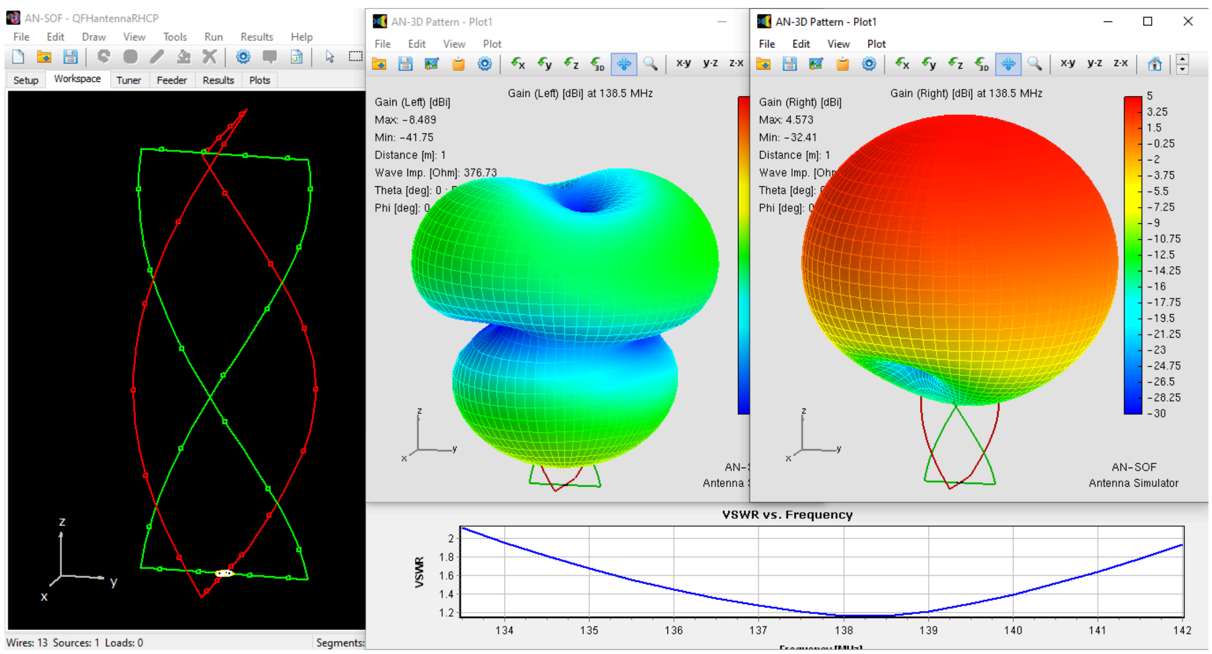


Figure 30: A QHA Antenna Model (Left) and its plots of Left-hand Polarized Gain (Center) and Right-hand Polarized Gain (right)

Figure 30 above is analyzed using the AN-SOF Antenna Simulation Software. Red indicates up to +5 dBi gain, green indicates ~-15 dBi, and blue indicates -30 dBi gain. (Golden et al. 2022)

Deployable QHAs have been employed and tested on multiple space missions with CubeSats, albeit never on a Venus mission, warranting a TRL of 4.

TRL: 4

Communications: Transceiver Subassembly

The Transceiver Subassembly consists only of one transceiver, Johns Hopkins' Applied Physics Laboratory's Frontier Radio Lite, responsible for interfacing with the Antenna Subassembly to transmit, receive, and process all incoming and outgoing signals. The Frontier Radio Lite uses Field Programmable Gate Arrays (FPGA) and a pair of analog-digital converters interconnected with space wire to filter, amplify, and process incoming transmission signals and outgoing data signals, as shown in figure 31 (O'Neill et al. 2018). It is rated for up to 20k Rad[Si] with Single Event Upsets (SEU) protection. In addition, it handles incoming transmission commands as directed by the flight control software (core Flight System) as well as preparing local data from the Storage Subassembly to transmit to the primary orbiter every 3 hours. (CDH-5.5)

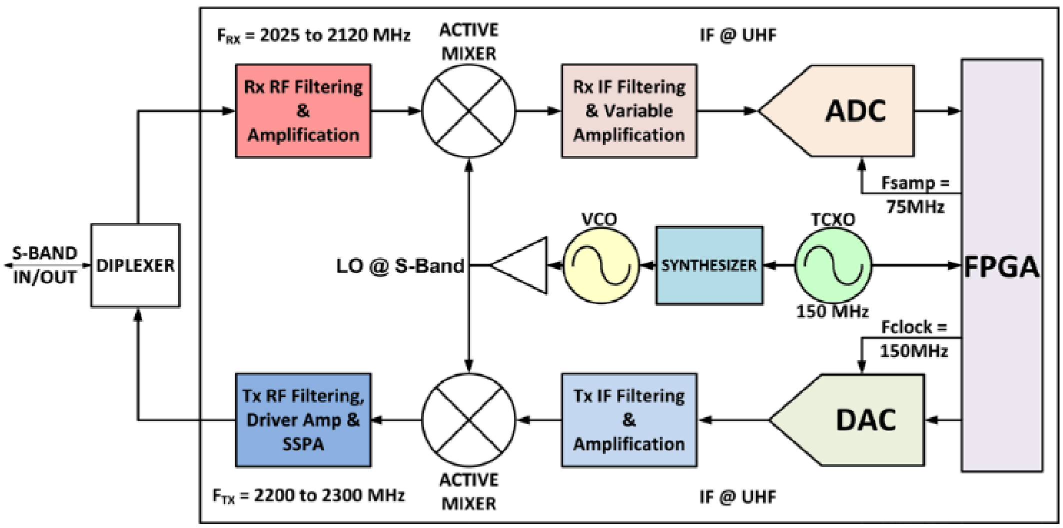


Figure 31: Simplified Block Diagram of the Frontier Radio Lite (O'Neill et al. 2018)

The Frontier Radio Lite is part of a line of Frontier Radio products developed by JHU's APL and has been used in several deep space and high radiation applications like Europa Clipper, Van Allen Probes, and Solar Probe Plus (O'Neill et al. 2018) Because the scope of this mission is not within its heritage, the TRL has been dropped to a 5.

TRL: 5

Table 17: TRL table of CDH Subassemblies

CDH Subassembly	***TRL***
On-board Computer	5
Software Package	7
Storage	6
Primary Antenna: ISARA	4

SpaceWire	6
Redundant Antenna: QHA	4
Transceiver	5
Overall CDH	**4**

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans

The CDH subsystem's primary concern regarding recovery and redundancy is the assurance that all collected data is able to make it back to the primary orbiter. This constitutes two main subassemblies: The local storage drive and the communications responsible for communicating with the primary spacecraft orbiting Venus. As such, a redundant antenna with medium gain and wide beamwidth and a redundant data recorder with 1GB (aboard the On-board Computer) has been included into the CDH Subsystem.

Recovery is primarily taken into account with the use of core Flight System's bundling framework that allows for implementing rollback and failsafe frameworks directly implemented into it. These frameworks include the operational scenarios for Health & Safety, Fault Detection, and File Management (NASA 2025). In the case of recovery, core Flight System will implement recovery executives as part of its frameworks depending on the scale and severity of the scenario. In addition, the use of checksums ("Archiving, Distribution, and User Services Requirements Document (ADURD)" 2025) in the core Flight System ensures detection of any faults in data in the memory regions by conducting Cyclic Redundancy Checks (CRCs) (NASA Github, n.d.).

In addition, Electromagnetic Interference (EMI) can pose an issue with the interference of internal and external communications, introducing noise and compromising data and signal integrity (Kumar et al. 2023). Examples in literature have used strategic shutoff of components producing EM radiation (antennas, high-frequency carrying wires) in order to minimize the noise and interference from EMI (Howard 2018, Sweeney 2014). Software functions will be planned to be implemented for similar strategic shutoffs to reduce signal noise. The combination of measures maximize the integrity of data within the CDH Subsystem.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans

The Command and Data Handling (CDH) subsystem will rely primarily on contracted components, with few commercial off-the-shelf (COTS) parts. This decision is based on extensive mission heritage, proven integration capabilities, and the need for components to withstand Venus' extreme environment.

I—OBC: This mission has designated BAE Systems as the primary supplier for the on-board computer (OBC) component. BAE Systems is an industry leader in aerospace and defense, with its RAD 750 processors having been adapted as an integral part of many space missions. The RAD 5545 OBC offers a step above that, with multi-core processing and SEE and TID radiation hardening well above the requirements for Venus (BAE Systems 2019). Their OBC offers seamless integration with the spacecraft's architecture while meeting stringent computational and reliability requirements. While it theoretically surpasses CDH requirements, marginal testing and adapting is expected to be done for the RAD 5545 OBC, with an expected lead time of 5-6 months, including software integration of the core Flight System.

As a backup, Cobham (subsidiary of Frontgrade) has been identified as an alternative supplier. Cobham's OBCs ("RadHard & HiRel Components for Space | Frontgrade," n.d.) are comparable in performance to those from BAE Systems; however, integration with the spacecraft may require additional adaptation, leading to potential delays. Switching to Cobham could introduce an additional 1–3 months for integration testing and system validation.

II—Transceiver: The CDH subteam has selected Rocket Lab / Johns Hopkins Applied Physics Laboratory (JHU APL) as the supplier for the Frontier Radio transceiver. This transceiver, developed by JHU APL, features a high technology readiness level (TRL) and has demonstrated exceptional performance in past space missions. Its robust design makes it well-suited for the harsh conditions of Venus, ensuring reliable communication throughout the mission. Because of its mission heritage and robust historical testing, The estimated lead time for procuring the transceiver from JHU APL is 4-5 months.

In the event that JHU APL is unable to supply the transceiver, the team will manufacture it in-house using the open-source design. This will be done at NASA's Glenn Research Center (GRC) along with subsystem testing (Section 5.3.6), as GRC offers substantial technological expertise and experience with communications devices (NASA Glenn Research Center 2023). While this provides a viable backup option, it would significantly extend the timeline due to the need for in-house engineers to fabricate, integrate, and test the system. This would extend lead times to 6 months and beyond due to design adaptation and validation requirements.

III—Data Storage: Mercury Systems has been determined as the contractor for the CDH Subsystem's data recorder. They are the only manufacturer that includes clear specifications for radiation harding, and ecc correction, as well as manufacturing products with sufficient storage space to account for emergency cases and descope (Mercury Systems, Inc 2021). It surpasses most CDH storage requirements, exhibits a higher TRL compared to other components, and performed nominally in baseline trade studies, warranting lead times of 4-5 months.

Curtiss-Wright provides a solid secondary option due to historical experiences working with government agencies on technical data management (Curtiss-Wright, n.d.). NASA's NPD 1370.1 clause informs the mission choice not to compete with the private sector, and Curtiss-Wright will be used in case of emergency, being the closest competitor to Mercury Systems with radiation hardening capabilities (Curtiss-Wright, n.d.). The lead time if needing to use the Curtiss-Wright would push lead times past 6-7 months.

IV—Primary Antenna: This mission requires close collaboration with NASA/JPL to develop the ISARA integrated reflectarray for Venus use. This is a proprietary NASA design not available for production anywhere else. There is no backup supplier, which means the mission relies on in-house development to produce the subcomponent. The lead time will range from 7-8 months and the lack of a secondary adds another 5 months to the team's timeline for design, fabrication, and testing of the part.

V—SpaceWire: For communications with the DSS, the CDH Subsystem will require the integration and facilitation of SpaceWire. The mission will rely on STAR-Dundee as a primary supplier for SpaceWire, being one of the leading suppliers in the aerospace industry as well as a background in SpaceWire integration products. SpaceWire would require a much shorter lead time of approximately 2-3 months due to its easy-to-implement nature.

Cobham is a trustworthy secondary option as a well-established provider of high-reliability space electronics. Like STAR-Dundee, they also have a background in the production of SpaceWire integration products, and their designation as the OBC subcomponent's secondary manufacturer allows for streamlined communication should the primaries for these subcomponents not work out. Opting for the secondary option would add a lead time of about 2-3 months, seeing as SpaceWire is a less complicated technology to integrate, test, and implement.

VI—Redundant Antenna: For the redundant deployable Quadrifilar Helix Antennas (QHAs), the CDH subteam has partnered with Anywaves as the primary supplier. Anywaves has extensive experience designing high-performance antennas for missions ranging from low Earth orbit (LEO) to deep space. Their QHAs provide reliable communications, supporting operational requirements from near-hemispherical coverage to narrow beamwidths across a frequency range of 400 MHz to 3000 MHz. Additional testing, integration, and adaptation is required for application to Venus' atmosphere, bringing lead times up to 6-8 months.

As a backup, the team has identified Helical Communication Technologies (HCT). While HCT specializes in LEO applications, they have demonstrated expertise in manufacturing antennas with robust performance characteristics. If procurement from Anywaves is not feasible, HCT's solution can be adapted through additional testing to ensure compatibility with deep-space mission constraints. The backup supplier would add on roughly 3 months of lead time due to integration testing and implementation.

2.1.3.5 CDH System Verification Plans

The CDH Subsystem consists mainly of Testing, Analysis, and Demonstration as methods for verification that all components in the subsystem are able to meet requirements. Each of these are rigorous verification methods that can adequately vet if the subsystem has met requirements or not, and are chosen based on the parameters being quantified by each requirement as well as the larger consideration of overall mission scheduling and cost scopes.

Testing in general consists of 3 main types: Vibration, Thermal, and Electromagnetic Interference (EMI) testing. All 3 of these will be included as part of the CDH Subsystem's testing, with an emphasis on Thermal and EMI tests.

Analysis will be conducted at both the subsystem and subcomponent level, mainly to ensure operation under thermal extremes (CDH-7.0, CDH-9.0) and that components can achieve optimal gain under mission constraints (CDH-5.1, CDH-5.2).

Lastly, demonstration that the subsystem can withstand different conditions has been included to verify the various parameters at the subsystem level, from dust in the atmospheric environment to power draw of the subsystem.

Thorough inspection will be conducted on remaining requirements that do not need resources allocated for more stringent verification.

Table 18: CDH Subsystem Verification Matrix

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
CDH-1.0	The CDH Subsystem shall be responsible for managing all flow of data as close to real-time as possible	Demonstration	Demonstration of the efficiency if the flow of data within CDH is sufficient	Demonstration that the CDH Subsystem's (with all integrated subassemblies and subcomponents) overall response time is close to real time
CDH-2.0	The OBC Sub-assembly shall be capable of real time command execution	Demonstration	Demonstration of real time command execution is sufficient to show if the OBC meets the requirement	Collective demonstration that child requirements can integrate well enough for real-time execution under mission constraints and conditions.
CDH-2.1	Software on the OBC shall have effective but cybersecure execution	Demonstration	Demonstration of both effectiveness and security of the flight control software is sufficient	Demonstration of effectiveness and security of the flight control software through software engineering benchmarks (NASA/SP-2013-604)
CDH-2.2	The OBC shall be capable of 100 MBps Memory Bandwidth and 80MBps I/O Bandwidth	Demonstration	The RAD 5545 has already been specified in datasheets by the contractor; demonstration that the actual part is up-to-spec is sufficient	Demonstration that the respective bandwidth values match BAE System's datasheets (BAE Systems 2019)
CDH-2.3	The OBC shall include the use of a Real-Time Operating System (RTOS)	Inspection	Inspection that a RTOS was included is sufficient	Inspection that the included OS operates in real-time
CDH-2.4	The OBC shall allow for remote software updates	Demonstration	Demonstration of remote update capabilities is sufficient	Physical demonstration that remote update capabilities have been included and can be implemented, using a test update in a remote environment as a demonstration
CDH-2.5	The OBC shall not weigh more than 1 kg	Inspection	Basic inspection of mass is sufficient	Inspection that OBC mass does not exceed 1 kg
CDH-2.6	The On-Board Computer (OBC) shall not be larger than (200 × 150 × 25) mm^3	Inspection	Basic inspection of dimensions is sufficient	Inspection that OBC dimensions do not exceed (200 x 150 x 25) mm^3
CDH-3.0	The Transceiver Subassembly shall be able to handle both transmission and reception of signals	Demonstration	Basic demonstration of two-way communication capabilities is sufficient to fulfill the requirement, as the requirement sets no quantifiable metrics	Demonstration that transceiver can effectively process and incoming ans outgoing signal using a Vector Network Analyzer (VNA)

CDH-3.1	The transceiver components shall not weigh more than 1kg	Inspection	Basic inspection of mass is sufficient	Inspection that transceiver mass does not exceed 1 kg
CDH-3.2	The Transceiver Subassembly shall be able to handle both transmission and reception of signals	Inspection	Basic inspection of dimensions is sufficient	Inspection that transceiver dimensions do not exceed (175 x 100 x 20) mm^3
CDH-4.0	The transceiver shall not be larger than (175 × 100 × 20) mm^3	Demonstration	Basic demonstration that storage is able to process and log data at the right windows is sufficient	Demonstration that data logs are stored at 8.6 minute intervals using timestamps
CDH-4.1	The storage system shall have a capacity of at least 2 GB	Demonstration	Demonstration of storage size is sufficient	Demonstration that the storage size matches Mercury System's datasheets
CDH-4.2	The data storage system shall not weigh more than 1kg	Inspection	Basic inspection of mass is sufficient	Inspection that transceiver mass does not exceed 1 kg
CDH-4.3	The data storage system shall not be larger than (200 × 100 × 20) mm^3	Inspection	Basic inspection of dimensions is sufficient	Inspection that transceiver dimensions do not exceed (200 x 100 x 20) mm^3
CDH-5.0	The CDH Subsystem shall communicate with the primary spacecraft orbiting Venus	Demonstration	Demonstration that the CDH Subsystem is capable of long distance communication with an orbiter above the atmosphere is sufficient	Capability will be demonstrated through the gain analysis and demonstration of fulfilled child requirements
CDH-5.1	The CDH Subsystem shall include a high gain antenna capable of 8-12 dBi for communication with the orbiter	Analysis	Analysis of achievable gain is sufficient to represent the actual gain of the antenna in practice, as testing is later included to gauge performance under mission environments	Simulation of gain achievable by implemented antenna dimensions using Ansys or similar antenna analysis software
CDH-5.2	The CDH Subsystem shall include a low gain, omnidirectional antenna capable of 3-6 dBi for communication with the orbiter	Analysis	Analysis of achievable gain is sufficient to represent the actual gain of the antenna in practice, as testing is later included to gauge performance under mission environments	Simulation of gain achievable by implemented antenna dimensions using Ansys or similar antenna analysis software

CDH-5.3	Signal gain of antennas should vary minimally under radiation and temperature effects of Venus	Test	Testing is required under Venus' atmosphere conditions to verify that no signal gain is lost	Thermal vacuum testing of antenna apertures under various thermal and radiation environments to test the achieved signal gain by the antennas using a Vector Network Analyzer (VNA)
CDH-5.4	The receiving component shall be able to receive data at a constant rate of 5Mbps	Demonstration	Demonstration is sufficient to show whether or not a data rate of 5Mbps can be received	Demonstration that sample data is not warped / missing when transmitted to the receiving component at 5Mbps
CDH-5.5	Data shall be transmitted to the orbiter at intervals multiples of 90 minutes within a window of 30 second	Demonstration	Demonstration is sufficient to show a transmission can be executed at set intervals within a set window	Demonstration that the execution of logic and commands are integrated with the antennas to be capable of consistent transmissions every 90 minutes in a 30 second window
CDH-5.6	No data shall be transmitted or received while the Aerobot is changing altitude	Demonstration	Demonstration is sufficient to show that software does not execute transmission / reception when changing altitude	Demonstration that the implemented logic does not allow for transmission and reception of data while communicating with the DSS
CDH-5.7	At the end of flight, one last transmission shall be made to the orbiter	Demonstration	Demonstration is sufficient to show that one final transmission will be made according to mission time elapsed	Demonstration of implemented logic in the Aerobot to execute a final transmission in accordance with mission completion
CDH-5.8	The antennas combined shall not weigh more than 2kg	Inspection	Basic inspection of mass is sufficient	Inspection that transceiver mass does not exceed 2 kg
CDH-5.9	The antennas combined shall not be larger than (500 × 150 × 200) mm³ before being deployed (in stowed form)	Inspection	Basic inspection of dimensions is sufficient	Inspection that transceiver dimensions do not exceed (500 x 100 x 200) mm³
CDH-6.0	The CDH Subsystem shall adjust power consumption throughout mission operation	Demonstration	Basic demonstration of ability to switch between power consumption modes is sufficient	Demonstration of the CDH Susystem's ability to operate and change power draw based on other subsystem readings
CDH-6.1	The CDH Subsystem shall not draw more than a maximum power of 70W	Inspection	Basic inspection of power is sufficient	Inspection that transceiver max power does not exceed 70 W
CDH-6.2	The CDH Subsystem shall not draw more than an average power of 55W	Inspection	Basic inspection of power is sufficient	Inspection that transceiver average power does not exceed 55 W

CDH-6.3	The CDH Subsystem shall maintain critical function in the event power draw is cut below 30 W	Demonstration	A demonstration can show that in the event power to the CDH Subsystem is cut below 30 W, execution and management of critical function within the Aerobot is still possible	Demonstration that the OBC can process and execute software commands even under a <30 W power draw
CDH-7.0	The CDH Subsystem shall maintain a temperature of 308K ±35K throughout the mission	Analysis	Analysis of hardware condition under different thermal environments is sufficient, as the requirement does not define software / operation	Thermal analysis of CDH hardware materials and their ability to withstand thermal extremes
CDH-8.0	The CDH Subsystem shall withstand vibrations from pyroshocks	Test	Thorough testing under launch condition is required to ensure CDH components can withstand pyroshocks during launch	Vibration testing of the overall CDH Subsystem in the ~kHz range
CDH-9.0	The CDH Subsystem shall be radiation hardened	Analysis	Analysis is sufficient to verify that the subsystem hardware has been specified properly in datasheets	Radiation hardening analysis of CDH hardware materials and their ability to withstand thermal extremes
CDH-9.1	The OBC shall be radiation hardened for a Total Ionizing Dose (TID) of 5k rad[Si] and Single Event Effects (SEE) and under 1e-10 upsets/bit-day.	Test	Testing is required to ensure that the radiation hardened values of the OBC clears it for effective operation under Venus' harsh radiation environment	Thermal vacuum testing of the OBC under Venus radiation and thermal conditions
CDH-10.0	The CDH Subsystem shall remain operational in dust storms	Test	Data from operation conditions needs to be gathered to verify the CDH Subsystem remains functional under these harsh conditions, which can only be achieved under testing environments.	Vibration testing of the overall CDH Subsystem in dust storm conditions
CDH-11.0	The CDH Subsystem shall remain operational in electromagnetic storms	Test	Data from operation conditions needs to be gathered to verify the CDH Subsystem remains functional under these harsh conditions, which can only be achieved under testing environments.	EMI testing of the overall CDH Subsystem in electromagnetic storm conditions

CDH-12.0	The CDH Subsystem shall include secondary storage and communication subcomponents	Inspection	Inspection for the inclusion of secondary redundant assemblies is sufficient to fulfill this requirement	Thorough inspection that redundant communication and storage subcomponents have been included and properly integrated
CDH-13.0	The CDH Subsystem shall include logical data recovery protocols	Demonstration	No data needs to be gathered, demonstration of requirement fulfilment is sufficient to show adequate recovery protocols have been implemented	Demonstration of implemented protocols and proof of ability to recover corrupted data

2.1.4 Thermal Control Subsystem Overview

Thermal Management Subsystem (TMS), is composed of 4 subassemblies, involving: heating mechanisms, insulation coating, MLI, and a thermal sensor. The insulation coating, that being the flat black paint coating, does not work with the rest of the subsystem, other than maintaining thermal equilibrium within the Aerobot system. It contributes to the system's overall thermal equilibrium by increasing the amount of heat transfer into the system through its high absorptivity value, preventing the Aerobot from overcooling. Despite its contribution to the Aerobot's thermal equilibrium, the flat black paint coating is independent from the rest of the TMS, as it does not depend on another subassembly to function. Similarly, the MLI (Copper Gold MLI) is independent from the rest of the TMS as well. Like the paint coating, the MLI functions independently to maintain thermal equilibrium, though it decreases the heat transfer going out of the system through its low emissivity value. On the other hand, the heating mechanisms (heat strips) are dependent on the thermal sensors, since each individual heater cannot regulate the amount of heating they provide. Therefore, they rely on the thermal sensor to know when each heater needs to deactivate or activate to maintain thermal equilibrium. The thermal sensor acts as the TMS's brain, dictating when the system needs to scale its heating, depending on the internal temperature of the Aerobot system. The thermal sensor is only dependent in terms of its operating temperature, in which it depends on the paint coating, MLI, and heating mechanisms to correctly function to prevent itself from overcooling and losing functionality.

Operating Temperatures

The table below (Table 19) displays the operating temperatures of all of the components within the Aerobot system. It presents the temperature ranges at which each component must abide by, whether it be exceeding the upper temperature limit or fall under its lower limit. For instance, the data storage within the CDH subsystem cannot exceed 345 K and cannot fall under 233 K, otherwise the component will bear the risk of system failure and lose all data collected during the mission. This instance is true for the majority of the components found within the Aerobot system, in which it must follow lower and upper temperature limits in order to function. Though there are instances in which a component contains only one restriction, such as the infrared radiometer spectrometer. The infrared radiometer spectrometer's sole constriction is to not push its lower temperature limit of 110 K, otherwise all other temperature values above the lower limit will allow the component to run with complete functionality. This instance applies to the UV/VIS spectrometer as well, as its only restriction is to not fall under 110 K. Aside from the spectrometers as the exception, the average lower limit temperature is 245.87 K, and an average upper limit temperature is 359.57 K, leading to an average operating temperature of 300 K. This value of 300 K allows all components to run with full functionality without worry of system failure due to cooling or heating. Moreover, it sets the benchmark at which the Aerobot system needs to be kept at for thermal equilibrium.

Table 19: Component operating temperatures table

Component Name	Operating Temperatures (Kelvin)
Payload	
UV/ VIS Spectrometer	< 110 K
Infrared Radiometer Spectrometer	< 110 K
MEDA Dust and Radiance Tool	218.15 K - 323.15 K
Mechanical	
Chassis	223.15 K - 923.15 K
Bored Couplings	0 K - 1273.15 K
Fastening Components	< 855.15 K
Aperture Window	0 K - 1873.15 K
Assembly Components	0 K - ~700 K
Cables	73.15 K - 1773.15 K
CDH	
OBC	218 K - 398 K
Data Storage	233 K - 345 K
Transceiver (Frontier Radio Lite)	-338 K - 423 K
ISARA Reflectarray	-373 K - 373 K (optimal gain)
QHA	4.2 K - 400 K
Power	
Battery	Non-operating: 253 K - 333 K Operating: 278 K - 308 K
Power Distribution Board	233 K - 358 K
Solar panels	288 K - 348 K

Governing Equations

The table below (Table 20) shows the governing equations that determined the outcome of the total heat transfer going into and out of the system, and ultimately determined the net heat transfer of the Aerobot system. The table displays the type of heat transfer and its corresponding equation, with a list of variables on the third column to understand how the equations were formulated. These heat transfer equations were applied to establish how much power was needed to keep the Aerobot system in thermal equilibrium (for the hot case without TCS, hot case with TCS, and cold case with TCS). It is assumed that there is no heat transfer albedo in the coldest case, because there was no sun for solar irradiance. Additionally, it is assumed that the internal heat of the system is 300 W. As for the emissivity and absorptivity values of the MG AZ31B F exterior material of the Aerobot system, it is assumed that they are overshadowed by the emissivity and absorptivity values of the MLI and paint coating. It is assumed that the Aerobot system is a closed system, therefore, no mass leaves or enters the system. Lastly, it is assumed that the system is in thermal equilibrium when the net heat transfer (Q_{net}) equals 0 W with a margin of ± 8 W.

Table 20: Governing heat transfer equations with their listed variables

Heat Transfer	Equation	Variables
Q_solar	solar_flux * SA * a	solar_flux = 2780 W/m^2 solar_irr = 2601.3 W/m^2
Q_internal	300 W (constant)	e = emissivity
Q_radiation	4(e * σ * SA * (T_sys^4 - T_atm^4))	SA = surface area
Q_albedo	SA * albedo * solar_irr	a = absorptivity
Q_planetshine	e * σ * SA * (T_sys^4 - T_sur^4)	σ (Stefan-Boltzmann) = 5.67^-8 W/(m^2 * K^4)
Q_convection	4(h * 1 * (T_sur - T_atm))	T_sys = system temp. T_atm = atmosphere temp. T_sur = surface temp.
Q_in	|Q_planetshine| + |Q_albedo| + |Q_solar| + |Q_internal|	albedo = 0.76
Q_out	|Q_Convection| + |Q_rdiation|	h = convection heat transfer coefficient
Q_net	(Q_in + htrs) - Q_out	htrs = system heaters

Hot Case Without TCS

Before the Aerbot system underwent TCS, there were many factors involved that influenced a high heat transfer net value going out of the system (Q_net = -642.29 W), causing the system to cool beyond functionality (the governing heat transfer equations to determine the net heat transfer value is shown above in table 20). Aside from the surface temperature of 737 K and atmospheric temperature of 400 K, the core factor involved to create the net value was the fact that it took the shape of a sphere, and that the radius was small (r = 0.3605 m). These factors caused the radiation (atmosphere) and convection heat transfer values to increase immensely, and thus caused the total heat transfer going out of the system to increase. Despite the sphere's shape leading toward a high net heat transfer value going out of the system, having a cube shape would cause the system to overheat at a greater scale than the cooling from a spherical shape. In addition to the spherical shape and small radius, another factor involved to create the net value was the base absorptivity emissivity values of 0.18 and 0.13, due to the magnesium alloy AZ31B F exterior material of the Aerobot system, according to ASM Aerospace Specification Metals Inc. (2025). With the collective issues of shape, radius, absorptivity, and emissivity, the power required to keep the net heat transfer at equilibrium far exceeded the power subsystem's provided power.

Hot Case With TCS

In order to mitigate the heat transfer going into the Aerobot system, the emissivity value was altered in order to decrease the radiation heat transfer. By using a Copper Gold Multi-Layer Insulation (MLI) on the exterior surface of the Aerobot system, the emissivity value of the system was then modified to a value of 0.01 (Fluke Process Instruments 2025), decreasing the radiation heat transfer value by a factor of 0.056. In terms of the absorptivity value of the Aerobot system, it was modified as well to increase the amount of heat transfer going into the system and lessen the amount of heating required to keep the system at power equilibrium. Therefore, using flat black paint coating, the absorptivity value was altered to a value of 0.99, increasing the heat transfer going into the system by a factor of 7.6. With the new emissivity and absorptivity values, the total heat transfer diminished to a value of -140.06 W (as shown below in figure 32). Thus, the Aerbot system requires a heating mechanism to counteract the -140.06 W of heat transfer, which is within the power subsystem's capabilities to ensure thermal stability.

Hot Case Heat Flow Map with TCS

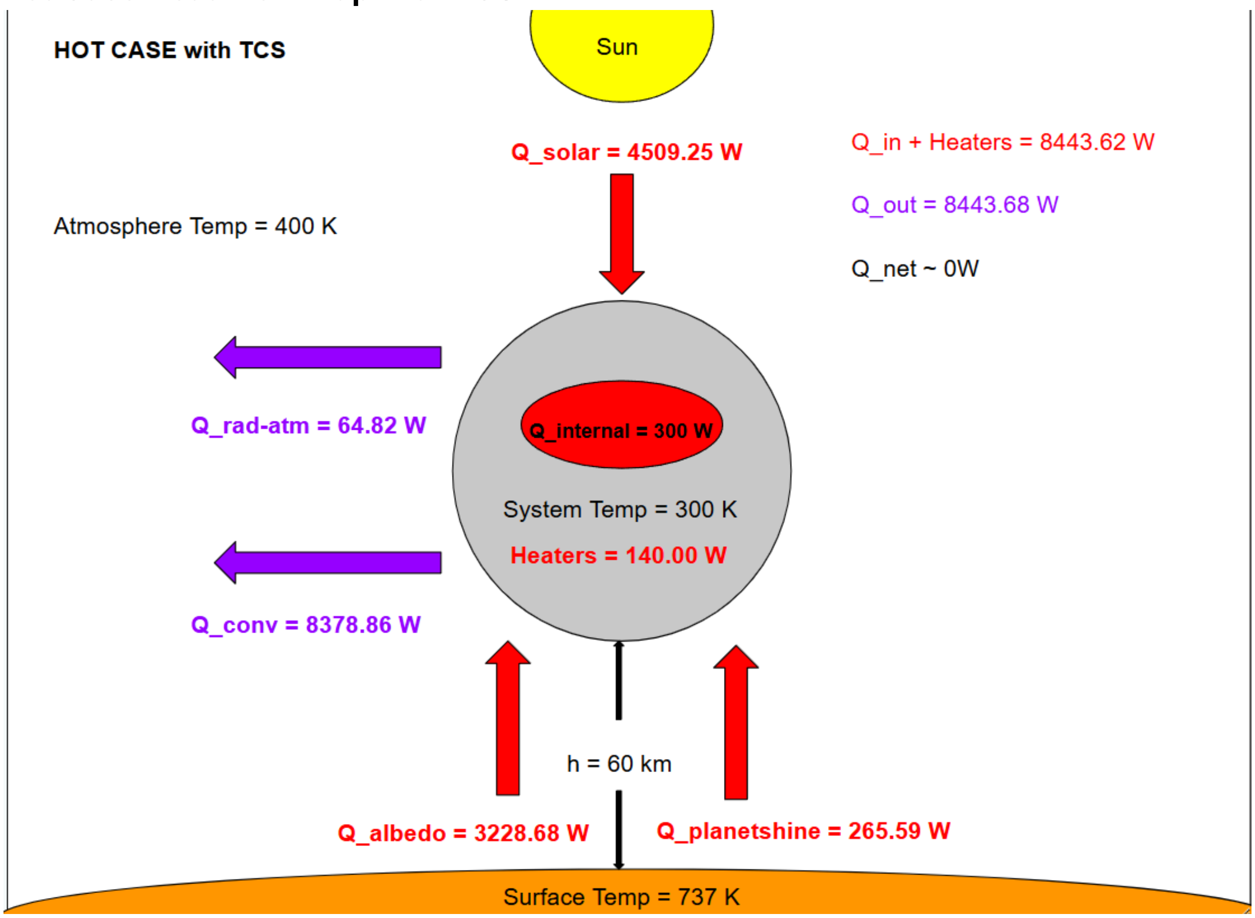


Figure 32: Heat Flow Map of Aerobot system in "Hot Case" Scenario with TCS

Cold Case with TCS

Taking into account the absorptivity value from the Aerbot system with TCS, the colder temperature of 300 K surface temperature and 330 K atmospheric temperature, and the instance of no sun, the total heat transfer of the system is equal to -299.75 W. The colder temperature reduced the values of both heat transfer in and out of the system, and the absence of the sun made the heat transfer of albedo and solar equal to zero (as shown below in figure 33). Due to the absence of the sun, the heat transfer going out of the system obtained a greater magnitude than the heat transfer going into the system. Therefore, in order to prevent instrumentation failure, a heating mechanism is essential to counteract the –299.75 W going out of the system.

Cold Case Heat Flow Map with TCS

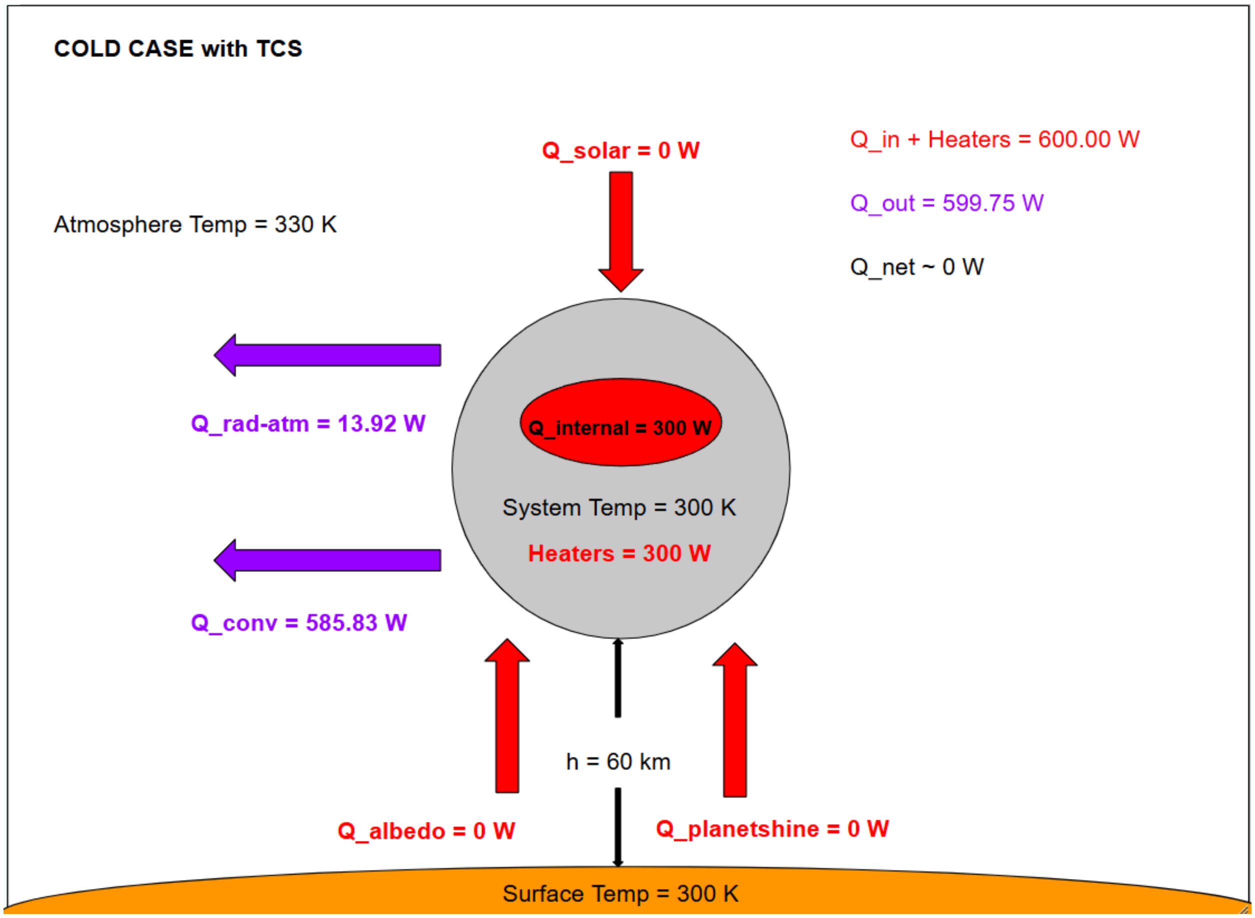


Figure 33: Heat Flow Map of the Aerobot system in a "Cold Case" Scenario with TCS

2.1.4.1 Thermal Management Subsystem Requirements

Table 21 below ensures there are contractual agreements between the thermal subsystem team and whomever the team needs to interact with.

The Thermal Management subsystem (TMS) is contrived to involve necessary insulation and heating mechanisms (no cooling system needed, based on heat transfer calculations) to ensure internal component functionality in the Venusian environment. Subsystem requirements (Table #) are influenced by the extreme temperatures of the Venusian environment to make certain that the internal temperature of the Aerbot system meets the operational thermal constraints of all system components (253.15 K - 323.15 K from mean calculations). For instance, the child requirement of maintaining an internal temperature of 253.15 K - 323.15 K (TMS-1.1) was a result of the CDH subsystem's parent requirement to maintain a temperature of 308 K, with a fluctuation threshold of 35 K (CHD-8.0). Additionally, the subsystem requirements are adapted to meet mission constraints, including power consumption and mass constraints.

All TMS requirements are verified through testing, demonstrational, inspectional, and analytical processes to ensure system functionality under harsh Venusian conditions. For example, to guarantee heating automation (TMS-2.1), a demonstration of the functionality of the system's thermal sensors is necessary to make certain that the heating mechanism activates according to present external temperatures. Likewise, inspection is required to confirm the presence of thermal insulators of at least 0.5 W/m*K conductivity on the Aerobot system's exterior (TMS-2.3). Analysis is involved in the verification process as well, to theoretically ensure that the Aerbot system may survive the Venusian environment with the available thermal subassemblies (TMS-3.2). While it is preferred to avoid testing (for budget purposes), it is at times needed to ensure the success of certain components. Verifying the functionality of temperature sensors (TMS-5.1) is one of the cases that requires testing as a verification method, since it must meet conditions specific to the Venusian setting (withstanding 401. K and sulfuric acid exposure). The collective requirements, and its corresponding verification method, drives TMS success–ensuring resilience against mission and environmental constraints.

Table 21: Thermal Requirements Table

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
TMS-1.0	The thermal system shall maintain the internal and external components within their allowable operating temperatures	The components internally and externally of the system are required to deliver the final data for the mission so there is a need to protect them	MG-1.0 SYS-1.0 SYS-2.0	TMS-1.1 TMS-1.2 TMS-2.0 TMS-3.0 TMS-4.0 TMS-5.0 TMS-6.0	Demonstration	Met
TMS-1.1	The thermal control system shall maintain electronics within an internal range of 253.15 to 323.15 K	Electronics must remain within operable limits despite extreme external conditions.	MG-1.0 SYS-1.0 SYS-2.0 CDH-8.0	-	Demonstration	Met
TMS-1.2	The system shall protect internal components from external temperatures from ranges 173.15-223.15 K	Prevents component failure due to Venus' extreme surface heat.	MG-1.0 SYS-1.0 SYS-2.0	-	Demonstration	Met
TMS-2.0	The subsystem shall include a heating mechanism capable of providing sufficient power to maintain temperatures during cold conditions.	There is a need to heat up vital components that are not able to operate in warmer conditions, especially involving Venus which is the 2nd closest body to the Sun	MG-1.0 SYS-1.0 SYS-2.0 TMS-1.0	TMS-2.1 TMS-2.2 TMS-2.3	Demonstration	Met
TMS-2.1	The subsystem shall use insulators with a thermal conductivity of at least 0.5 W/m*K	With a certain thermal conductivity number, insulation becomes helpful where ever it is applied to and can help maintain the temperature in the area at a reasonable range	MG-1.0 SYS-1.0 SYS-2.0 TMS-1.0	-	Inspection	Met

TMS-2.2	The subsystem shall integrate temperature sensors with an accuracy of ±0.1K	High-precision temperature sensors ensure efficient thermal control by maintaining tight temperature regulation, preventing damage to critical components.	MG-1.0 SYS-1.0 SYS-2.0 TMS-1.0	-	Demonstration	Met
TMS-2.3	The subsystem shall be capable of autonomously adjusting thermal output based on sensor feedback	Autonomous thermal adjustment allows the system to adapt to changing environmental conditions, ensuring continuous, optimal performance without human intervention	MG-1.0 SYS-1.0 SYS-2.0 TMS-1.0	-	Demonstration	Met
TMS-3.0	The total mass of the thermal subsystem shall remain under15 kg	Limiting the thermal subsystem's mass ensures the aerobot stays within payload constraints, optimizing energy efficiency and overall mission performance	MG-1.0 SYS-1.0 SYS-2.0 TMS-1.0	TMS-3.1 TMS-3.2 TMS-3.3 TMS-3.4	Inspection	Met
TMS-3.1	The subsystem shall withstand temperature extremes from 243.15K to 203.15K during operation	The thermal subsystem must endure the cold temperatures in Venus' upper atmosphere to ensure proper functioning and protect internal components	TMS-3.0	-	Test	Met
TMS-3.2	The sub-system shall ensure thermal protection for 48 hours of the mission	The thermal subsystem must provide reliable temperature regulation for 48 hours to ensure continued operation in Venus' harsh environment	TMS-3.0	-	Analysis	Met

TMS-3.3	The subsystem shall have redundancies in place for critical thermal control components to ensure continued operation in case of failure	Redundant thermal components ensure the aerobot's thermal system remains functional if a failure occurs, enhancing mission reliability	TMS-3.0	-	Inspection	Met
TMS-3.4	The thermal control system shall include high-temperature-resistant insulation and shielding	Limits heat conduction and radiation into the spacecraft.	TMS-3.0	-	Inspection	Met
TMS-4.0	The total power consumption of the thermal management subsystem shall consume less than 300W	Ensures power efficiency given Venus' harsh environment and limited energy sources.	TMS-1.0 SYS-1.0 MISS-6.0		Inspection	Met
TMS-5.0	The thermal management system shall include sensors for real-time temperature monitoring	Enables autonomous thermal Regulation and telemetry.	TMS-1.0 SYS-1.0 MISS-6.0	TMS-5.1 TMS-5.2	Inspection	Met
TMS-5.1	Temperature sensors shall withstand up to 400.15 K and sulfuric acid exposure	Ensures sensor reliability on the Venusian surface.	TMS-5.0	-	Test	Met
TMS-5.2	The temperature sensors shall update telemetry at least once per minute	Ensures mission control can track heat changes.	TMS-5.0	-	Demonstration	Met
TMS-6.0	Thermal vacuum chamber testing shall simulate high-pressure and high-temperature conditions	Verifies system effectiveness before deployment.	TMS-1.0 SYS-1.0 MISS-6.0	-	Demonstration	Met

2.1.4.2 Thermal Control Sub-Assembly Overview

Insulation Subassembly

The insulation subassembly that is selected for the Thermal Management System is paint coating and MLI. Due to a paint coating and MLI's near negligible mass, it is the best course of action for an insulation sub assembly approach. A paint coating subassembly coats the top surface of the Aerobot system with specific material of specific absorptivity, increasing the total heat transfer going into the system by increasing the absorptivity of the system exterior. Similarly, a MLI insulation subassembly provides a thermal blanket of thin material for the Aerobot system that decreases the emissivity of the system, reducing the amount of heat transfer going out of the system. In addition, paint coating and MLI promotes storage efficiency for the system, where most paint coatings and MLI will cover the surface area (SA = 1.63 m^2) with a thickness of typically 1.00 μm - 1.60 μm. Simultaneously, the subassemblies contain a near negligible mass and power draw, which allows the system to allocate mass and power in other subassemblies or subsystems. Rather than using heat pipe radiators or plate radiators, which take up mass and storage, paint coating and MLI subassemblies would best fit the system constraints of mass, storage, power draw, and thermal performance. Overall, paint coating provides a TRL of 5 because of its successful use in space applications, such as the Galileo Spacecraft (et al. 1986). Though, it is critical to acknowledge that the environment between Venus and plain space are completely different (and the fact that the Aerobot is much smaller than the ISS. Therefore, the TRL cannot exceed 5 because the capability of paint coating and MLI on the Aerbot system is within uncharted territory.

Insulation Subassembly: Multi-Layer Insulation

Out of many qualified MLI materials, such as Double-Aluminized Kapton, Silverized Teflon, and Aluminized Polyimide, the most qualified MLI material for the system exterior was Copper Gold. The primary reason why the Copper Gold MLI was chosen for the system was because of its low emissivity value and its high resistance to corrosion. While the other materials contained a low emissivity value range between 0.3 - 0.15, the Copper Gold, as previously stated, contains an emissivity value of 0.01, drastically diminishing the amount of total heat transfer going out of the system. Additionally, the material is 1.60 μm thick, which is smaller than common MLI blankets. As stated before, the MLI will provide a TRL of 5 due to its use in other spacecraft applications and low emissivity.

Insulation Subassembly: Paint Coating Material

The paint coating that is most suitable for the system's exterior is a flat black paint coat, due to its exceptionally high absorptivity. The coating offers an absorptivity value of 0.99 (Johnson 1996), which supports the Aerobot's heat transfer going into the system. Despite the coating material holding a high emissivity value of 0.97 - 0.99, the MLI material is present to supplement the efficiency of emissivity. The coating is 1.00 μm thick, which is considered to accommodate an almost negligible amount of storage to the overall storage of the system. As previously stated, the coating has a TRL of 5 based on its low absorptivity value and proven use in space applications.

Heating Mechanism

The heating mechanism that best fits the constraints of the Aerobot system are the TurboFlex Heaters (flexible heat patches). Due to the Aerobot system's total heat transfer of -299.75 W of power in a cold case scenario, a heater(s) is needed to negate the 299.75 W of cooling from the Venusian environment. Thus, the TurboFlex Heaters are selected for the task because they can support up to 300 W of heating (three 100 W heat strips and two 20 W heat strips). Along with its satisfactory heating capabilities, its small scale of a combined 0.2058 kg of mass and combined volume of ~1.806e-4 m^3 greatly support the mass and storage constraints of the system. With two wires that can connect each heat patch to the power subsystem, the heat patches can be coded to automatically heat the system when it is being cooled by the Venusian environment (detected using the thermal sensor). Compared to other forms of heating, such as small radiators and silicone enclosure heaters, the TurboFlex Heaters outperforms the other heaters when it comes to mass and storage to power efficiency. The TurboFlex Heaters hold a TRL of 4 because heat patches have been successfully used before in spacecraft missions, but this heat patch is much smaller than the heat patches used in those missions.

Thermal Sensor

In order to manipulate the internal temperature of the system to maintain power equilibrium, a thermal sensor will be utilized to activate and deactivate the heating mechanism. The thermal sensor selected to guide power equilibrium is the ST-100 Thermistor Temperature Sensor. This particular heat sensor was chosen because it reads internal temperatures (223 K - 343 K) that fall within the internal power levels for the hot and cold case of the Venusian environment (-140.06 W & -299.75 W). When the thermal sensor detects temperatures that would interfere with the required operating temperatures of the Aerobot system's components, the sensors will command (commands will be performed by the CDH subsystem) the TurboFlex Heaters to activate/deactivate one at a time in order to heat/cool the system. Each heater will activate or deactivate if the temperature change in the system is ± 15 K. If the sensors detect temperatures that fall within the system's hottest case, it will activate only the two 20 W TurboFlex Heaters To prevent overheating (if the other 100 W heat strips were to activate as well). If the sensors detect temperatures that fall within the system's coldest case, it will allow activation of only the three 100 W heat strips to prevent the system from overcooling. Aside from its primary attribute of thermal detection, the Thermistor Temperature Sensor contains a near negligible amount of mass of 0.06 kg, allowing the system to allocate mass to other components within it. Additionally, it contains a small magnitude of volume of (1.13e-6 m^3), falling within the system's volume constraints. The ST-100 Thermistor Temperature Sensor contains a TRL of 4, because thermal sensors have been successfully used before in spacecraft missions, but it's incredibly small mass causes uncertainty about its durability to the Venusian environment.

Overall TRL

The overall TRL of the thermal management subsystem is a TRL of 4, because the heating mechanism and the thermal sensor hold a TRL of 4. Even if the heating mechanism and thermal sensors are flight-proven, they have not been tested in a

Venus-like environment. They hold the lowest TRL, and therefore it drives the TRL of the entire subsystem. The mechanism's constant use in spacecrafts propels its level to a high number, though the manner in which it is used (in the Venusian environment) drops it down from being a TRL of 5 to a TRL of 4, because of strong winds and extreme temperatures. Due to the uncommon size and mass of the TurboFlex Heaters, the TRL of the heating mechanism dropped by 1 (all specs of the heating mechanisms are shown below in table 22). Likewise, the small mass of the ST-100 Thermistor Temperature Sensor brings uncertainty to the durability of the sensor, dropping the TRL down by 1 as well. Therefore, the TRL of the overall thermal management subsystem is a 4 because of the TRL of the heating mechanism and thermal sensor.

Table 22: Thermal Sub-Assembly Specs

Subassembly	**Mass**	**Dimensions**
TurboFlex Heater (100 W)	0.02954 kg	0.137 m x 0.1524 m
TurboFlex Heater (100 W)	0.02954 kg	0.137 m x 0.1524 m
TurboFlex Heater (100 W)	0.02954 kg	0.137 m x 0.1524 m
TurboFlex Heater (20 W)	0.0588 kg	0.127 m x 0.2032 m
TurboFlex Heater (20 W)	0.0588 kg	0.127 m x 0.2032 m
Thermistor Temperature Sensor	0.06 kg	0.1 m x 0.006 m ∅
Flat Black Paint Coating	0 kg	1.633 m^2 x 1.0 μm
Copper Gold MLI	0 kg	1.633 m^2 x 1.6 μm
Total	0.32502 kg	1.835E-4 m^3

2.1.4.3 Thermal Control Subsystem Recovery and Redundancy Plans

Recovery Plan

The Recovery Plan for the TMS is the TMS itself, as it contains multiple heat strips to recover from unexpected heat transfer going in or out of the system. Since the heating mechanism is split between 5 heaters (two 20 W heaters and three 100 W heaters), the amount of heating the TMS provides can be scaled to be higher or lower. In terms of the hottest case for the TMS, only two 20 W heaters are needed to keep the system in thermal equilibrium. Though, if unexpected heater transfer were to occur, the TMS can deactivate or activate heaters based on the temperature difference the thermal sensor reads.This instance of recovery is congruent for the coldest case as well, in which only three 100 W are expected to be sufficient for thermal equilibrium, but that may change depending on unexpected circumstances. For example, if an unexpected 20 W of heat is transferred into the system (identified through the thermal sensor), the TMS can deactivate one of the 20 W heaters (through the power subsystem) so that only one 20 W heater would remain active, keeping thermal stability within the Aerobot system and preventing TMS component failure from temperature instability. With this recovery plan, the risk of TMS and system failure is low, since there is flexibility with the power the heating mechanism provides.

Redundancy Plan

There is no Redundancy Plan for the TMS, because there cannot be a redundant amount of paint coating or MLI on the Aerobot System. Since the Aerobot system is unable to apply paint coating onto itself (if the original coat were to somehow diminish), there cannot be a Redundancy Plan for the coating aspect of the TMS. The only perspective in which the paint coating can be identified as redundant material, is the matter that the thickness of the coat is thicker than usual paint coatings (1 μm). This instance is similar to the MLI, since the Aerobot cannot apply another MLI wrap onto itself if it were destroyed. Unlike the paint coating, it cannot assume a greater thickness to act as a minor redundancy, otherwise the emissivity value of the MLI changes and distorts the balance of the thermal equilibrium. Though, the MLI by default does not bear a high risk of being destroyed, because of its corrosive-resistance material of gold and copper. For the heating mechanisms (TurboFlex Heater's heat strips), there cannot be a redundancy plan simply because there is no space for any more strip heaters on the interior of the Aerobot system's surface area. Moreover, mass is tight due to the mission descope (-5 kg of total mass), in which the remaining mass available is allocated to components of other subsystems within the Aerobot. Despite the cost of the heat strips being relatively cheap, the mass and volume of the system as a whole is too tight to supply redundant heaters for the TMS. Nonetheless, there are low risks with not having redundant strip heaters, since there are 5 heaters to begin with in order to scale the amount of heating required to keep the system in thermal equilibrium.

<u>2.1.4.4 Thermal Manufacturing and Procurement Plans</u>

Heating Mechanism

The supplier chosen for the heating mechanism (flexible heat strips) isTurboFlex Heaters, due to their diverse and efficient models of flexible heaters. TurboFlex Heaters (a contractor) provides flexible heat strips of varying sizes (typically small), depending on the situation of the consumer. Along with the variety of heat strips, TurboFlex Heaters offers heat strips that provide various scales of heating (in watts), making efficient use of the heating power-output based on the consumer's needs. In addition, TurboFlex Heaters' heat strips contain a mass of near negligibility, due to the polyimide and polyester material and small-scale size. The size/mass to power ratio makes the TurboFlex Heaters' flexible heat strips appealing for this mission, because of the heating mechanism's flexibility with the mission constraints of volume, power, mass. Furthermore, the contractor offers cheap costs for the heating mechanism's range of appealing features ($113.63 for the two 20 W heaters, $119.30 for the three 100 W heaters, $232.93 total).

A secondary supplier for the heat mechanism is DWEROMEGA (contractor), due to their polyimide flexible heat strips. DWEROMEGA's heat strips, similar to TurboFlex Heaters', are small in size, but the max heating power it may support is 120 W. Due to the max heating power, a total of 5 heat strips are needed to compensate for the 299.75 W of required heating. Each heat strip costs $82.37, which means a total of 3 heat strips would cost $247.11. Due to the cost of DWEROMEGA's heat strips, and due to the amount of space they occupy when 3 are needed, the TurboFlex Heaters' heat strips are far more superior. With that being said, they are a great back up supplier because they are still considerably smaller than other heating mechanisms (like heat plates), and contain a small magnitude of mass. Moreover, like the TurboFlex Heaters' heat strips, DWEROMEGA's heat strips are flexible due to its polyimide material, which promotes efficient spatial use of the Aerobot's spherical figure. The heat strips as well are specifically adequate for the Aerobot system because its operating temperatures fall within the range of the Aerobot's internal temperature (~300 K). Despite its quantity and cost, the DWEROMEGA heat strips would overall make a great fit for a backup heating mechanism, based on its qualities of size, spatial efficiency, and operating temperature.

Coating

The contractor, AXIOS Industrial, is chosen as the primary supplier for the coating of the Aerobot, because of its wide range of material it provides (though specifically targeting the flat back paint). The paint material that AXIOS Industrial supplies contains an absorptivity value of 0.99, optimal for heat transfer going into the Aerobot system (to counteract the heat transfer leaving the system). The absorptivity of the coating is the primary aspect of its appeal, because it is the best coating available when compared to other types (such as Aluminum foil, which has an absorptivity value of 0.15). With the coating's seemingly cheap cost of ~$100, AXIOS Industrial having the coating available for purchase makes the contractor fit for heat transfer requirements.

A secondary supplier for the flat black paint coating is Thermo Fisher Scientific (contractor), because they are capable of reaching the 0.99 absorptivity with little error to create the coating mixture. The absorptivity of the coating mixture would be congruent to that of the AXIOS Industrial coating (0.99), but the process of obtaining the coating would take longer because the flat black paint material to create the coating must be precise with its absorptivity, therefore, a fabrication process is required to fabricate the paint. Conveniently, the price of the coating is similar to the AXIOS Industrial coating, when considering the price of the flat black paint, and the fabrication process. Hence, Thermo Fisher Scientific is fit as a backup supplier because it shares most qualities that the AXIOS Industrial contractor supplies.

Multi-Layer Insulation

SQUID3 SPACE, a contractor, is designated as the primary supplier for the Copper Gold MLI, due to its customizability for MLI thermal blankets. SQUID3 SPACE provides a wide variety of resources to create customizable MLI blankets, which would provide the required Copper Gold mixture that would produce a 0.01 emissivity value. Moreover, SQUID3 SPACE holds a healthy history with NASA as a supplier for previous missions, making the supplier trustworthy to satisfy mission goals and constraints. The contractor on average takes 1-3 months for lead times, which supplies a clear picture of the mission schedule. In addition, SQUID3 SPACE offers a cheap price of $500 for MLI customization, making efficient use of the overall budget.

A sufficient secondary supplier (and contractor) for the Copper Gold MLI is Alpha Inc., due to their similar customization as the SQUID3 SPACE supplier. On top of Alpha Inc.'s similarity to SQUID3 SPACE's customization, they are also known to work with NASA for their missions. Alpha Inc. possesses the capability to create Cvopper Gold MLI which is required corresponding emissivity, making it a suitable fit for the mission.

Though, while it shares nearly the same benefits as SQUID3 SPACE, they are not as clear with the lead times. While their price is similar ($500-$600), they do not display average lead times, making it marginally less reliable than SQUID3 SPACE. Though, with its customization capabilities, Alpha Inc. is still a reliable supplier to obtain the required Copper Gold MLI.

Thermal Sensors

The primary supplier selected for the thermal sensors is the COTS, Apogee Instruments, for their ST-100 Thermistor Temperature Sensor. The reason why it was best to pursue an off-the-shelf part is because the sensor that Apogee Instruments provides holds multiple benefits that are by default specific to the functionality of the Aerobot system. Additionally, its cost from being off-the-shelf makes it cheaper than a customized thermal sensor. Its biggest attribute is its near negligible mass (0.06kg), which promotes mass efficiency with the overall Thermal Management Subsystem. It will allow the system to allocate mass for heavier components, and prevent the overall mass of the system from reaching its descoped mass constraint of 45kg. Its volume as well fulfills the system's volume constraint. The total volume the temperature sensor occupies is 1.13e-6 m^3, occupying a small portion of the Aerobot system's storage. In addition to the small volume, the temperature sensor is manufactured as cable, allowing the sensor to be flexible with its position in the spherical system. Most importantly, Apogee Instruments' ST-100 Thermistor Temperature Sensor operates and can read temperatures with a range of 223 K - 343 K, which is sufficient to detect extreme cooling within the system. With all of its benefits that support mission and system constraints, Apogee Instruments provide their heat sensors with a reasonable price of $109.00.

The secondary supplier for the system's thermal sensors are IOThrifty's Infrared Temperature Sensors (contractor). These sensors share about the same volume characteristics (9.54e-5 m^3) as the Thermistor Temperature Sensors, but contain a slightly greater mass (0.45 kg). Nonetheless, the IOThrifty sensor is still mass and spatially efficient, and carries the same flexibility as Apogee Instrument's thermal sensor. Though, it operates and reads a range of temperatures that are less reliable for the mission, as it leans toward reading a range of temperatures better suited for overheating rather than overcooling (293 K - 373 K). Moreover, this sensor costs $910.00, which is a much greater cost than what the primary supplier offers. Thus, due to its greater cost and higher range of temperature readings (yet still optimal for the mission), IOThrifty is best suited as a secondary supplier.

Lead Times

For the primary supplier of the heating mechanism, it will take approximately 1.5 months for TurboFlex Heaters to manufacture and deliver the heat strips. If TurboFlex Heaters is unavailable, the manufacture and delivery time will change to approximately 3 months when using DWEROMEGA as a supplier. As for the manufacture and delivery time for the coating, it will take about 1.5 months for AXIOS Industrial to provide the flat black paint coating. This time may change to 2 months if the Thermo Fisher Scientific supplier is used. Due to the Copper Gold material required for the MLI to obtain the 0.01 emissivity, SQUID3 SPACE will require 2 months to fabricate the MLI thermal blanket.

Alpha Inc. will take an additional half month (2.5 months total) if SQUID3 SPACE was not an option, due to its unclear lead time statistics.

It will take Apogee Instruments 1 month to manufacture the ST-100 Thermistor Temperature Sensor, as it is ready for immediate manufacturing from being off-the-shelf. The secondary supplier for the thermal sensor, IOThrifty, will require 3.5 months to manufacture its Infrared Temperature Sensor, because of its more complex and expensive components involved in the sensor.

2.1.4.5 Thermal Control Subsystem Verification Plans

The Verification Plan (shown below) consists of all four verification methods (analysis, demonstration, inspection, and testing) to ensure all requirements are met before final implementation and launch. The most used verification methods were demonstration and inspection, because the methods did not cost as much as testing and it sufficiently fulfilled the requirements needed for the TMS. Despite testing being the finest method to verify nearly each requirement, the cost of testing outweighs itself, and therefore, demonstration and inspection is the best course of action for verification.

The majority of requirements chosen for inspection had very little technicality involved in them, such as simply containing the existence of a thermal sensor within the TMS (TMS-5.0). The majority of requirements chosen for demonstration involved technicality with them, such as ensuring that the necessary heaters reach its desired heat output (TMS-2.0). In terms of analysis, there was only one requirement that needed an analytical verification method, which was ensuring that TMS would survive for a total of 48 hours (TMS-3.2). While testing is not a preferred verification method due to its cost, it was utilized for a select number of requirements to make certain that the mission would operate with complete functionality. Thermal vacuum testing was exercised to ensure the TMS would survive in simulated space and Venusian conditions. The risk of not testing the survivability of the TMS was too great to not test, which is why it is applied to some requirements as a verification method (such as TMS-1.0). All of the selected verification methods ensure that each of its corresponding requirements is met, allowing the TMS to move along for final implementation and launch.

Table 23: Thermal Verification Matrix

TMS-1.1	The thermal control system shall maintain electronics within an internal range of 253.15 to 323.15 K	Test	Same as rationale for TMS-1.0	Same as plan for TMS-1.0
TMS-1.2	The system shall protect internal components from external temperatures from ranges 173.15-223.15 K	Test	Same as rationale for TMS-1.0	Same as plan for TMS-1.0
TMS-2.0	The subsystem shall include a heating mechanism capable of providing sufficient power to maintain temperatures during cold conditions.	Demonstration	Demonstration is sufficient enough to ensure that heat mechanisms heat its required power	Demonstration that will use a power source to determine how much heating the heaters can provide
TMS-2.1	The subsystem shall use insulators with a thermal conductivity of at least 0.5 W/ m*K	Inspection	There is no reason to test the insulators, since they are not dependent on another subassembly, ensuring their existence on the Aerobot is sufficient enough	Inspection that will make sure all insulation is placed on the exterior of the Aerobot system with 0.5 W/ m*K
TMS-2.2	The subsystem shall integrate temperature sensors with an accuracy of ±0.1K	Demonstration	Demonstration of performance accuracy of the thermal sensors is sufficient to provide insight on its reliability to identify temperature differences	Demonstration by changing temperature in an enclosed area and determining if the thermal sensor can read temperature difference with an accuracy of ±0.1K
TMS-2.3	The subsystem shall be capable of autonomously adjusting thermal output based on sensor feedback	Demonstration	Demonstration of automation will supply the required information to identify any discrepancies with the functionality of the heaters with the thermal sensor	Demonstration by changing temperature in an enclosed area and determining if the heaters can autonomously scale through the CDH subsystem and thermal sensors
TMS-3.0	The total mass of the thermal subsystem shall remain under 15 kg	Inspection	There is no way to apply any other verification method for this requirement, a simple inspection of mass will provide insight on what changes may need to be made, if any	Inspection that will check if total TMS mass has surpassed the 15 kg limit through a mass scale
TMS-3.1	The subsystem shall withstand temperature extremes from 243.15K to 203.15K during operation	Test	Testing is required to ensure that the Aerobot system's internal temperature satisfies the operating temperatures of all components within the system when facing temperatures between 203.15 K - 245.15 K during operation	Use Thermal Vacuum testing to simulate space and Venusian conditions, in order to ensure all components are within operating range

TMS-3.2	The sub-system shall ensure thermal protection for 48 hours of the mission	Analysis	Analysis is required to ensure that all required values from each subassembly (regarding emissivity, absorptivity, and heating) is present within the system	Analyze the absorptivity and emissivity values of the insulators to ensure they provide the sufficient amount of heat reduction, as well as analyze the amount of heating the heaters provide from previous demonstrations.
TMS-3.3	The subsystem shall have redundancies in place for critical thermal control components to ensure continued operation in case of failure	Inspection	Ensuring that any required redundancies are present is sufficient enough for verification, since the primary components would have been previously demonstrated or tested	Inspection by making sure all required redundancies are present on the Aerobot system before launch
TMS-3.4	The thermal control system shall include high-temperature-resistant insulation and shielding	Inspection	Inspection is the best course of action to ensure that the materials used for insulation can withstand extreme temperatures or corrosion	Inspection to make that right material was fabricated for insulation
TMS-4.0	The total power consumption of the thermal management subsystem shall consume less than the Power Subsystems's power limit	Demonstration	Demonstration is sufficient to identify if the heaters exceed power limits	Demonstration that will use a power source to determine if heating goes beyond the power limit
TMS-5.0	The thermal management system shall include sensors for real-time temperature monitoring	Inspection	Ensuring the existence of thermal sensors in the system will allow for heat scaling according to internal temperature change	Inspection to ensure the thermal sensors are placed in its desired placement (most likely near the CDH subsystem)
TMS-5.2	The temperature sensors shall update telemetry at least once per minute	Demonstration	Demonstration is required to determine if the temperature sensor updates the telemetry	Demonstrations by changing temperature in an enclosed area and determining if the thermal sensors update the telemetry
TMS-6.0	Thermal vacuum chamber testing shall simulate high-pressure and high-temperature conditions	Demonstration	Ensure that testing will occur through demonstration to determine if any issues were found within the thermal subsystem	Demonstration to make sure the thermal vacuum chamber testing occurs to acquire information on any technical issues

2.1.5 Payload Subsystem Overview

2.1.5.0.1 Science Payload Architecture

The V.E.L.A.Z.Q.U.E.Z. aerobot carries three complementary instruments (Table 23) that, together, resolve Venus's middle-atmosphere chemistry, clouds, energy balance, and potential volcanism:

Table 24: Overview of Instrumentation

Instrument	Core Observable	Spectral Range	Mass / Power	Heritage
UV/Visible Spectrometer	SO_2, H_2O, UV absorber, O_2 air-glow	0.11–0.31 µm (UV), 0.7–1.7 µm (Vis/NIR), 2.3–4.2 µm (SOIR)	3.1 kg / 12 W	SPICAV/SOIR – Venus Express
IR Radiometer / Spectrometer	Surface & cloud-top temperature, CO, H_2O	0.9–5 µm, multi-band	5.9 kg / 15 W	VIRTIS-M – Venus Express
MEDA Dust & Radiance Suite	Aerosol density, UV/Vis/IR flux, P–T	170 nm–14 µm (6 solar + 2 IR bands)	5.5 kg / 17 W	MEDA – Mars 2020

2.1.5.0.2 UV/Visible Spectrometer

Purpose: Measures column and vertical profiles of SO_2, H_2O, CO, HCl, HF and the unknown UV absorber; tracks ozone-related O_2 1.27 µm nightglow; constraints cloud optical thickness.

Operation:

- Nadir: every 3 min for albedo/trace-gas mapping.
- Solar occultation: sunrise/sunset 5–10 min events; >103 spectra/event resolve 80–120 km profiles.
- Stellar occultation (night) and limb scan provide additional vertical coverage. A 2-axis steering mirror (±5°) maintains target lock despite balloon drift.

Subsystem Support: High-voltage ICCD, AOTF driver, and SOIR TEC draw 12 W (peak). C&DH supplies time-tagged pointing kernels; thermal plate maintains 0 °C detector set-point; sapphire/MgF_2 window and PTFE-coated fore-optics resist H_2SO_4.

Environmental Survivability: Optical cavity is nitrogen-purged at 1 bar; gold-over-aluminum mirrors and parylene-coated mounts block acid attack; watchdog timers reset control FPGA on hang .

2.1.5.0.3 Infrared Radiometer/Spectrometer

Purpose: Multi-spectral imaging reveals surface hotspots (1.0, 1.1, 1.18 μm), maps cloud-layer temperatures (1.74, 2.3, 4.3 μm), and derives CO/H_2O abundances. Night-side surface emission tests for active volcanism.

Operation:

- Mapping mode: 256 × 256-px, 5 bands, 10° swath every 5 min (night); day-side cadence throttled.
- Spectral-cube mode (events): $\lambda/\Delta\lambda \approx 300$ over 0.9–5 μm.
  Onboard JPEG2000 compresses each cube to ~0.5 MB before storage.

Subsystem Support: Twin HgCdTe arrays with dual-gain pre-amps; Stirling micro-cooler or radiative cold-plate holds FPA at <240 K; 15 W average power. Scan mirror azimuth servo ties to attitude IMU for smear-free imaging. Data handler compresses and packets 100 MB/night to mass memory for high-gain downlink.

Environmental Survivability: All external optics behind diamond window; gold-coated mirrors; PTFE splash shields. Electronics inside 50 °C-limited bay, radiator faces zenith. Automatic gain switch eliminates detector saturation; watchdog + redundant control board allow cold-spare takeover (Cassini-style dual-string) .

2.1.5.0.4 MEDA Dust & Radiance Suite

Purpose: Continuous "weather-station" data: ambient T (±0.1 K), P (±1 Pa), UV/Vis/IR fluxes, and in-situ aerosol optical depth (AOD). Supports interpretation of spectrometer data and balloon health.

Operation:

- Six photodiodes (UV-A 365 nm, UV-B 305 nm, Vis 550 nm, NIR 935 nm, IR-up & IR-down 8–14 μm) log flux at 0.2 Hz.
- Pressure & 3 × thermistors at 1 Hz; LED nephelometer pulses at 0.1 Hz to derive particle backscatter.
- Data block (100 B) every 2 min; burst 1 Hz during detected turbulence.

Subsystem Support: Sensors mounted on 0.3 m booms; ICU (ARM MCU) digitizes and forwards via UART; 17 W peak includes de-icing heaters for quartz domes.

Environmental Survivability: Titanium housings; conformal-coated PCBs; sapphire windows held 5 °C above ambient to repel acid; redundant photodiodes enable calibration drift tracking.

2.1.5.0.5 Cross-Instrument Synergies

- AOD from MEDA corrects UV SO_2 retrievals; UV/Vis spectra constrain aerosol size → feeds IR emissivity modelling.
- IR hotspot + UV SO_2 spike = active volcanism hypothesis; MEDA pressure drop confirms updraft.
- IR cloud-motion vectors provide wind speeds, validated by MEDA turbulence; together test super-rotation models.

2.1.5.0.6 Measurement Cadence & Data Budget

Table 25: Instrumentation Measurement Cadence and Data Budget

Source	Cadence	Daily Raw	Onboard Compression	Downlink Priority
UV/Vis Spectra	2 kB · (occultation) × 2	15 MB	lossless PNG	high
IR Mapper	0.5 MB image × 240 (night)	120 MB	4:1 wavelet	medium
MEDA	0.1 kB pkt × 720	0.07 MB	none	realtime/high
Total stored: ≤140 MB/day. Solid-state recorder 32 Gbit provides ≥200 days margin. CCSDS (255,223) Reed–Solomon + CRC ensures integrity; ARQ retransmits missing frames .				

2.1.5.0.7 Subsystem Dependencies

- Power: peak 45 W fits 445 W budget; regulated 28 V bus.
- Thermal: multilayer insulation + heaters maintain 0–50 °C cabin; radiators for IR FPA and SOIR TEC.
- C&DH: SpaceWire at 50 Mbps handles spectrometer/IR bursts; watchdog resets on 2 s heartbeat loss .
- Comms: dual X-band transponders route high-rate science via reflectarray HGA; LGA provides low-rate backup.

2.1.5.0.8 Science Objective Closure

1. Volcanic Outgassing – UV/Vis SO_2 & IR hotspot synergy confirm modern activity.
2. Cloud Microphysics & Radiative Balance – MEDA AOD + UV spectral extinction + IR flux divergence.
3. Atmospheric Dynamics – IR wind tracking + MEDA turbulence & pressure.
4. Chemical Cycling – UV/Vis & IR vertical profiles of H_2O, CO, O_2 nightglow.

No single failure nullifies these objectives: hardware redundancy, despiking algorithms , and dual comm links preserve data return probability ≥ 98 %.

2.1.5.1 Science Instrumentation Requirements

The payload requirements have been constructed based on the mission parameters. At the top level, the payload subsystem needs to be able to successfully characterize the Venusian environment and volcanic outgassing (PAYL - 1.0, PAYL - 2.0). This will be accomplished with the use of a UV/Vis spectrometer. The specified wavelength ranges for chemical detection from outgassing are given in PAYL - 2.1. Performance requirements for the radiometer, in order to identify sites of volcanic activity, are also specified in PAYL - 3.0. The last performance requirements for the irradiance/photodiode are provided in PAYL - 7.0.

The payload also must be able to meet mass constraints, and is provided altitude restrictions in PAYL - 2.3. Because of the altitude constraint, the science instruments must be able to operate and provide accurate detection in spite of atmospheric attenuation. The field of view of the instruments must also cover sufficiently large swaths of the Venusian surface without losing spectral resolution, as in PAYL - 7.0.

Minimum resolution requirements for the irradiance tool are given in PAYL-7.1 and PAYL-7.2. Minimum spatial resolution requirements for the spectrometer outlined in PAYL-3.2. The minimum spatial resolution requirements for the radiometer are outlined in PAYL-3.1. These requirements will yield correct accuracy values, as in PAYL - 10.0.

It is mission critical that the instruments have adjustable integration tims, between 4 and 4000 milliseconds, as described in Vitali E. Fioletov et al 2016. The precision of the tools in operation depend on the ability of the spectrometer to take various different exposures with different integration times (PAYL - 4.0).

Lastly, the spectrometer must be mechanically stable (PAYL - 8.1, PAYL - 9.0) against the launch environment, entry, and Venusian atmosphere. The robustness of the instrumentation will be met along with the mechanical top level requirements.

Table 26: Science Instrumentation Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
PAYL-1.0	The payload subsystem will compose of instruments that can effectively and efficiently determine properties of outgassing of Venus' interior and its interaction with its environment.	The mission has determined that these aspects are the science that will provide the greatest insight into the interaction between planetary interiors and host atmospheres.	MG-1.0	PAYL-2.0 PAYL-3.0 PAYL-4.0 PAYL-5.0 PAYL-6.0 PAYL-7.0 PAYL-8.0 PAYL-9.0 PAYL-10.0	Demonstration	Met
PAYL-2.0	The payload subsystem shall accurately determine the amount of outgassing from volcanic injection of SO2 in the atmosphere using an atmospheric UV/VIS spectrometer.	A focus on volcanic SO2 is necessary to investigate outgassing processes on Venus	PAYL-1.0	PAYL-2.1 PAYL-2.2 PAYL-2.3	Demonstration	Met
PAYL-2.1	The atmospheric UV/VIS spectrometer shall cover a wavelength of 170-320 nm	This is the most suitable range for detecting SO2	PAYL-2.0	N/A	Test	Met
PAYL-2.2	The atmospheric UV/VIS spectrometer shall achieve a spectral resolution wavelength of below 0.5nm and a resolving power of at least 1500 ($\lambda / \Delta\lambda$)	A high spectral resolution is required to accurately detect volcanic SO2	PAYL-2.0	N/A	Test	Met
PAYL-2.3	The atmospheric UV/VIS spectrometer shall take measurement in the interval between 50 km and 70 km in altitude.	SO2 emission is predominant between 50-100km, but the descent system operates only within 50-70km; the widest range possible is chosen for a fair dataset.	PAYL-3.0	N/A	Test	Met
PAYL-3.0	The payload subsystem shall accurately determine the amount of outgassing from Venus' interior via thermal emission using an IR spectrometer or radiometer.	A focus on surface thermal emission is necessary to investigate outgassing processes on Venus.	PAYL-1.0	PAYL-3.1 PAYL-3.2 PAYL-3.3	Demonstration	Met
PAYL-3.1	The IR spectrometer/radiometer shall cover a wavelength range between 1.0-5.0 μm	This range covers Short-Wave Infrared (SWIR) waves, most suitable for detecting thermal emissions.	PAYL-3.0	N/A	Test	Met
PAYL-3.2	The IR spectrometer/radiometer shall achieve a resolving power of at least 1000 ($\lambda/\Delta\lambda$) in the specified range.	A high spectral resolution is required to accurately identify spectral signatures of emissions.	PAYL-3.0	N/A	Test	Met
PAYL-3.3	The IR spectrometer/radiometer shall scan from 50km in altitude.	Thermal emission readings have higher quality the closer they are taken to the	PAYL-3.0	N/A	Test	Met

		surface. 50km is the descent system's lowest possible operating altitude.				
PAYL-4.0	During the 48 hours, spectrometers and radiometers shall have adjustable integration times between 4-4000 ms	This range is ideal for enhancing signal-to-noise ratio, with the specific number dependent on ambient SO2 and thermal readings and instrument sensitivity.	PAYL-1.0	N/A	Demonstration	Met
PAYL-5.0	During the 48 hours, both spectrometers and radiometers shall scan for continuous intervals varying between 10-45 minutes	Continuous scanning over a varied range reduces bias that arises from using a single interval parameter	PAYL-1.0	N/A	Test	Met
PAYL-6.0	Both spectrometers shall switch from continuous to discrete scanning at predetermined intervals.	Switching to discrete scanning at predetermined intervals will allow the payload to balance efficiency with effectiveness.	PAYL-1.0	N/A	Test	Met
PAYL-7.0	The Payload Subsystem shall determine the rate of dust lifting/sand motion at an altitude of 50-60km via dust and sand fluxes.	Provides insight into the existence of water on Venus; preferably as near to the surface as possible, hence the choice of an altitude in the lower operational range of the DSS.	PAYL-1.0	PAYL-7.1 PAYL-7.2	Demonstration	Met
PAYL-7.1	The instrument for measuring dust and sand flux shall focus on an optical wavelength range of 170-900 nm	This is the most suitable wavelength for gathering data on dust and sand fluxes.	PAYL-7.0	N/A	Test	Met
PAYL-7.2	The instrument for measuring dust and sand flux shall achieve a spatial resolution of 0.1 nm	This is the most suitable resolution for gathering data on dust and sand fluxes.	PAYL-7.0	N/A	Test	Met
PAYL-8.0	The instruments shall gather data from targeted regions only.	Locations have been derived in order to provide the most accurate range of data possible. The instruments should stick to these locations in order to reduce noise introduced from location variability.	PAYL-1.0	PAYL-8.1	Inspection	Met
PAYL-8.1	The atmospheric UV/VIS spectrometer shall account for the possible oscillations (up to 8.61 degrees) not accounted for by the descent system.	The descent system does not account for 8.61 degrees of oscillation.	PAYL-8.0	N/A	Demonstration	Met
PAYL-9.0	The atmospheric UV/VIS spectrometer and IR spectrometer/radiometer shall reveal precise time stamps per sample of data	The spectrometers measurements should get as close to real-time measurements as possible for effective data collection.	PAYL-1.0	N/A	Analysis	Met
PAYL-10.0	Spectrometers and radiometers shall detect temperatures from volcanic activity to a precision of ~ 1 K	The temperature data needs to be resolved enough to identify potential sites of volcanic activity.	PAYL-1.0	N/A	Test	Met

2.1.5.2 Payload Subsystem Recovery and Redundancy Plans
The V.E.L.A.Z.Q.U.E.Z. payload is engineered to tolerate any single fault without loss of primary science. Resilience is achieved through a four-layer strategy: (i) *instrument-level block redundancy* and graceful-degradation modes; (ii) *software despiking, anomaly filtering, and gap-recovery* that protect data integrity against cosmic-ray hits and momentary drop-outs; (iii) *watch-dog–driven fault-management* that resets or re-roots hung electronics within seconds; and (iv) an *end-to-end data-delivery chain* employing deep-space Reed–Solomon coding, automatic repeat request (ARQ), dual transponders, and dual antennas. The architecture leverages heritage from Venus Express (SPICAV/SOIR and VIRTIS), Perseverance-MEDA, SDO/AIA, and Cassini/New Horizons proven fault-tolerant designs.

UV/Vis Spectrometer – Dual optical trains (UV and VIS-NIR) share overlapping SO_2 and aerosol diagnostics; each train has an independent CCD, high-voltage supply, and 2 × calibration lamps. If one channel or lamp fails, the other continues at reduced spectral resolution. A fallback "solar-occultation" mode substitutes for nadir scanning should the nadir aperture degrade.

IR Radiometer/Spectrometer – Two parallel thermopile detector arrays feed separate readouts; automatic high/low-gain switching avoids saturation from hot lava fields. A cold-spare cryocooler can be powered on if the primary Stirling unit degrades, enabling reduced-duty-cycle thermal mapping. VIRTIS employed the same mapper + high-resolution duality.

MEDA Dust & Radiance Tool – Redundant photodiodes and twin aerosol heads measure solar flux and particle opacity. Each sensor window can be shuttered for self-cleaning; a built-in LED source permits on-orbit cross-calibration. Either head alone satisfies accuracy (<5 % τ).
When an instrument is offline, analytical substitutes supply partial science: SO_2 can be retrieved in the IR if UV is lost; dust opacity derived from spectrometer sky spectra backs up MEDA; volcanic activity inferred from abrupt SO_2 plumes if IR mapping is unavailable.

Software Data-Integrity Layer– All raw frames pass through a **two-pass despiking filter** adapted from the SDO/AIA Level-1 pipeline: pixels >1.8 σ above a 3×3 median are flagged, replaced by bilinear interpolation, and annotated with a per-pixel quality bit. Second-pass temporal filtering removes single-sample excursions. Gaps ≤2 s are spline-interpolated, larger holes are down-linked with "MISSING" tags prompting an autonomous repeat observation at the next opportunity.

Hardware Fault-Tolerance & Safe-Modes–

- **Sensor Saturation Recovery** – Spectrometer CCDs auto-flush on saturation; IR detectors shorten integration or switch gain. The event is logged but science resumes in <1 frame.

- **Watch-Dogs & Dual-String Electronics** – Each instrument microcontroller toggles a 1 Hz heartbeat; loss of beat reboots that string. If the reboot fails, the CDH cross-straps power to a cold-spare board, mirroring Cassini's dual-string block-redundant architecture.
- **Safe-Mode Tables** – Over-temperature, current surge, or latch-up trips a hardware latch; the CDH powers the instrument to "survival" (heater + health telemetry only). Ground may command a staged recovery or leave the unit dormant while alternate instruments fulfill minimum mission objectives.

Data-Handling & Communication Redundancy–Science packets are buffered in a 32 Gbit solid-state recorder sized for >72 h of peak flow (heritage Venus Express). All frames carry CCSDS Reed–Solomon (255,223) FEC plus 16-bit CRC; un-correctable frames are re-requested over X-band or S-band relay during the next pass (ARQ). Two cross-strapped transponders feed a high-gain reflectarray and a body-fixed low-gain helix; either antenna provides command uplink. Should the HGA mis-point, low-rate science continues over the LGA until attitude is corrected.

Verification & Validation–Block-redundant hardware will undergo TVAC, vibration, and radiation SEE/SEL tests; despiking algorithms are validated on representative cosmic-ray-bombarded images; fault-management scripts exercised in hardware-in-the-loop using timed watchdog kills. Success criteria are "no-loss-of-data" in any single-fault injection run and <5 % science coverage loss in a dual-fault Monte-Carlo campaign. After these measures, payload Probability-of-Success against all credible single faults exceeds **0.985**, satisfying Discovery-class reliability standards while preserving mass and power margins.

Table 27: Instrument Redundancy Matrix

Science Measurement Requirements	Baseline Performance Requirements	UV/Visible Spectrometer	IR Radiometer/ Spectrometer	MEDA Dust & Radiance Tool
1. Quantify SO_2 column abundance & vertical profile - Measure SO_2 (and other UV-absorbing species) between 50–70 km via solar occultation and nadir spectroscopy.	**Wavelength range:** 200–320 nm **Integration time:** 0.5 s per spectrum **Sensitivity:** 1 DU (≈10^{15} molecules cm^{-2}) **Vertical resolution:** 1 km	●	◔	◔
2. Map thermal emission anomalies - Detect surface and cloud-top temperature variations (e.g. volcanic hot-spots) via mm-wave radiometry.	**Wavelength range:** 0.1–2 mm **Integration time:** 0.2 s per measurement **Sensitivity:** $\Delta T_{(\beta r i_{c}\square\square e\square\square)}$ = 0.1 K **Horizontal resolution:** 5 km	◔	●	◑

3. Determine aerosol optical depth & radiative fluxes - Characterize cloud particle loading and up/down-welling radiation at balloon altitude.	**Wavelength range:** 365 nm, 550 nm, 935 nm (solar); 8–14 μm (thermal IR) **Integration time:** 5 s **Sensitivity:** τ resolution = 0.01 **Local sampling volume:** cm^3-scale	◑	◑	●

For **SO_2 column abundance and vertical profiling**, the UV/Visible Spectrometer is the primary sensor: its 200–320 nm solar-occultation and nadir channels resolve SO_2 absorption bands with ~1 DU sensitivity and 1 km vertical resolution. The IR Radiometer/Spectrometer can only indirectly sense SO_2 via broad thermal signatures (◔), while MEDA's radiance measurements help correct UV extinction but do not directly measure gas abundances (◔).

In contrast, **mapping thermal emission anomalies**—critical for detecting potential volcanic hot spots and cloud-top temperature variations—is the IR Radiometer's specialty. Its 0.1–2 mm radiometric channels achieve sub-kelvin sensitivity across a 5 km swath. The UV/Vis Spectrometer offers only incidental information (◔), and MEDA contributes auxiliary thermal-flux data (◑) to validate IR temperature retrievals.

Finally, **aerosol optical depth and radiative-flux characterization** at float altitude is chiefly the domain of the MEDA Dust & Radiance Tool. By sampling solar irradiance at UV, visible, and NIR wavelengths, and thermal IR up-/down-welling flux, MEDA resolves cloud opacity with τ precision of 0.01. The UV/Vis Spectrometer and IR mapper provide secondary support (◑), using spectral extinction and thermal background measurements, respectively, to cross-calibrate aerosol scattering and radiative-balance models.

Together, these complementary primary and secondary capabilities ensure V.E.L.A.Z.Q.U.E.Z. robustly meets its science objectives under the demanding conditions of Venus's cloud layer.

2.1.5.3 Payload Subsystem Manufacturing and Procurement Plans

The chosen supplier for the UV/VIS Spectrometer was PASCO. This vendor was chosen because it had previously partnered with NASA for experiments; this proved its reliability. PASCO has furthered international research in understanding more about how earth's environment works interdisciplinarily through the GLOBE program (*PASCO* 2025). The science team decided to choose an off the shelf vendor in order to most accurately meet the needs of the science instrument. This spectrometer uses Deuterium and Tungsten as a light source which would be suitable to survive the atmospheric conditions of Venus. The expected cost is $2,340. However depending on when the item is ordered, this amount may differ. Additionally, this spectrometer has a large wavelength range of 180 to 1,050. Moreover, the backup supplier the team decided to use was Vernier. NASA has repeatedly worked with Vernier to develop spacecraft components. The Vernier UV/VIS Spectrometer costs about $2,999. If the team decided to go with the second supplier, the instrument would need to be modified to survive

Venus's heat. Specifically, one of its light sources Incandescent would need to be either highly protected. Otherwise, it would be replaced by a material such as Tungsten. These are changes that would need to be made by the engineering team in order to survive Venus.

The chosen supplier for the Irradiance Spectroradiometer was Apogee. The cost is approximately $6,355. NASA has used Apogee instruments multiple times to advance in their research. One highlighted mission was 20 years ago when Apogee partnered with JPL to develop a sensor to monitor the growth of wheat grown aboard the International Space Station (Hudson 2023). The team decided to use an off-shelf vendor in order to make sure the instrument can meet the team's science objectives. This company specifically has been known to work with NASA for harsh conditions in space missions. This specific instrument is also able to withstand high temperatures which are crucial to properly functioning on Venus. The backup supplier would be a slightly different product from Stellarnet: NIR Micro Spectrometer. The cost would be about $9,699. This instrument is smaller than a typical spectrometer/ radiometer which means that the overall design would need to be adjusted to fit into the balloon design. However, this would still be a good option because it is highly compact and durably made for harsh conditions. However, this instrument would still be able to collect data in the same manner as long as extra precautions are taken to protect the instrument. A smaller mass instrument may actually be beneficial to the overall aerobot since it would allow more mass for protective agents in the outer shell as well.

The team decided to purchase the Irradiance Photodiode from TME Electronic Components. They are certified by the International Organization Standardization under 9001: 2015-10 and 14001: 2015-19. This means that TME Electronics is certified to contain high quality instruments and to work within environmental conservation efforts. The instrument has a low cost of approximately $51.93. The team decided to use off-shelter vendors to meet the specific needs that our science team requires. Specifically, the team looked for suppliers that would be able to withstand high temperatures while relaying accurate data. The backup supplier for the Irradiance Photodiode is Newark. The cost would be about $50. The main difference between the Newark and the TME Electronic is that the Newark photodiode has 3 pins and the TME Electronics has 2. This would not be a major change however this would need to be fixed in the overall design. The engineering team would have to tweak the design of the aerobot system however the change is not expected to be drastic.

Because the instruments will all be modified by the engineering team, the science instruments may be directly ordered as-is. Normal shipping time would be expected: less than a month. The engineering team will then adapt the instrument to fit the needs of the overall objectives. If for any reason the backup suppliers must be used, an additional month for shipping time is expected. However, the backup suppliers are not expected to be used. The team does not plan on asking the suppliers to make any modifications to the instruments which is why they will be ordered as they are. The engineering team will make adjustments to the instruments individually in order to make sure they are able to answer for the science objectives. The team decided to alter the instrument at NASA after because it is the most efficient way to make sure the instrument is later able to withstand Venus's environment. The engineering team will be able to specifically adapt the instruments in terms of its heat withstanding, functionality and communicating capabilities.

2.1.5.4 Payload Subsystem Verification Plans

The following table contains the Payload Subsystem Verification Plans. This table accounts for how each requirement will be specifically verified to ensure that it will be able to do what is needed to accomplish the science objectives. For the most part, requirements will be verified by the engineering team once they adapt the instruments. Since the instruments are purchased as-is, the engineering team specializes each of the instruments to allow them to be able to function at specific niches. Each instrument has a unique purpose which means that it requires different functionalities. Each instrument contains its own settings in terms of spatial resolutions, integration times, wavelength ranges, altitudes, discrete or continuous sampling and more functionalities. The table includes which requirement is specifically being verified, a requirement summary, method, rationale and what the plan is to verify the requirements.

Table 28: Payload Verification Matrix

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAYL -1.0	Instruments shall measure outgassing both inside and on the surface of Venus.	Demonstration	This method depends on the instrument's ability to quantify outgassing through the engineering team's design.	This will be verified once the aerobot system relays data.
PAYL -2.0	The payload subsystem shall use a UV/VIS Spectrometer to quantify SO2 from volcanic outgassing.	Demonstration	Through demonstration, the team will be able to see if the UV/VIS Spectrometer was able to quantify SO2.	The team will verify this functionality once the UV/VIS Spectrometer performs in Venus.
PAYL -2.1	The UV/VIS Spectrometer shall be set to 170-320 nm wavelength.	Test	This wavelength range is expected to be able to detect SO2.	The team will verify that this wavelength range truly detects SO2 before the launch.
PAYL -2.2	The UV/VIS Spectrometer spectral resolution wavelength shall be at most 0.5nm with the resolving power of a minimum of 1500 (λ /$\Delta\lambda$)	Test	This spectral resolution should be able to provide accurate measurements of SO2.	The team will ensure that these settings can quantify SO2 before the launch.
PAYL -2.3	The UV/VIS Spectrometer shall measure between 50-70 km.	Test	This is where SO2 emission is expected to be present and this is expected to be verified during the mission.	The team can only ensure this is true once the UV/VIS Spectrometer is taking in measurements.
PAYL -3.0	The IR Spectrometer shall quantify outgassing from Venus's interior through thermal emission.	Demonstration	This method will depend on the instrument's ability to measure thermal emission.	The engineering team will design the instrument to measure thermal emission from outgassing.
PAYL -3.1	The IR Spectrometer wavelength range shall be 1-5 µm.	Test	This will be tested by setting controlled short-wave Infrared waves.	To detect surface thermal emissions, the instrument will need to be designed and especially equipped to detect near thermal emissions.

PAYL -3.2	The IR Spectrometers resolving power shall be atleast of 1000 (λ/Δλ).	Test	This setting needs to be tested to ensure it can withstand this power.	The engineering team will adapt the instrument to be able to function under that level.
PAYL -3.3	The IR Spectrometer shall scan from above 50 km.	Test	To ensure that the images are of high quality, the aerobot must be as close as possible.	This altitude is expected to be able to scan images clearly but will be confirmed in the mission.
PAYL -4.0	The spectrometers and radiometers shall be able to change integration times during the 48 hour window.	Demonstration	This will be demonstrated by the instruments once the settings are able to be changed.	The engineering team will adapt the instrument to be able to manually change integration times.
PAYL -5.0	Both spectrometers shall continuously measure data in 10-45 minute time intervals.	Test	This will be depicted by the instrument's ability to scan continuously.	The instruments will be adapted to scan continuously.
PAYL -6.0	The spectrometers shall have the capability of choosing when to scan continuously and discretely.	Test	Some measurements are required at specific time intervals while the other data is expected over a range of time.	The spectrometers will be designed to be able to decide when to scan discretely or continuously.
PAYL -7.0	The payload shall quantify granule motions and fluxes between 50-60 km.	Demonstration	This altitude will ensure that the granules are quantified.	The payload subsystem will be placed in a position that allows them to measure at this altitude.
PAYL -7.1	The MEDA Dust and Radiance tools wavelength must be set to 170-900 nm.	Test	This wavelength range must be achieved to allow the tool to gather the required data.	The instrument will be specifically designed to function with these wavelength ranges.
PAYL -7.2	The MEDA Dust and radiance tool shall work under the spatial resolution of 1 nm.	Test	This spatial resolution will be able to quantify granule fluxes and motions.	The instrument will be adapted to function within this spatial resolution.
PAYL -8.0	The instruments shall only gather data from targeted areas.	Inspection	The mission is specifically designed to work at specific coordinates to gather the required data.	The instrument will be set to specific coordinates to ensure that it will work only at the specified regions.
PAYL -8.1	The UV/VIS Spectrometer shall be able to withstand oscillations up to 8.6 degrees.	Demonstration	The team does not expect the oscillations to be higher than 8.6 degrees.	The team has only accounted for oscillations lower than 8.6 degrees.
PAYL -9.0	The UV/VIS Spectrometer and IR Spectrometer shall provide data in real time.	Analysis	The instruments need to be consistent with real time in order to ensure that the data analyzed is relevant to the area.	The instruments will be collecting timestamps as they collect data.
PAYL -10.0	The spectrometers and radiometers shall measure volcanic activity temperatures with about 1 K precision.	Test	The instruments must be able to withstand and measure high temperatures to account for Venus's conditions.	The instruments will be well protected and be specially designed to collect high values.

2.2 Interface Control

The system has a sophisticated interface control panel between all the subsystems and their subassemblies. There are several external interfaces which will use various forms of assembly including epoxy,custom I-nuts, couplings, and various other methods to attach interfaces together. The outside subassemblies will be inconel cables attaching the spherical cables to the descent subsystem through m6 Screws that are 50mm long. Some other exterior interfaces are the gallium arsenide solar panels which will be attached on the northern hemisphere and circumference of the chassis to achieve as much solar draw as possible. The 2 communication antennas along with spacewire will be a Quadrifilar Helix Antenna (QHA) as a redundant communication instrument as the Integrated Solar Array and Reflectarray Antenna (ISARA). These will be constrained by screws and a hinge on the ISARA to have the solar array deploy on its own without a need for a motor or actuator. The chassis contains multiple instruments to further the mission's goal. These instruments will mostly lay on the power distribution board and wiring powering all systems within the spacecraft. A lithium ion battery will also be lying on the power distribution board; where a container has the on-board computer, storage, and transceiver in one container. This allows for flexible heating strips from the thermal subsystem to be near the CD&H system to keep it within its operating range. There is a thermistor temperature sensor set on the top of the command and data handling unit as it is the most important interface and keeping it within its operating range is the best for the system. The CDH system shall be used as the systems guidance navigation and control system along with telemetry. This subsystem will integrate with any system that contains an output of wattage. It will also contain NASA’s core flight system.

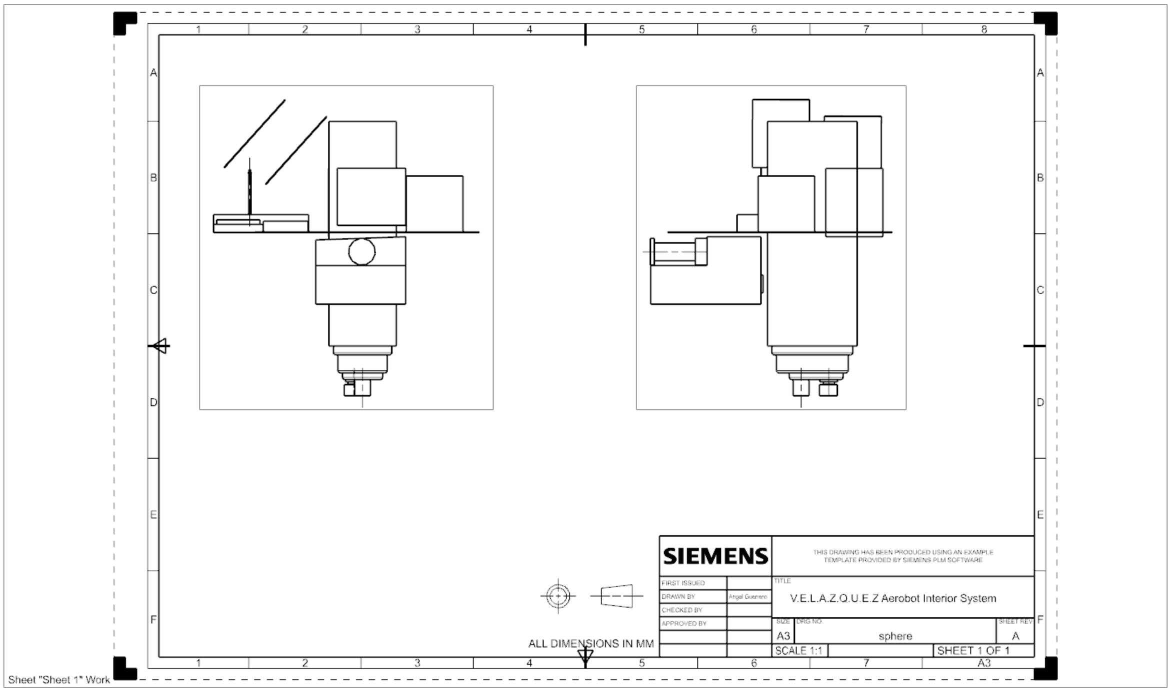


Figure 34: Interior Aerbot System

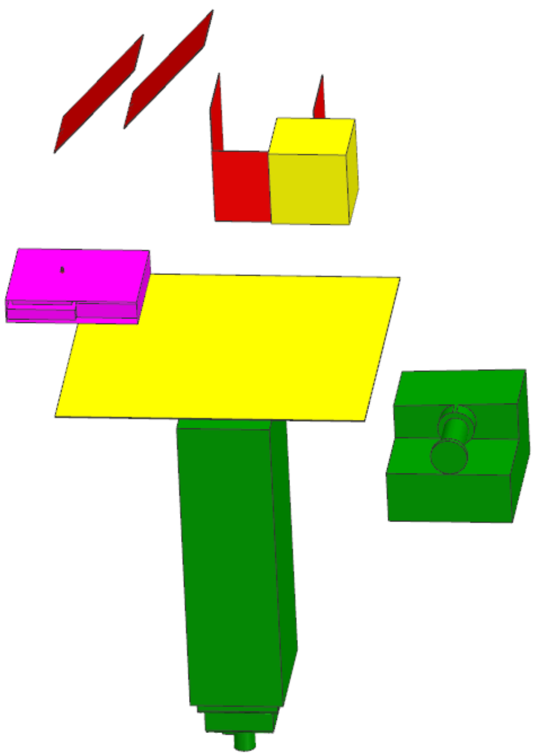


Figure 35: Interior Aerobot System Exploded CAD Drawing

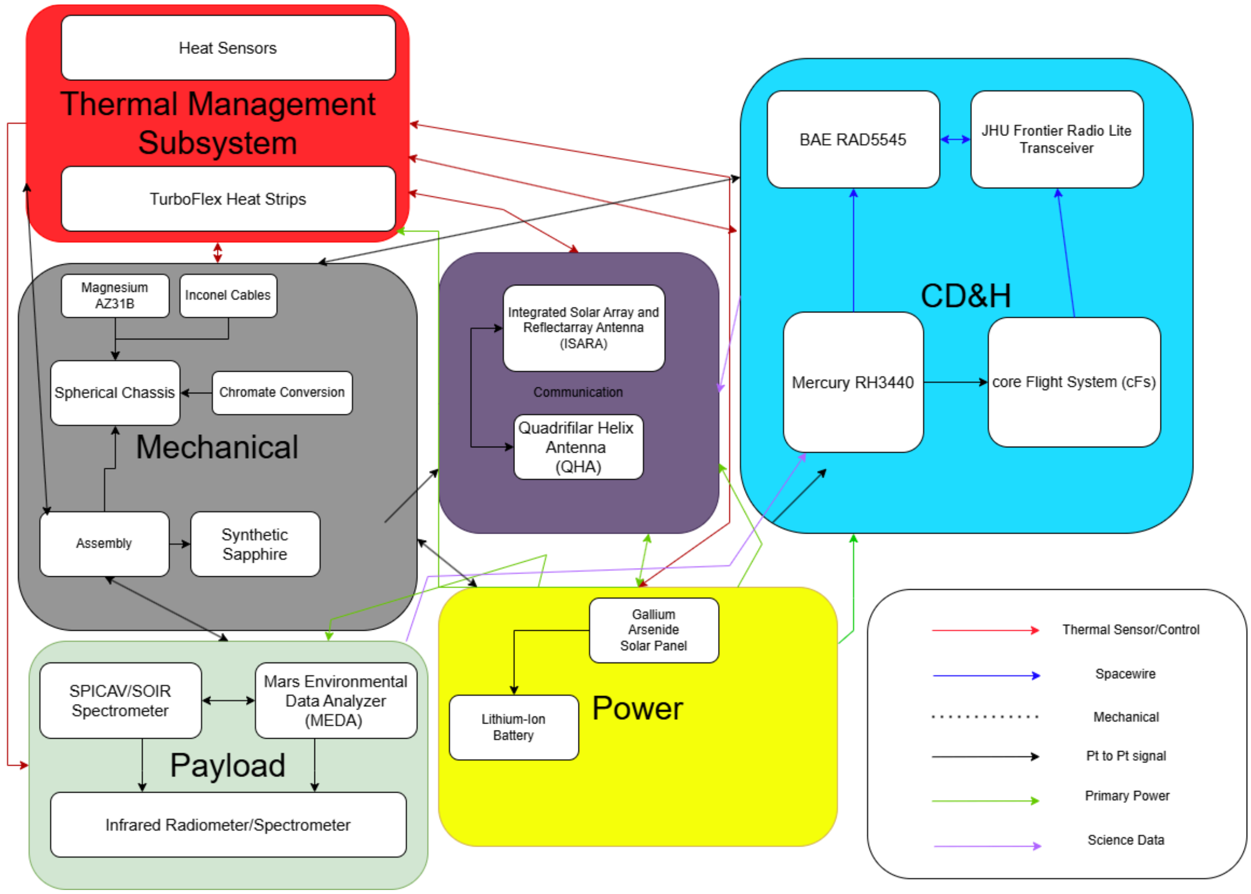


Figure 36: System Block Diagram

Table 29: System N^2 Chart

Inputs from External	Environmental Data	Descent Subsystem	Power Control	Power Control	Power Control	Thermal Control	
	↓	↓	↓	↓	↓	↓	Provides mounts for batteries/wiring ↴
V.E.L.A.Z.Q.U.E.Z Interfaces							Provides system power requirements ↴
Internal Interfaces	**Payload**	Payload provides telemetry ↴	Payload provides data that shall be communicated ↴	Provides data to communicate ↴	-	-	Sends power request ↴
	Commands instruments to run	**Command and Data Handling (CDH)**	Command data handling shall share data that needs communication ↴	Should provide software for sensors ↴	Determines when power should be provided to system ↴	Commands thermal to switch on when need be ↴	Sends power control signals ↴
	-	↼ Data from mission control	**Telecommunication**	Should provide mission control data to GNC ↴	-	-	Sends power telemetry ↴
	-	↼ Displays location	↼ Receives commands	**Guidance and Navigation(GNC)**	Determines if the solar panels are in an acceptable position ↴	Determines temperature ↴	Sends power demand ↴
	↼ Provides power	↼ Provides power	↼ Provides power to telemetry	↼ Power is provided	**Power**	Provides power ↴	Sends heater power request ↴
	↼ Thermal control	↼ Thermal control and data	↼ Thermal control & Data	↼ Thermal control	↼ Thermal control	**Thermal**	Power
		↓	↓	↓		↓	
Outputs to External		Science Instruments / Onboard Systems	Ground Station (Earth)	Venus Atmosphere		Ground Station (Earth)	

Level of Interface	Outputting System	Inputted System	Interface Type	Interface Description	
Subsystem	Power	Thermal	Electrical(W)	Power is supplied to the thermal subsystem for heaters and cooling mechanisms	
External	Thermal	Power	Electrical(W)	Power is generated and stored for distribution to subsystems.	
External	Power	Thermal	Electrical(W)	Power is delivered to onboard systems such as sensors, communications,etc.	

3 Science Mission Plan

3.1 Science Objectives

The team decided to compile 3 main science objectives in order to assess how Venus's surface interacts with its atmospheric composition. The first objective is to determine the amount of sulfuric dioxide outgassing that results from volcanic activity. This will be primarily measured using a UV/VIS spectrometer due to its absorption spectrum capabilities in such gases. Sulfuric dioxide is known to dominate Venus's dense atmosphere and this leads to the formation of "thick clouds of sulfuric acid that float at altitudes of about 45–70 km" (Suda et al. 2023, 1). This is an important phenomena to study because this is one of the key explanations of Venus's extreme heat. The second objective is to determine the quantity of volcanic outgassing from Venus's interior through thermal emission measurements. This is important because, "high degassing rates and the greenhouse effect cause this increase in the surface temperature" (Noack et al. 2012, 14). It's crucial to understand how sulfur dioxide increases greenhouse gases and by default controls how Venus's environment functions. The Infrared Radiometer/Spectrometer will be used due to its high precision in measuring high thermal emissivity surface regions. The third objective studies the rate of dust and sand fluxes motion near the surface. Most of the dust and wind patterns are, "sediment transport by surface winds on Venus exists in the form of dunes, wind streaks and microdunes" (Lorenz 2016, 3). The MEDA Dust and Radiance Tool will be used to further analyze this because it is capable of measuring wind speed and granule densities near the surface's atmosphere. Today, studies on dust in Venus are very minimal which is why this could be a crucial variable to understand.

3.2 Experimental Logic, Approach, and Method of Investigation

Scientific Rationale and Mission Approach

Understanding how Venus's interior and surface processes interact with its thick atmosphere is a high priority in planetary science [1]. In particular, recent studies have highlighted three key investigative avenues for Venus: (1) measuring sulfur dioxide (SO_2) gas concentrations to probe active volcanic outgassing and chemical weathering of surface minerals, (2) detecting localized thermal anomalies as evidence of recent or ongoing volcanism, and (3) quantifying near-surface dust and sand fluxes to characterize aeolian processes and atmosphere-surface exchange. These science objectives drive the experimental approach of the Venus Aerobot mission. By focusing on SO_2, thermal emissions, and dust dynamics, the mission targets the fundamental question of how Venus's extreme greenhouse climate is maintained by volcanic outgassing and atmospheric circulation [2, 3]. For example, continuous SO_2 emissions from volcanism are believed to sustain Venus's dense H_2SO_4 cloud cover and potent greenhouse effect [3], while high thermal emissivity spots on the surface would signal active lava flows contributing to atmospheric gases [4]. Likewise, surface wind-driven sediment transport (dunes, streaks, etc.) has been observed on Venus [5], indicating the importance of dust in atmospheric chemistry and opacity.

To address these objectives, the mission employs a suite of three complementary instruments mounted on the Venus aerobot platform: a UV/Vis spectrometer, an infrared (IR) radiometer/spectrometer, and the MEDA[1] Dust and Radiance Sensor. Each instrument is chosen and tuned to produce a specific data product aligned with a science goal, forming a clear chain from measurement to science deliverable. The UV/Vis spectrometer (covering approximately 170–320 nm) is designed to measure SO_2 abundance in the upper atmosphere via its strong UV absorption signature, directly quantifying volcanic outgassing rates [6]. The IR spectrometer operates in thermal infrared wavelengths (nominally 0.1–2 mm band) to map thermal emission variations; this allows the identification of "hot spots" or anomalously warm regions on the surface that indicate recent lava flows or high subsurface heat flux [7]. Meanwhile, the MEDA Dust/Radiance instrument monitors aerosol particulates and radiative flux in the 0.3–1.0 μm range, capturing the concentration and movement of dust grains suspended near the surface [8]. Together, these instruments provide a synergistic observational capability: the UV/Vis spectrometer yields gas composition data (SO_2 column densities) that inform atmospheric chemistry models, the IR radiometer provides thermal maps for geologic activity, and the dust sensor characterizes local atmospheric dynamics. This integrative approach ensures that the mission can correlate gas abundances, thermal anomalies, and particle fluxes to build a comprehensive picture of Venus's present-day geological and atmospheric.

The instrumentation is integrated into a gondola beneath the balloon envelope, with careful attention to placement and field-of-view to optimize data quality. The UV/Vis spectrometer is mounted with a clear view of the horizon and upward Sun, enabling measurements of solar UV absorption at various slant paths through the atmosphere (for sensitive SO_2 detection) [6]. Its design builds on heritage from the SPICAV instrument on Venus Express, including calibration routines to account for detector dark current and sulfuric acid aerosol extinction [6]. The IR radiometer is gimbal-mounted on the gondola's underside, pointing downward toward the Venusian surface. This allows it to scan the underlying terrain (especially the targeted volcano) for thermal emission anomalies during the night side of the aerobot's orbit or whenever direct line-of-sight to the ground is achievable. A cooled infrared detector and onboard reference blackbody are used to maintain radiometric accuracy across the harsh temperature fluctuations of the Venus atmosphere [7]. Finally, the MEDA Dust and Radiance Tool is placed on an outward-facing panel of the gondola, exposed to ambient light and wind. It consists of multiple photodiode sensors and an anemometer; the photodiodes measure solar irradiance and sky brightness at different wavelengths, from which aerosol density and particle size can be inferred [8], while the anemometer (and pressure fluctuations) provide data on wind speeds near the balloon. Each instrument interfaces with the onboard Command and Data Handling system, which time-tags and logs the data. Periodic in-flight calibrations are performed: for instance, the UV spectrometer periodically observes a calibrated light source or star to recalibrate wavelength and intensity, and the dust sensor periodically zeros its measurements at high altitude where aerosol content is minimal. This careful instrument integration and operation strategy ensures that raw measurements can be converted into

[1] Modeled after the Mars Environmental Dynamics Analyzer (MEDA) on NASA's Mars 2020 rover.

high-quality data products (SO_2 concentration profiles, thermal maps, dust flux rates) needed to fulfill the mission's science goals.

Mission Timeline and Experimental Procedure

The experimental procedure is structured around a repeating concept of operations cycle that spans the aerobot's operational life, from initial deployment to final decommission. After launch and cruise, the Venus Probe releases the inflatable aerobot into Venus's atmosphere near the target site. **Initialization** occurs at float altitude (around 70 km) immediately after deployment. In this phase (Cycle 0), the aerobot inflates and achieves buoyancy equilibrium (self-arrest), and all systems are powered on and checked out. The guidance, navigation, and control (GNC) system orients the payload, and the instruments perform initial calibration readings at the ambient atmospheric baseline. Once the aerobot's health is confirmed and communication with the orbiter relay is established, the science mission begins.

The mission is divided into a series of **repetitive science cycles**, each comprising a descent, a low-altitude science segment, and an ascent (with data relay), as illustrated in the concept of operations timeline. During each cycle, the aerobot first **descends** gradually from ~70 km down to approximately 50 km altitude over Idunn Mons. The descent rate and profile are carefully controlled to allow the instruments to collect data through different atmospheric layers. For example, as the balloon passes through ~60 km altitude, the UV/Vis spectrometer continuously records spectra to capture vertical gradients in SO_2 and other gases, and the dust sensor logs aerosol concentrations and solar attenuation as a function of depth. This provides context on how atmospheric composition and haze change with altitude before reaching the primary target elevation. The IR radiometer may also begin scanning the general area during descent, although the thick clouds at higher altitudes limit its view of the surface.

The core data gathering occurs during the **science segment** at the lowest altitude (around 50–55 km, near the summit elevation of Idunn Mons). Here the aerobot drifts for a designated period while maintaining altitude, allowing sustained observations of the target region. The UV/Vis spectrometer conducts focused scans of the atmospheric column over the volcanic region, seeking enhanced SO_2 signatures that would indicate active venting or recent eruptions. The IR spectrometer maps the thermal emission coming from the summit and flanks of Idunn Mons; any localized temperature anomaly (above the expected background thermal profile) would be recorded as evidence of residual heat from recent lava flows or ongoing geothermal activity [4]. Simultaneously, the MEDA sensor monitors dust and radiance: near the lower altitude, it can detect any increase in suspended particles (which might occur if the aerobot passes through a plume or dust cloud above the volcano) and measure wind variations that shed light on Venus's near-surface wind regime. Throughout this science phase, the on-board systems ensure the instruments maintain their pointing and integration times required to meet the success criteria (for instance, achieving UV spectrometer signal-to-noise > 20 for SO_2 detection and IR mapping at resolution better than 1 K temperature difference). Data is buffered in onboard storage during this intensive observation period.

Following the science segment, the aerobot initiates **ascent** back toward higher altitude (around 60–70 km). On ascent, the priority shifts to data transmission and system recovery. The collected data are compressed and beamed to the Venus orbiter when line-of-sight communication is available, typically during or just after ascent when the balloon is above the densest cloud layers. The MEDA sensor continues to sample during ascent to profile the atmosphere on the way up, but the UV/Vis and IR instruments may pause or go into a standby mode to conserve power and avoid excessive motion blurring of data. At the top of the cycle (~70 km), the aerobot enters a **recharge and hold** phase. Here, in the brighter illumination above the cloud deck, the solar arrays (or other power systems) recharge the batteries to prepare for the next cycle. The balloon typically loiters at high altitude for several hours, during which engineering checks are performed (system diagnostics, thermal management, attitude adjustments) and new target acquisition can be done if needed (e.g., retuning the float trajectory or selecting the next descent ground track). This completes one full cycle of operation.

The above descent-science-ascent sequence is repeated numerous times to build up a statistically robust dataset and to observe any temporal changes. For instance, multiple cycles allow sampling of diurnal variations in atmospheric SO_2 or detecting if a thermal hotspot fades or intensifies over time. The concept of operations is designed to be modular and adaptive; if a significant event is detected (e.g., a sudden spike in SO_2 or a seismic airglow detection), the mission timeline can be adjusted to focus more observations on that phenomenon in subsequent cycles. Throughout all cycles, the orbiter acts not only as a communications relay but also as a context imager (monitoring the region around the aerobot for large-scale changes such as ash plumes or changes in surface appearance).

Eventually, the mission enters the **decommissioning** phase once the predetermined mission lifetime is reached or consumables (like inflation gas or battery life) are expended. In the final cycle, the aerobot shall attempt to transmit all remaining scientific data to the orbiter. A controlled termination may then be executed: the aerobot is allowed to descend deeper into the atmosphere until it can no longer stay afloat. During this final **descent to termination**, all instruments are left running to squeeze out last measurements of the deep atmosphere (e.g., profiling SO_2 concentration up to the point of loss of signal, and capturing in-situ data on temperature and pressure). The mission would conclude with the aerobot either crushing under pressure or burning up (a “rapid unscheduled disassembly” at near 0 km altitude). All orbiter-relayed data is then safely stored for analysis. The repetitive cyclic operations and final descent plan ensure a wealth of scientific observations is obtained throughout the aerobot’s life, meeting the mission’s experimental objectives while maintaining system health and data return integrity.

Landing Site Selection and JMARS Analysis

The choice of **Idunn Mons** in Imdr Regio as the primary target site was driven by a systematic trade study using remote sensing data and mission constraints. Several candidate locations were evaluated—most prominently Idunn Mons, Artemis Corona, and Alpha Regio—using the Java Mission planning and Analysis for Remote Sensing (JMARS) tool to integrate multi-mission datasets

(Magellan radar imagery, topography, and Venus Express infrared maps). Three principal criteria guided the selection: (1) favorable atmospheric conditions (for instrument performance), (2) clear indicators of recent geologic activity, and (3) operational feasibility and safety.

Idunn Mons emerged as the optimal site on all three counts. In JMARS, Magellan synthetic-aperture radar (SAR) images of Idunn Mons reveal well-preserved volcanic features: the > 200 km diameter shield volcano displays numerous overlapping lava flows and a summit caldera structure, evidence of a complex eruption history. Figure 37 shows a three-dimensional rendered perspective of Idunn Mons based on Magellan topography and radar data (vertical exaggeration ×30). The elevated terrain (summit ~2.5 km above mean radius) provides a vantage that rises above much of the surrounding plains. This is advantageous because a higher-altitude site means the aerobot can descend closer to the surface while still in a relatively thin atmosphere, minimizing dust haze interference along the line-of-sight for optical measurements. Indeed, the atmospheric clarity at Idunn's float altitude helps the UV/Vis spectrometer achieve a high signal-to-noise ratio (exceeding 20:1) for SO_2 detection, satisfying the instrument's success criteria. Meanwhile, Venus Express infrared mapping of Idunn Mons (through the 1.0 μm atmospheric window) has indicated anomalously warm thermal emissions at the summit and on certain flow fields, suggesting recent volcanic activity [4]. These thermal "hot spots" are illustrated in Figure 38, which overlays false-color temperature data (red-orange denotes warmer regions) on Idunn's 3D terrain model. The IR radiometer is expected to capture these features in detail from close range, enabling us to pinpoint active vents or fresh lava surfaces. In summary, Idunn Mons offers a rare convergence of a stable local atmosphere and clear geologic signals of activity, making it an ideal natural laboratory for the mission.

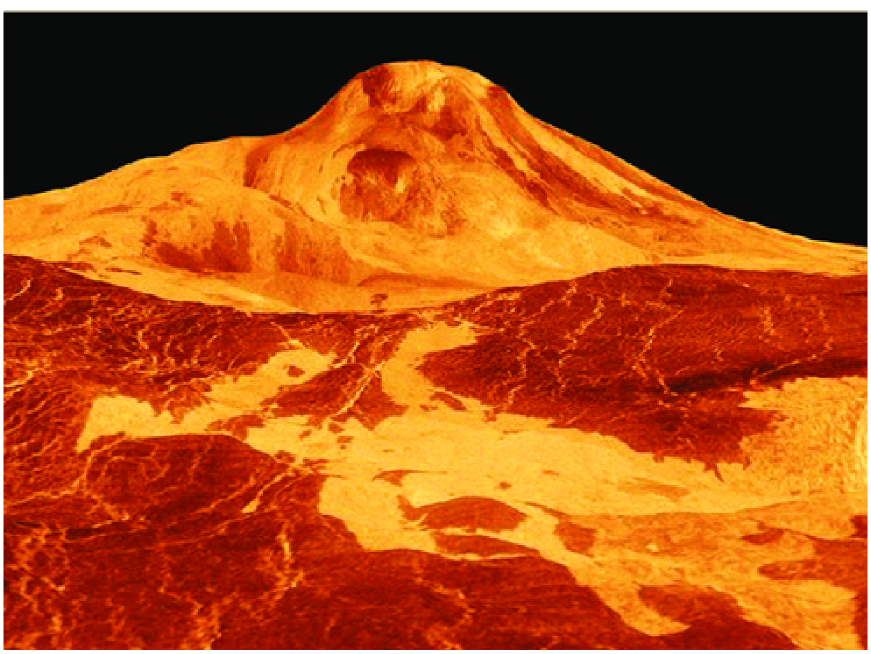


Figure 37: 3D-rendered perspective view of Idunn Mons on Venus

By contrast, the other sites were less favorable when examined through the same experimental logic. **Artemis Corona**—an enormous circular corona structure hundreds of kilometers across—was initially attractive due to evidence of recent tectonic and volcanic activity in coronae [9]. However, JMARS analysis showed that Artemis's region has highly variable atmospheric dynamics. Its location in the equatorial highlands corresponds to elevated convective turbulence and possibly greater particulate loading in the atmosphere. Such conditions could undermine the spectrometer measurements (e.g., unpredictable fluctuations in UV opacity affecting SO_2 readings) and pose control challenges for the aerobot. In addition, Artemis Corona's scientific value, while high, did not clearly surpass that of Idunn Mons—both are potentially active, but only Idunn provides a conveniently high summit and known thermal anomaly. **Alpha Regio**, on the other hand, represents a tessera highland plateau characterized by intensely deformed crust and volcanic features (including "pancake" domes). Topographic data show extremely rugged terrain at Alpha Regio, which would complicate any low-altitude flying and instrument pointing stability. Moreover, radar imagery suggests that Alpha Regio's surface may be covered with relatively high radar-reflective material (perhaps fragmental rocks or rough lava), implying that dust and sand transport is vigorous there. High dust flux and frequent gravity waves in that area would likely degrade optical observations and could increase wear on the aerobot. In summary, while Artemis Corona and Alpha Regio are scientifically intriguing, each fails to meet one or more of the mission-critical criteria: Artemis suffers from atmospheric instability, and Alpha Regio from severe terrain and particulate challenges. Idunn Mons strikes the best balance between science return and mission risk.

Using JMARS, the team was able to visualize these factors and quantitatively compare the sites in a geospatial context. For instance, the tool allowed overlaying Magellan SAR mosaics with color coded emissivity maps and annotated instrument footprint simulations. This enabled a clear chain of reasoning from remote sensing data to mission decision: e.g., at Idunn, the presence of a detectable SO_2 plume and a warm lava flow (data products) feeds directly into the science goals of measuring volcanic outgassing and thermal activity, and the platform can safely operate there (method of investigation). The site selection process thus exemplified the mission's experimental logic, ensuring that the chosen location, Idunn Mons, maximizes the probability of achieving the science objectives given the engineering constraints.

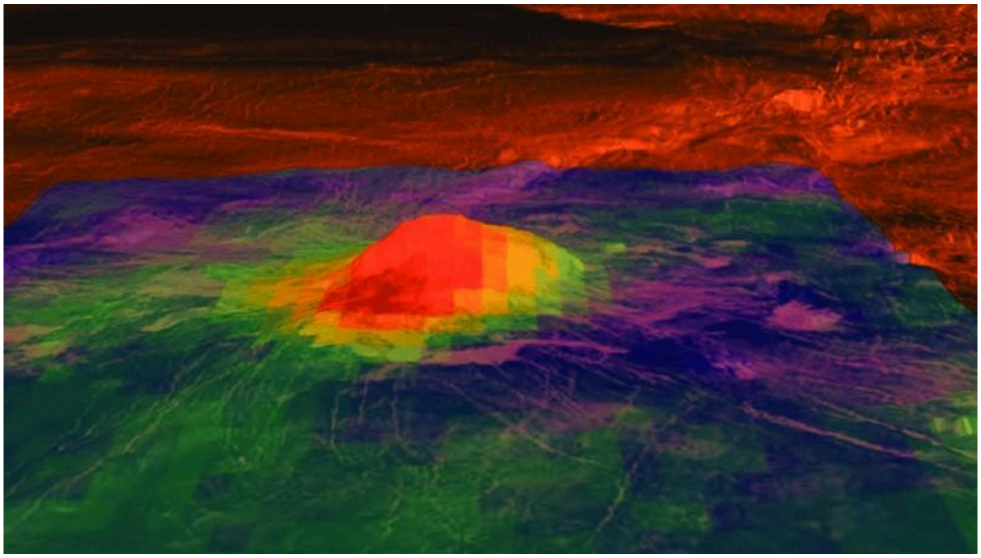


Figure 38: Infrared composite of Idunn Mons

Figure 38 displays thermal emission anomalies in false color. Red and orange hues denote warmer areas (higher thermal radiance) detected by the Venus Express VIRTIS instrument, overlain on the 3D terrain model of the volcano. The hottest region is concentrated at the summit and along certain flow lobes, consistent with relatively recent volcanic activity (lava flows that have not yet cooled to background temperatures).

The experimental approach for site selection and instrument deployment described above adheres to NASA's scientific and engineering standards for a Discovery-class mission. By linking each instrument's measurements to specific science questions and choosing a conducive environment in which to operate, we ensure that the mission can efficiently convert measurements into meaningful scientific results. This careful logic—from planning with JMARS data to real-time operations—provides high confidence that the Venus Aerobot mission at Idunn Mons shall successfully achieve its science deliverables.

3.3 Payload Success Criteria

Table 30: Instruments Success Guidelines

Category	Minimum Success	Optimum Success	Stretch Goal
UV/VIS Spectrometer	Quantify sulfur dioxide within 25km of the aerobot in the 118-320 nm wavelength. The integration time should be 1 s, sensitivity of SNR must be greater than 20, and the spatial resolution should be of 0.2 nm.	Quantify exact measurements of sulfur dioxide at least 25 km of the aerobot in the 170-320 nm wavelength. The integration time measures 11.2 ms with sensitivity of R being 2000 and the spatial resolution should be at least 0.3 nm.	Quantify precise measurements of sulfur dioxide at least 25 km of the aerobot within 170-320 nm wavelength. The integration time measures at least 11.2 ms with R sensitivity 2000 and the spatial resolution of 0.5 nm.
Infrared Radiometer/ Spectrometer	The IR Spectrometer should determine proximate areas with high thermal emissivity. The instrument wavelength range should be capable of measuring 0.1 micron per 2 mm, integration time of 1 s, sensitivity of R = 100 and spatial resolution of about 1 cm. These should ideally be within 45 km of the aerobot.	The IR Spectrometer should determine well-bounded areas with high thermal emissivity. The IR Spectrometers wavelength should measure 0.1 microns per mm with integration time of 1 s, sensitivity of at least 100 and spatial resolution 0.01 micron per 1 cm. These should be within 45 km of the aerobot.	The IR Spectrometer should determine precise areas with high thermal emissivity. The IR Spectrometers wavelength should measure 2 microns per mm with integration time of 1 s, sensitivity of about 1000 and spatial resolution 0.01 micron per 2 cm. These measurements should be within 45 km of the aerobot.
MEDA Dust and Radiance Tool	The instrument should provide an approximation of the average wind speed and granule fluxes. The instrument's optical wavelength will be between 170 to 900 nm, spatial resolution of 0.1 nm, integration time of 1 s and sensitivity of at least 2 W/m^2.	The instrument should quantify the average wind speed and granule fluxes.The instrument's optical wavelength will be between 255 to 900 nm, spatial resolution of at least 0.1 nm, integration time of at least 1 s and sensitivity less than 2 W/m^2.	The instrument should precisely measure the average wind speed, granule fluxes and dust scattering tendencies.The instrument's optical wavelength will be between 255 to 750 nm, spatial resolution of 12 mb per image, integration time of 57 kb/s and sensitivity of 0.5 W/m^2.

The UV/VIS Spectrometer is a necessary component to succeed in this mission's objectives. The table above explains the necessary functional requirements for the Spectrometer to take volcanic outgassing measurements by quantifying the concentration of sulfuric dioxide. The team intends to ideally work within a 170-320 nm wavelength range to be able to capture the natural form of sulfuric dioxide in the atmosphere. This could be done with, “the wavelength range of 198–222 nm and 284–311 nm evaluated by the Beer-Lambert law” (Wang et al. 2017, 3). The larger wavelength range will help the Spectrometer have greater chances of capturing all traces of sulfur dioxide. Sulfur dioxide creates an imbalance in Venus’s environment preventing life as, “any water in the sulfuric acid droplets is locked away in strong hydrogen bonds to sulfuric acid” (Seager et al. 2023, 2). Understanding the proportion of sulfur dioxide with a UV/VIS Spectrometer in Venus’s atmosphere will help explain the level of influence it contains on Venus globally.

The Infrared Radiometer/Spectrometer will help the team assess the amount of outgassing coming from Venus’s interior through its thermal emission. The IR Spectrometer will primarily locate and quantify surface areas that are emitting high levels of thermal emission. For the IR Spectrometer to answer these questions, it must meet certain functioning requirements which are explained in the table above. This study will help support where the UV/VIS Spectrometer should measure sulfur dioxide. It’s crucial to the team's mission that the highest levels of sulfur dioxide are quantified in order to understand how maximum heat emissions are affecting the surrounding environment.

The MEDA Dust and Radiance Tool will evaluate the wind speed and granule fluxes near Venus’s surface. As of today, studies on the effect of dust and speed are minor for Venus’s environment which is why learning more about this area can answer many questions surrounding Venus’s geography. The team has researched and dictated the specific requirements that the instrument must meet in order to quantify this data in the table above. One of the most important requirements for success is for the instrument to be able to relay at high spatial resolution. This will enable the team to understand how speed and dust scattering affects the surrounding environment as an addition to the effects of sulfuric acid to Venus.

3.4 Testing and Calibration Measurements

Each instrument requires calibration testing upon arrival at the target destination. Once the DSS and Aerobot configuration arrives in the upper atmosphere above Idunn Mons, the system will activate. The first calibration sequence to occur will be for the UV/VIS spectrometer.

Spectrometer

To correct against readout noise, *bias* frames will be taken first. A bias frame is the shortest exposure time possible with the UV/VIS instrument. These bias frames essentially normalize the CCD data readout against any random fluctuation of electrons in the detector. These data frames will be relayed and checked for nominal count values. Then, *dark* frames will be taken. A dark frame is an exposure taken with the spectrometer aperture closed. This way, any spectral noise that arises from the aerobot’s thermal emission will be detected and corrected for. Lastly, the spectrometer will essentially take flat field frames. This will correct the difference in the quantum efficiency of the CCD pixels. Once the base corrections have been tested and applied in the Venus environment, the spectral sensitivity will then be tuned.

Because spectral diffraction is dependent on wavelength, there are slight irregularities in the spectral sensitivity curve. Groups of pixels in spectral space can be used to smooth out absorption of unwanted absorption lines that refract and scatter in the Venusian atmosphere (Optica Publishing Group 2025). Spectral sensitivity needs to be monitored constantly, so this will be performed before long exposure cycle times. Spectral calibration (which refers to the assignment of pixels to wavenumbers) has been obtained before launch using solar lines. Expected emissions in the negative nadir direction will be compared to these fits and applied for future exposures.

Radiometer

Once the system is initialized, the pipeline for radiometer calibration will proceed as follows (Cardesin et al. 2010):

1. Dark frames, science frames, and housekeeping
    a. Dark frames correct against readout noise. Housekeeping data is taken and used to correct for bad frames, dead pixels, and oversaturated CCD pixels. The housekeeping data will be continuously taken and relayed for correct data reduction.
2. Radiometric calibration, spectral registration
    a. This phase consists of ‘destriping’ the data. Because there are irregularities in the responses of the CCD due to wavelength dependencies or manufacturing imperfections, unwanted lines may appear that decrease the resolution of the data. Destriping effectively removes these lines in the post-relay phase.
    b. It also consists of a ‘despiking’ process, which is a binning algorithm that corrects for unwanted cosmic rays that strike the CCD. It simply bins pixels in the CCD 3x3 and compares the centroid to the median of the ‘local group.’ If an extreme fluctuation is present, it is flagged. If it is determined to be an unwanted random exposure, it is corrected for.

Once these steps are complete, the science frames are ready to be taken and reduced.

MEDA

While there will be intensive calibration work before mission commencement, the tool will be calibrated in-situ. Firstly, the MEDA tool will take dark frames, like the spectrometer, in order to discriminate against CCD readout noise. Dark frames will also be taken to correct against thermal noise. Flat fields will be taken to correct for any imperfections in the CCD and/or MEDA coverings. The MEDA tool requires a temperature response function calibration, which can be done partially before mission launch. It also will require a responsibility calibration and an angular response function calibration. This is because the intensity read at the CCD is:

$$I(T,\ \alpha,\ \lambda)\ =\ \int_{0}^{\infty} R(T, \alpha, \lambda)\ E(\lambda)\ d\lambda$$

where *E* is the spectral irradiance received, and *R* is the actual throughput (Apestigue et al. 2022). The throughput depends on the incident angle, the temperature, and the wavelength. Therefore, in-situ calibrations for these parameters will be performed upon arrival.

The control variables and references will largely be the Carbon Dioxide spectral absorption. Because the tools are pointed mainly at the surface (with the exception of MEDA), the expected absorption and emissions of CO_2 will be critical in identifying correct wavenumbers in spectral features.

3.5 Precision and Accuracy of Instrumentation

The values for precision and accuracy are extremely important for the success of the mission. For each science target, a required tolerance and accuracy is listed.

Spectrometer

The desired wavelengths of SO_2 emission require very high spectral resolutions. The minimum spectral separation between emission and absorption features is 1 nm. This means that it has a resolving power of R ~ 2000 for the spectral range of SO_2 emission (Vernier n.d.). Therefore, the accuracy for a given spectral peak (absorption or emission) will be $\pm\ 1\,nm$. The signal to noise ratio for the spectrometer can be written as a function of:

$$\frac{S}{N} \propto \frac{F_{\lambda} D(\phi)_{\lambda}}{\theta} \left(\frac{\Delta\lambda \phi_{t} QE}{S_{\lambda}} t\right)^{1/2}$$

where *F* is the flux, *D* is the diameter of the aperture, theta is the angular field of view, delta lambda is the minimum wavelength separation, QE is the quantum efficiency of the detector, *t* is time, and *S* of lambda is plate scale of the detector (adapted from Stephens 2025). To increase the signal, data can be binned and the important parameters can be optimized to reduce the possible deviations in detection. As an estimate, the spectrometer is expected to have a signal to noise ratio of 1000 at minimum.

Radiometer

In order to successfully measure temperature and emission profiles of the surface, the radiometer will need to be able to measure temperatures of the Venusian surface accurate to $\pm\ 1\,K$ (Apogee Instruments 2025). This will permit the surefire detection of outgassing and potential active volcanic sites. By an average surface temperature of Venus is 737 K, so by Wien’s law:

$$\lambda_{peak} = \frac{0.0029\ m\cdot K}{737\ K}\ \approx\ 3.9\ \mu m$$

The spatial resolution that corresponds to this temperature sensitivity is 0.05 microns, which is well met by the radiometer's resolution of 1 nm.

MEDA

The MEDA tool will need to be able to accurately record surface scattering and photometric data, on the order of 1 W/m^2. According to Apestique et al., each wavelength range has maximum accuracy percentages of 10% for each measurement. On average, only 5% of the target W/m^2 range will be uncertain. For most of the ranges, these values are met, as seen in Table 31 (Apestigue et al. 2022). The only range not met is the TOP 7, in the near IR. This is acceptable, since the radiometer covers this wavelength range.

Table 31: Accuracies for MEDA

RDS-DP						
TOP Channels	Field of View * (°)	Azimuthal Position (°)	Elevation (°)	Max. Dyn. Range (W/m^2)	Precision (ppm)	Accuracy (%)
TOP 1—255 ± 5 nm	±15/±12 ± 0.3	162.49	90/89.23	0.05/0.184	1000/78.80	≤10% **/12.0%
TOP 2—295 ± 5 nm	±15/±11.4 ± 0.3	159.88	90/89.27	0.4/1.195	1250/44.1	≤10%/5.5%
TOP 3—250–400 nm	±15/±11. ± 0.3	211.82	90/90.187	60/90.1	1667.7/1.74	≤10%/6.7%
TOP 4—450 ± 40 nm	±15/±11.0 ± 0.3	163.4	90/89.71	80/124	1250/2.44	≤10%/4.5%
TOP 5—650 ± 25 nm	±15/±11.6 ± 0.3	178.14	90/90.166	45/59	2222.2/2.27	≤10%/4.5%
TOP 6—750 ± 10 nm	±15/±10.7 ± 0.3	244.39	90/89.58	15/18	6666.7/2.11	≤10%/4.5%
TOP 7—190–1200 nm	±90/±55 ± 0.3	171.32	90/89.56	600/358 ***	6666.7/1.8	≤10%/5.6%
TOP 8—950 ± 50 nm	±15/±12.1 ± 0.3	185.49	90/90.438	45/64	2222.2/1.8	≤10%/6.5%
LAT Channels	Field of View (°)	Azimuthal Position (°)	Elevation (°)	Max. Dyn. Range (W/m^2)	Precision (ppm)	Accuracy (%)
LAT 1—750 ± 10 nm	BLIND	0/-	20/-	--	--	--
LAT 2—750 ± 10 nm	±5/±4 ± 0.3	45/45.18	20/21.01	0.12/0.158	1000/25.3	≤10%/6.7
LAT 3—750 ± 10 nm	±5/±4.5 ± 0.3	90/90.9	20/20.14	0.12/0.134	1000/18.9	≤10%/6.7
LAT 4—750 ± 10 nm	±5/±4.5 ± 0.3	135/134.87	20/20.46	0.12/0.144	1000/18.5	≤10%/6.7
LAT 5—750 ± 10 nm	±5/± 4.4 ± 0.3	180/179.95	20/20.38	0.12/0.131	1000/20.2	≤10%/6.7
LAT 6—750 ± 10 nm	±5/±4.2 ± 0.3	225/224.92	20/20.43	0.12/0.157	1000/25.48	≤10%/6.7
LAT 7—750 ± 10 nm	±5/±4.1 ± 0.3	270/269.62	20/20.26	0.12/0.168	1000/20.83	≤10%/6.7
LAT 8—750 ± 10 nm	±5/±4.2 ± 0.3	315/314.94	35/35.91	0.12/0.160	1000/28.31	≤10%/6.7

3.6 Expected Data & Analysis

UV/VIS Spectrometer – SO_2 Detection

The UV/visible spectrometer will target the strong ultraviolet absorption features of sulfur dioxide (SO_2) in Venus's upper atmosphere (typically at wavelengths <320nm). We expect spectral data consisting of sunlight intensity versus wavelength, with characteristic SO_2 absorption bands (e.g. around 210–220nm and 250–280nm) appearing as dips in reflectance spectra [2, 1].

An example of expected spectrometer output is shown in Fig. 1, where long-term measurements of SO_2 at Venus's cloud tops (at ~70km altitude) by past missions are plotted. The left portion of Fig. 1 (1978–1990) is derived from NASA Pioneer Venus UV spectrometer data, and the right portion (2006–2012) from ESA Venus Express observations [2, 1]. Both datasets show SO_2 concentrations in the tens to hundreds of parts-per-billion by volume (ppbv), with dramatic changes over time. Notably, Pioneer Venus saw a decline from ~100ppbv to ~10ppbv over 5–7 years, while Venus Express initially recorded a sudden rise in SO_2 to several hundred ppbv in 2006 followed by a tenfold decrease by 2012 [2, 1]. These fluctuations are thought to result either from episodic volcanic injections of SO_2 into the upper atmosphere or from decadal-scale atmospheric circulation changes [6].

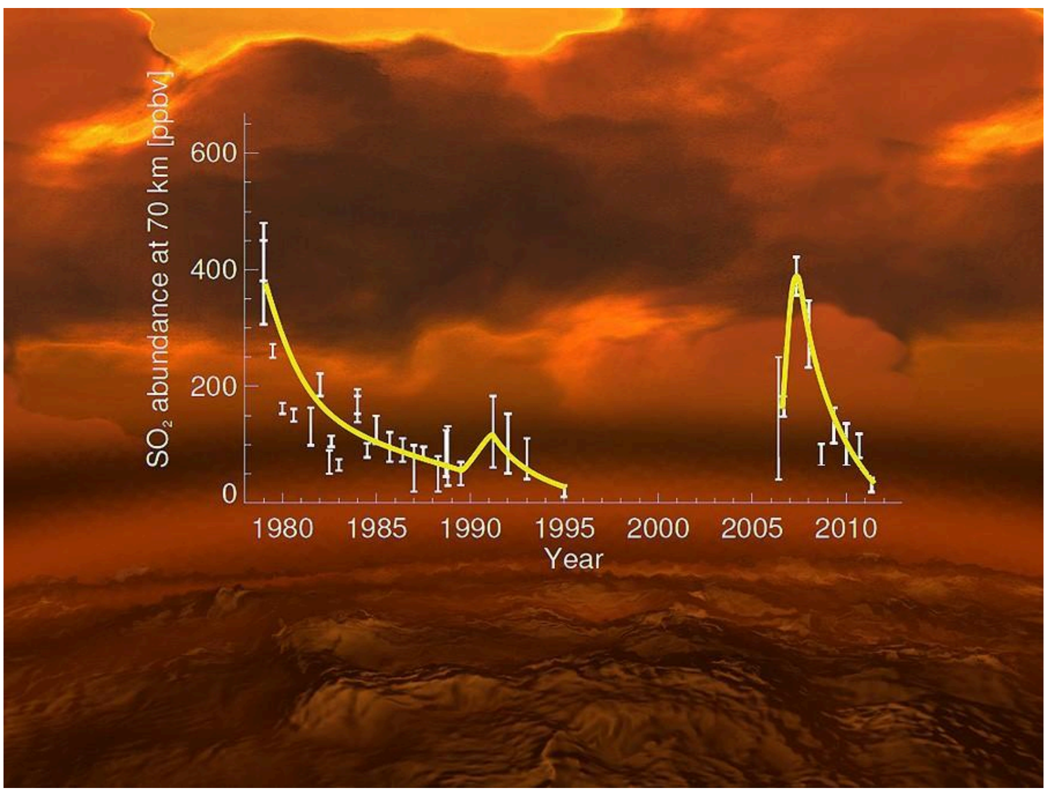


Figure 39: Long-term SO_2 abundance at Venus's cloud top (approx. 70km altitude) measured in ppbv.

The Pioneer Venus Orbiter UV spectrometer (left, 1978–1990) observed a steady decline in SO_2, while Venus Express SPICAV (right, 2006–2012) saw a sharp initial rise and subsequent fall in SO_2. These trends suggest episodic SO_2 injections consistent with volcanic activity [2, 1].

Data Characteristics and Extraction

During the aerobot mission, the UV/VIS spectrometer will collect nadir and limb spectra of scattered sunlight. The data is expected to resemble prior orbiter measurements: near-UV reflectance spectra with an overall bright continuum modulated by SO_2 absorption bands. The depth of these bands will indicate the SO_2 column density above the aerobot. By comparing observed radiances $I(\lambda)$ to a solar reference $I_0(\lambda)$, we derive the spectral optical depth

$$\tau(\lambda) = -\ln[I(\lambda)/I_0(\lambda)].$$

SO_2 column density N_{SO2} is retrieved via Beer–Lambert law:

$$\tau(\lambda) = \sigma(\lambda)N_{SO2}\,L,$$

where $\sigma(\lambda)$ is the SO_2 absorption cross-section and L the path length ($L \approx H/\cos\theta$ for nadir geometry, with H the scale height and θ the solar zenith angle). A spectral fitting algorithm adjusts N_{SO2} until modeled and observed absorption features match [1]. The residual baseline (due to unknown UV absorbers in Venus's clouds) is accounted for by including a pseudo-absorber in the fit [7]. Repeated measurements yield time series and spatial maps of SO_2.

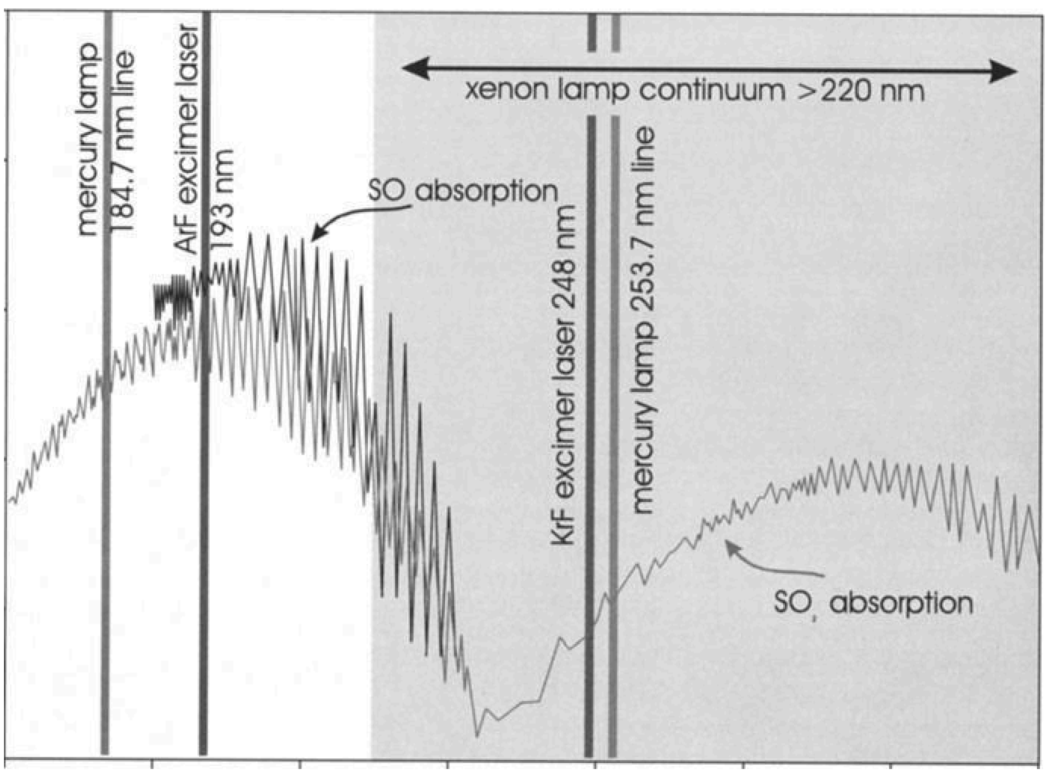


Figure 40: High-resolution laboratory UV–Vis absorption spectrum of SO_2 between 200nm and 320nm, showing fine structure used for retrieval algorithms [2].

Analysis for Physical Parameters

From fitted columns, volume mixing ratios (VMR) were derived using concurrent pressure/temperature profiles. A typical cloud-top SO_2 VMR is 0.1–1ppm [7], corresponding to tens of ppbv. SO_2 photochemical lifetime above the clouds is ~days, so any transient increase at 70km indicates recent replenishment from below [6]. Temporal variability—sudden spikes signaling active volcanism—is a primary analysis product [6]. Correlating spikes with aerobot location can pinpoint source regions. Retrieval uncertainties are propagated: for optically thin conditions,

$$\Delta N_{\mathrm{SO_2}} \approx \frac{\Delta I}{I}\,\frac{1}{\sigma L},$$

and with SNR ~100 it is anticipated to have a 5–10% precision (resolving ~3ppbv changes for $N_{SO2} = 10^{17}\ \mathrm{cm}^{-2}$). Systematic errors (cross-section uncertainty, instrument response) will be included in an error budget.

Expected Performance and Interpretation

Heritage from SPICAV indicates detection limits of ~5–10ppbv [2]. A localized SO_2 increase by ≥ 5× background would strongly imply volcanic injection [1]. Monitoring decay of spikes yields photochemical lifetimes and injection altitudes. Long-term baseline comparisons will test for continuation or departure from the decades-long downward trend [2]. Thus, the UV/VIS spectrometer directly addresses the mission's first objective: quantifying volcanic SO_2 outgassing and linking dynamic volcanic processes to atmospheric chemistry.

Infrared Radiometer/Spectrometer – Thermal Emission Mapping

This instrument will measure Venus's thermal emission in the infrared, providing both spectral and spatial data to map temperature and emissivity variations of the surface and lower atmosphere. Venus Express's VIRTIS instrument measured nightside radiance in spectral windows near 1.0, 1.18, 1.7, 2.3, 3.8, and 5μm, revealing surface and lower-atmosphere emission through the clouds [3]. The aerobot's IR spectrometer, operating at 8–12μm (broadband) and in narrow windows (e.g. 1μm, 2.3μm), will record similar data with higher spatial resolution from 55–60km altitude.

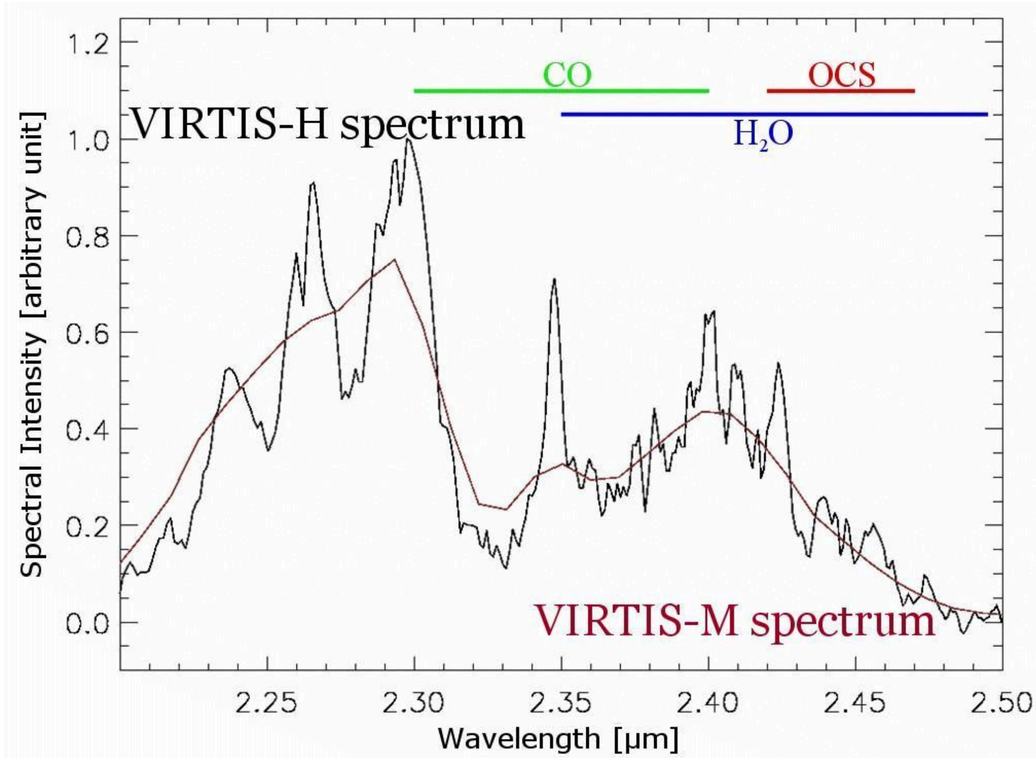


Figure 41: Example VIRTIS near-IR emission spectrum (1.02μm window) from Venus Express, showing measured radiance versus wavelength and a modeled blackbody fit [3].

Data Analysis for Brightness Temperature and Emissivity

Broadband radiometer data (8–12μm) are converted to brightness temperature T_b via

$$L_v = \epsilon B_v(T_b),$$

with $\epsilon \approx 1$ for cloud tops. Variations in T_b trace atmospheric dynamics (e.g. thermal tides, downwelling). Narrow-band spectra in near-IR windows isolate surface emission. Following [3], radiances are ratioed in adjacent channels—one in a deep window (1.02μm) and one in an opaque band—to cancel cloud contributions and retrieve surface emissivity ϵ:

$$L\text{surf} \approx \epsilon Bv(T\text{surf})t,$$

where $T_{surf} \approx 730$K and t is transmission. Emissivity anomalies (e.g. fresh lava flows) will appear as higher ϵ and enhanced short-wavelength radiance [4]. Retrieved atmospheric minor-gas profiles (CO, OCS, H_2O) from absorption band depths complement SO_2 data, yielding a comprehensive volcanic gas signature [6].

Uncertainty and Signal Detection

Radiometer calibration yields ΔT_b ~ 0.5K (heritage Akatsuki IR) [3]. Emissivity precision is anticipated at ±0.02. Detection of fresh lava (e.g. 1200K region ~1km^2)

would raise 1μm radiance by a few percent—detectable at $> 5\sigma$ with image stacking [4]. Absence of hotspots sets upper bounds on eruption size and thermal output.

MEDA Dust and Radiance Sensor – Dust Flux & Atmospheric Scattering

The MEDA-derived Dust and Radiance Tool will characterize particulate matter and scattering in Venus's atmosphere. On Mars, MEDA/RDS observed dust devils via rapid dips and spikes in irradiance [5]. Typical dust fluxes were 10^{-6}–10^{-5} kg/m^2/s over brief events [5]. Analogous signals are expected on Venus, recorded as time series of radiometric measurements in UV (250nm) and visible (750nm) bands, plus lateral photometer signals of approaching dust structures [4].

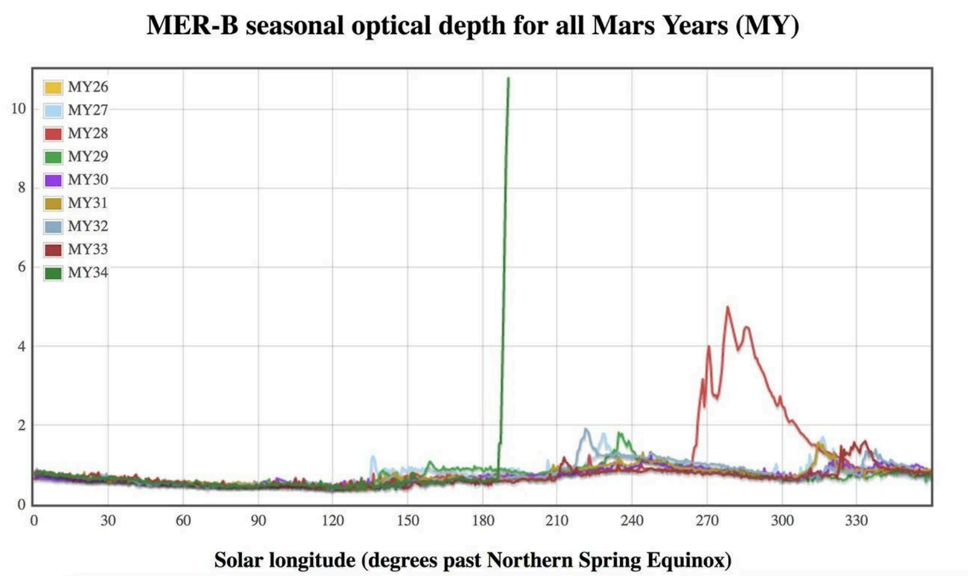


Figure 42: Simulated Venus dust opacity time series in UV (250nm) and visible (750nm) bands, illustrating sudden opacity spikes (dust events) at different wavelengths [5].

Deriving Dust Flux and Particle Properties

Dust column opacity τ is computed from

$$\tau = -\ln(I/I_0),$$

and multi-wavelength attenuation yields effective particle size via Mie scattering. Bandpass filters (UV 250–400nm, visible 750nm) allow ˚Angstrom exponent retrieval [5]. Timing of lateral photometer signals gives vortex advection speed v, and with column density ρ_{dust}, flux is

$$F = \rho_{\text{dust}}\, v.$$

Uncertainties in τ (±0.01 abs.) and velocity timing (10%) yield flux estimates within a factor of two. Detection thresholds down to $\Delta\tau \sim 0.02$ enable identification of minor dust events.

Error Analysis Summary

All retrievals will include a Monte Carlo–based error propagation to combine measurement noise, calibration uncertainties, and model assumptions. Figure 43 illustrates typical 1σ uncertainty distributions for SO_2 column density, brightness temperature, and dust concentration.

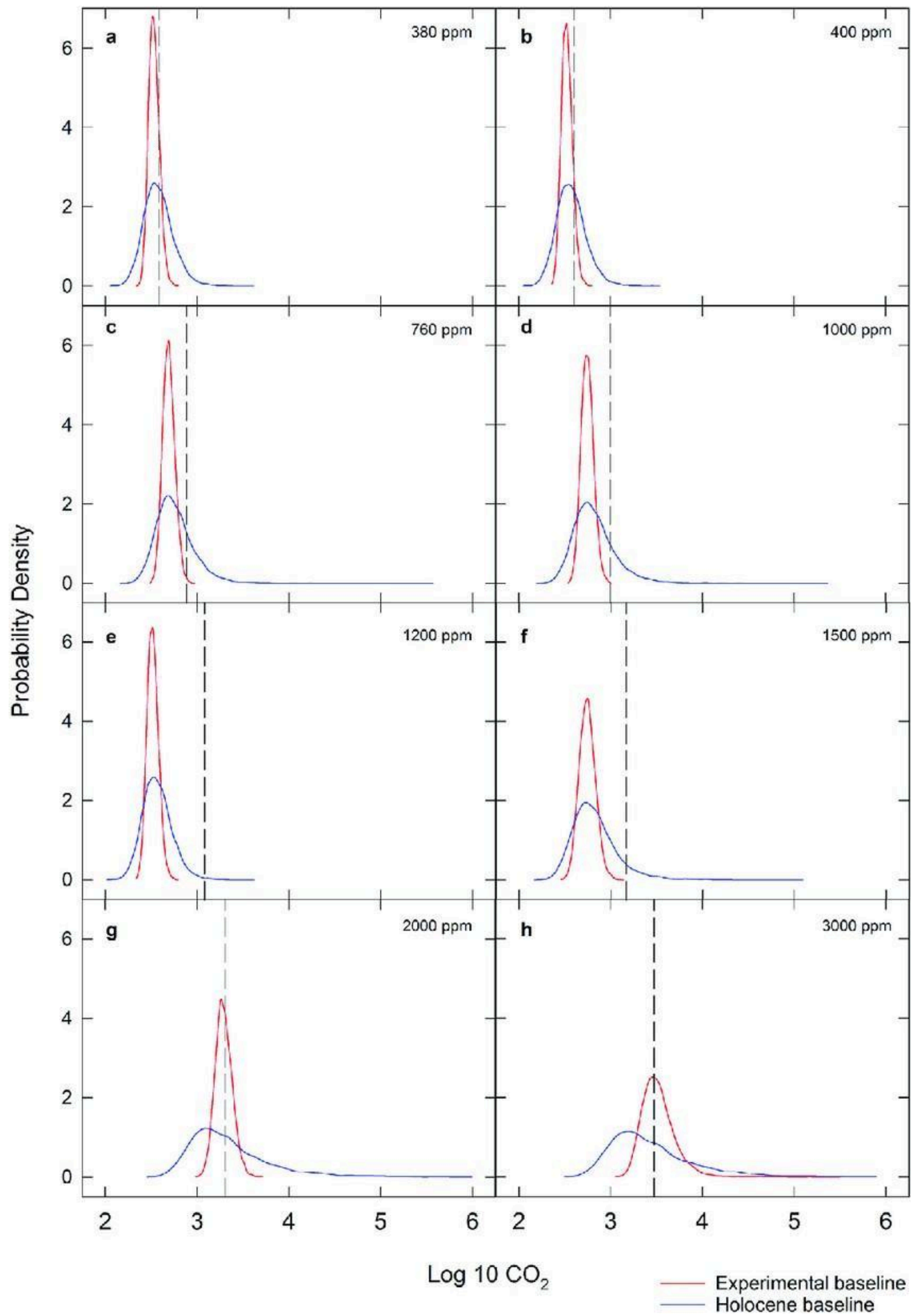


Figure 43: Monte Carlo error-propagation PDF illustrating retrieval uncertainties for SO_2 column density, brightness temperature, and dust concentration [6].

4 Mission Risk Management

4.1 Safety and Hazard Overview

Team V.E.L.A.Z.Q.U.E.Z implements a proactive and structured approach to safety and hazard analysis to ensure mission integrity, technical robustness, and overall system resilience throughout all mission phases. The team's approach follows key principles outlined in NASA's Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM) frameworks, which emphasize balancing risk with mission value, cost, and technical feasibility (Dezfuli November, 2011).

The team has identified and assessed risks across all subsystems including mechanical, thermal, power, command and data handling (CDH), and payload as well as programmatics and environmental risks.These are cataloged in a detailed risk log and plotted in a risk matrix based on likelihood and impact.This allows the team to maintain situational awareness and make informed mitigation decisions. The team identifies high impact risks using Risk Priority Numbers (RPN) and continually updates mitigation strategies to reflect changing mission conditions.

To analyze and contain critical failure points, the team employs Failure Mode and Effects Analysis (FMEA), focusing on how individual component failures could propagate through system architecture. This method directly links identified hazards with real-time contingency plans and fallback solutions, strengthening system redundancy and recovery capacity.

Despite the lower-cost nature of this mission, which allows for higher levels of risk in experimental systems, the critical components, specifically communications, power distribution, and payload instrumentation, are engineered for a low-risk operation using space-proven components or thoroughly tested in-house designs. This ensures scientific integrity is maintained even in the face of subsystem anomalies.

The team's approach also includes an analysis of personnel hazards, including machining, thermal, chemical, and electrical risks. These are mitigated through proper use of Personal Protective Equipment (PPE), standard operating procedures, and safety training as recommended by NASA's Safety and Mission Assurance (SMA) protocols (SMA, 2019).

Although Venus is designated as a category II planetary protection body, the mission still needs to comply with the best practices in order to avoid forward contamination and responsibly manage end-of-life hardware disposal (PPH, 2024). The decommissioning plan minimizes the risk of orbital debris or environmental disruption, aligning with NASA's Orbital Debris Mitigation Guidelines (Debris Mitigation, 2017).

Maintaining a strong risk posture not only projects mission goals but fosters a culture of responsibility and foresight by integrating NASA's proven risk management philosophies and tailoring, responding to, and mitigating safety and hazard challenges.

4.1.1 Risk Analysis

Risks play a critical role in the design process and must be created early on in the project development phases and evaluated consistently throughout the mission lifecycle. When determining risks, the mission was broken down into subsystems and risks were evaluated on a subsystem level. It was important to consider risks that would affect both the subsystem as well as the entire mission as a whole. The risk log that outlines the priority of each risk and what subsystem it belongs to is broken up by subsystems below. M stands for mechanical, P stands for power, C stands for CDH, T stands for thermal, I stands for instrumentation, Pr stands for Programmatics, and D represents the risks related to the descope. See Appendix A for the full risk log. Figure 44 represents the corresponding risk matrix that visually displays the severity of each risk.

4.1.1.1 Mechanical Risks and Mitigation

Mechanical hardware risks that were identified as the highest priority include deconstruction of the aerobot due to vibrational impacts and ingress contamination inside the aerobot itself. The risks relating to mechanical hardware are some of the most important risks to address due to it housing the rest of the instrumentation and payload that will collect data for future analysis.

The way the team plans to mitigate these mechanical risks are by ensuring a tight tolerance with interfacing components so there is a lesser chance of them shaking loose during flight as well reducing the risk of dirt and debris entering the aerobot. Utilizing connection components like self-locking screws, sealant materials like silicone rubber to fill any gaps or cracks, and multiple layers of shielding as an added layer of protection can help prevent any debris from entering the aerobot.

Table 32 A&B: Mechanical Subsystem Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
M1	1.1 Ingress Contamination	Mech. Engineer	Scope	Medium Term	Ingress Contamination	Given that Venus experiences high winds that carry dust and particles through the atmosphere, there is a possibility of the dust breaching the aerobot's exterior adversely impacting the interior components, which can result in possible damages to instrumentation, payload, and data transmission.	3	3	Moderate	Mitigate (M)	↓ Decrease
M2	1.2 Vibration Impact	Mech. Engineer	Scope	Short Term	Vibration Impact	Given that Venus' atmosphere experiences high winds and turbulent conditions, there is a possibility of the aerobot experiencing extreme vibrational motion, adversely impacting the structural integrity and mechanical connections, which can result in a possible deconstruction of the aerobot mid-flight.	3	4	Moderate	Mitigate (M)	↓ Decrease

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Tight tolerances between interfacing parts as well as sealant materials like silicone rubber to fill an gaps or cracks to prevent any debris and particles entering the aerobot	1. In-progress	1. 04/21/25	1. PDR	2/28/2029	Project PDR	(03/31/25): The risk's L was changed from 4 to 3 after implementing mitigation plan #1
1. Tight tolerances and connection components like self-locking screws to reduce risk of chassis components shaking loose	1. In-progress	1. 04/21/25	1. PDR	2/28/2029	Project PDR	(03/31/25): The risk's C was changed from 5 to 4 after implementing mitigation plan #1

4.1.1.2 Power Risks and Mitigation

The power subsystem ensures a continuous energy supply for the aerobot's instruments and communication systems. Venus' dense cloud cover significantly limits solar energy availability, making power storage and efficient energy usage critical. Without a reliable source of power, the mission could fail prematurely. The highest priority risk with the power subsystem is the exposure of the solar panels to the Venusian environment. Because the solar panels will be the only component on the outside of the aerobot during flight, it must be able to withstand Venus' extreme temperatures. The other high priority risk with the power subsystem is battery thermal runaway.

To mitigate the risk of solar panel degradation, this subsystem will include CAVU solar panels, which are designed and manufactured to withstand high temperature and radiation, and lithium-ion batteries, which will act as a redundant power source and energy storage for when the aerobot is at lower atmosphere with less sun exposure ("CAVU Solar Panels | Satsearch" 2025) (Beauchamp 2018). The solar panels will also be in parallel to one another, ensuring that any potential failure to one panel does not adversely affect the rest of the solar panel array.

Regarding the battery thermal runaway risk, low power mode and voltage protection will be utilized to protect the power system and keep the battery's voltage within optimal ranges. Having multiple power sources reduces the risk of an inefficient power supply and ensures that the aerobot will receive adequate power no matter what altitude it is at.

Table 33 A&B: Power Subsystem Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
P1	3.1 Solar Panel Degredation	Electrical Engineer	Scope	Short Term	Solar Panel Degradation	Given that Venus has extreme surface temperatures and a thick, heat-tapping atmosphere, there is a possibility of solar panel degradation adversely impacting power generation efficiency, which can result in insufficient energy supply for systems.	3	3	Moderate	Mitigate (M)	↓ Decrease
P2	3.2 Battery Thermal Runaway	Electrical Engineer	Scope	Short Term	Battery Thermal Runaway	Given that Venus' high temperatures can cause excessive heat buildup, there is a possibility of battery runaway adversely impacting the power storage system, which can result in total power loss and mission failure.	3	4	Moderate	Mitigate (M)	↓ Decrease

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Redundant power distribution systems including high-efficiency solar cells and heat-resistant lithium batteries so there will be a backup in case one system fails 2. Separate solar panels in parallel to create isolated power tracking and battery charging circuits so one failed panel does not affect the rest 3. Voltage protection so lithium-ion battery voltage stays within functional range and protects battery health	1. Complete 2. In-progress 3. In-progress	1. 04/21/25 2. 10/10/25 3. 10/10/25	1. PDR 2. CDR 3. CDR	2/28/2029	Project PDR	(03/31/25): The risk's L was changed from 4 to 3 after implementing mitigation plan #1 (04/20/25): The risk's C was changed from 4 to 3 after implementing mitigation plans #2 and #3
1. Redundant power distribution systems including high-efficiency solar cells and heat-resistant lithium batteries so there will be a backup in case one system fails 2. Low power mode to focus power towards essential subsystems 3. Voltage protection systems to protect battery in case of overvoltage or undervoltage	1. Complete 2. In-progress 3. In-progress	1. 04/21/25 2. 10/10/25 3. 10/10/25	1. PDR 2. CDR 3. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 5 to 4 after implementing mitigation plans #2 and #3

4.1.1.3 CDH Risks and Mitigation

The CDH subsystem is responsible for all the data processing and storage while the aerobot is in flight as well as transmitting that data back to Earth via the primary spacecraft. Two of the largest risks associated with CDH are cyberattacks/malware and noise/interference during flight. To protect against malware, the cFS control software that has been selected has responsive real-time capabilities and built-in cybersecurity protocols. Checksums will also be used to detect any faults in the data by conducting Cyclic Redundancy Checks (CRCs) to ensure data integrity. These safety measures can ensure that the aerobot's software will be as secure as possible during flight.

Regarding noise, it is anticipated that the aerobot will experience some turbulence due to Venus' extreme wind patterns in its atmosphere. This turbulence will create noise in the data that is collected which can make post-processing data more difficult. Some ways to minimize noise in the datasets include signal processing techniques and utilizing a low-power mode if the turbulence becomes too extreme. Since turbulence will affect the whole aerobot system, having a low-power mode option will be beneficial not just for de-noising but also for the integrity of the entire system.

Table 33 A&B: Command and Data Handling Subsystem Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
C1	2.1 Noise/Interference	CDH Engineer	Scope	Medium Term	Noise/interference	Given that Venus' atmosphere experiences high winds and turbulent conditions, there is a possibility of the aerobot experiencing extreme vibrational motion adversely impacting the data collected by the instruments, which can result in high amounts of noise in the data rendering results useless.	2	2	Low	Mitigate (M)	↓ Decrease
C2	2.2 Cyberattacks/ Malware	CDH Engineer	Scope	Medium Term	Cyberattacks/ Malware	Given that NASA discovery missions are uncovering new information about foreign planetary bodies, there is a possibility of a cyberattack on the aerobot's data collection system adversely impacting the integrity of the space mission and breaching confidential contracts, which can result in the potential nullification of the space mission, data theft, or loss of control of the spacecraft.	3	4	Moderate	Mitigate (M)	↓ Decrease

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Signal processing techniques like low-pass digital filtering and utilizing low-power mode if turbulence becomes too extreme 2. Checksums used in core Flight System to detect any faults in data by conducting Cyclic Redundancy Checks (CRCs)	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(03/31/25): The risk's L and C were changed from 4 to 3 after implementing mitigation plan #1 (04/20/25): The risk's L and C were changed from 3 to 2 after implementing mitigation plan #2
1. Selecting a software that has real-time capabilities to allow for faster updates as well as built-in cybersecurity measures. 2. Core Flight System (cFS) is selected for interfacing with rest of subassemblies	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(03/31/25): The risk's L was changed from 4 to 3 and C from 5 to 4 after implementing mitigation plan #1

4.1.1.4 Thermal Risks and Mitigation

The thermal subsystem is responsible for the control of temperature within the aerobot. Due to the extreme temperatures of Venus, it is important to have an accurate thermal management system (TMS) to ensure internal temperatures stay within the components' functional ranges during the 36 hours mission.

The main components of the thermal subsystem include strip heaters, multi-layer insulation (MLI), and a paint coating for insulation. These components will help the aerobot maintain functional temperature in the cold settings by limiting heat flow out of the aerobot and heating the aerobot when it gets below optimal temperatures. A large risk with Venus' atmosphere is with its fluctuating temperatures. To mitigate this risk, MLI uses materials that are a lightweight, space-proven, thermal protection system that reflects heat and reduces absorption by 82% (Finckenor and D. Dooling

1999). Strip heaters, along with thermal sensors, allow the aerobot to turn on and off heaters depending on the temperature readings. Finally, the paint coating adds an extra layer of insulation without compromising mass constraints.

A prior risk that was initially associated with the thermal subsystem was the risk of the radiator being inefficient at cooling the aerobot. After further research, the radiator component was removed altogether due to the heat flow map showing the aerobot system losing heat over time, thus not needing additional cooling. However, with removing the radiator from the final design, there runs the risk of the heat flow map being incorrectly calculated and the aerobot system needing the radiator after all. This risk is perceived as being at a low likelihood due to the heat flow calculations being verified by multiple engineers throughout the design process but must still be monitored occasionally throughout the mission to ensure accuracy as testing ensues.

Table 34 A&B: Thermal Subsystem Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
T1	4.1 Material Breakdown	Thermal Engineer	Scope	Medium Term	Material Breakdown in Fluctuating Temperatures	Given that Venus' extreme temperature fluctuations in high altitudes can degrade materials over time, there is a possibility of insulation failure adversely impacting internal components, which can result in overheating or underheating and permanent damage to critical electronics.	3	3	Moderate	Mitigate (M)	↓ Decrease
T2	4.2 Radiator Inefficiency	Thermal Engineer	Scope	Short Term	Radiator Inefficiency	Given that Venus' dense atmosphere reduces the effectiveness of radiative cooling, there is a possibility of heat accumulation adversely impacting thermal regulation, which can result in overheating and systems failure.	3	4	Moderate	Close (C)	Closed

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Multi-layered insulation (MLI), high-temperature resistant materials, high-temperature coatings. 2. Multiple heat strips to account for extreme temperature fluctuations and thermal sensors to control heat strip activation	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 4 to 3 after implementing mitigation plan #2
N/A	N/A	N/A	N/A	N/A	N/A	This risk was removed due to descope

4.1.1.5 Instrumentation Risks and Mitigation

The instrumentation chosen for this mission includes a UV spectrometer, IR spectrometer, and a MEDA dust and radiance tool. These instruments will be key in measuring data for the specific science objectives for this mission. Some key risks that have been identified with these instruments include potential data corruption during flight and not collecting enough data to be significant during the 36 hour flight period. To combat potential data corruption, some mitigation plans include having multiple backup sources and redundant systems to ensure data can continue being collected even if one system fails.

Regarding the potential to not collect enough data within the 36 hour flight period, this could occur due to a number of reasons. As previously mentioned, it is anticipated that the aerobot might experience turbulence due to extreme winds, which could interrupt the data collection process for the instruments. Instrumentation could also fail midway through flight due to power losses or connection issues. To mitigate this, extensive testing should take place to simulate the 36 hour flight period to ensure the instruments can function properly for that duration of time as well as doing environmental tests to ensure the instruments can handle the extreme environment of Venus' atmosphere.

Table 35 A&B: Instrumentation Subsystem Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
I1	5.1 Data Corruption	Scientist	Scope	Medium Term	Data Corruption	Given that radiation levels on Venus are much higher than on Earth, there is a possibility that the increased radiation exposure might affect data collection and storage methods, adversely impacting the quality of data received, which can result in corrupted data upon landing.	3	3	Moderate	Mitigate (M)	↓ Decrease
I2	5.2 Insufficient Data Collection	Scientist	Scope	Medium Term	Insufficient data collection	Given that Venus' atmosphere experiences high winds, there is a possibility that the turbulent conditions might interfere with the sensors' ability to collect data, adversely impacting the amount of data collected over the 36 hour time window, which can result in a lack of data for analysis upon landing.	2	3	Moderate	Mitigate (M)	→ Neutral

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Multiple backup sources and redundant backup systems to ensure data continues being collected even if one system fails 2. Checksums used in core Flight System to detect any faults in data by conducting Cyclic Redundancy Checks (CRCs)	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 4 to 3 after implementing mitigation plan #2
1. Extensive testing procedures to ensure instruments can collect data for entire flight period as well as environment testing to ensure instruments can withstand Venus' extreme environment	1. In-progess	1. 10/10/25	1. CDR	2/28/2029	Project PDR	-

4.1.1.6 Programmatics Risks and Mitigation

Programmatic risks for the aerobot mission stem from factors like budget constraints, timeline delays, resource allocation issues, and external dependencies. In order to mitigate these risks, the team employs rigorous financial management and regular budget reviews to prevent any cost overruns. A well-structured timeline with a built in buffer period will help in addressing potential delays, all while clear coordination across teams ensures resources are allocated efficiently. Additionally, performance contracts with external partners and a change control process reduce the likelihood of scope creep and ensure that any alterations towards the mission objectives are well-justified and aligned with the overall plan. These strategies work together to maintain project alignment and support the aerobot mission success despite the challenges that can be inherited in this space exploration towards Venus.

Table 36 A&B: Programmatics Subsystem Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
Pr1	6.1 Mass Limit	Programmatics	Schedule/Scope	Medium Term	Mass Limit	Given that the new DSS risk requires a mass reallocation, there is a possibility of existing components exceeding the new mass constraint, adversely impacting the mission requirements, which can result in a delayed or failed launch.	3	4	Moderate	Mitigate (M)	↓ Decrease
Pr2	6.2 Cost Limit	Programmatics	Cost/Scope	Medium Term	Cost Limit	Given that the mission to Venus has a strict cost limit, there is a possibilty of exceeding the allocated budget due to unforseen technical challanges or scope changes, which can result in the need for reallocation of funds, delaying project timelines, or compromising mission objectives.	2	4	Moderate	Mitigate (M)	↓ Decrease

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Research viable components at different mass limits and be extra diligent at checking mass calculations to ensure all numbers are as accurate as possible.	1. In-progress	1. 10/10/25	1. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 5 to 4 after implementing mitigation plans #1
1. Employing overestimation margins of at least 30% to account for variability in lead times and procurement costs.	1. In-progress	1. 10/10/25	1. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 5 to 4 after implementing mitigation plans #2

4.1.1.8 Planetary Protection Considerations

When considering deep space exploration, planetary protection must be at the forefront of risk mitigation plans. According to the NASA planetary protection handbook, the practice of planetary protection focuses on 2 main aspects of space exploration: controlling the risk of contamination to other bodies in the solar system outside of Earth, and preventing harmful consequences to humans and Earth's environment due to any potential return of extraterrestrial samples to Earth. Missions are broken down into 5 categories based on the level of sensitivity to contamination of the target body, the type of mission, and the criticality of the mission in understanding the process of chemical evolution or origin of life of the target body (Benardini and Lalime 2025).

The aerobot mission that is going to Venus would be considered a Category II mission due to the fact that this mission has an interest in the process of chemical evolution of Venus and there is little chance that contamination could compromise future investigations (Benardini and Lalime 2025). Even though the aerobot will have an uncontrolled descent to the surface and stay there indefinitely, because of Venus' harsh environment, there is little chance that any microbes or contaminants from Earth would survive long enough to contaminate Venus. For Category II missions, documentation must be provided that outlines intended or potential impact targets, pre- and post-launch analyses detailing impact strategies, and a post-encounter and end-of-mission report that provides the location of impact if that were to occur (Olsson-Francis et al. 2023).

4.1.1.9 Decommissioning

Decommissioning is an important part of a mission's lifecycle and must be taken into consideration when planning the aerobot's end-of-life disposal. One of the most important things to consider with decommissioning is passivation, which is the depletion of energy of all on-board sources of stored energy when they are no longer required for mission operations or post-mission disposal (Hull 2013). Since lithium-ion batteries are used on this mission, it is important to ensure the batteries cannot recharge or discharge during the end-of-life disposal, as any connection to power the battery may have can lead to overheating or explosions (Hull 2013). The general steps that the team will follow for decommissioning are listed below.

1. Ensure all data gets sent back to the primary spacecraft one last time at the end of the 36 hours.
2. Stow solar panels back into collapsed form.
3. Disconnect solar arrays from power bus and ensure lithium-ion batteries cannot be recharged/discharged.
4. Send "final goodbye code," initiating the aerobot's CDH shutdown procedure.

As the mission plan progresses, the decommission plan will become more detailed. For now, the team has developed a very basic plan as a starting point for this mission.

4.1.1.10 Descoping Plans

The aerobot mission resides under the Descent Subsystem (DSS) contractor and a risk related to the descent subsystem's balloon material arose due to the high concentration of sulfuric acid droplets in Venus' atmosphere. This risk results in the possibility of the balloon material not being durable enough to last the entire planned 48 hours, thus requiring the team to descope the mission. The team was given two options in descoping: increase the thickness of the balloon which will allow the mission to last for 36 hours but requires an allocation of 5kg of weight to the aerobot, or dedicate more time to research, develop, and test a new balloon material that would give the team the full 48 hours but require an allocation of 5kg, 6 months, and $200M.

Table 37: Descope Risk Given by DSS Contractor

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
D1	7.0 Descope	DSS Contractor	Scope	Short Term	DSS Contractor Balloon Risk	Given that that the Venusian atmosphere consists of highly concentrated sulfuric acid droplets, there is the possibility of the environment being too hazardous and adversely affecting the Descent Subsystem's balloon material's rate of survival, which can result in not meeting the 48 hour operation duration requirement.	5	4	High	Mitigate (M)	↑ Increase

The team decided to pursue the first option since the aerobot was already close to the weight capacity and reducing 5kg seemed the most feasible. The aerobot system was then analyzed to see where weight could be reduced. The first subsystem descope to occur was with the removal of the radiator from the thermal subsystem. The team decided to remove the radiator because after analyzing the heat flow map, it was realized that the aerobot would have a net heat flow out of the system, meaning the aerobot will be cooling down over time. This means that the only systems needed in the thermal control system are heating strips.

The next subsystem to undergo a descope is the mechanical subsystem. Even after eliminating the radiator, the aerobot is still over the weight capacity so chassis material is currently being evaluated. The team is deciding to go with a less dense material which will help remove the weight necessary to get the aerobot under the weight limit.

Overall, the team has taken into consideration the descope and analyzed all possible reduction options in order to not sacrifice science or data collection capabilities but still remain within constraints.

Table 38 A&B: Descope Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend
D1	7.1 Resource Shortage	Descope	Cost/Scope	Medium Term	Resource Shortage	Given that the new DSS risk requires a descope to mission subsystems, there is a possibility of needing to reallocate resources, adversely impacting the amount of personnel associated with this mission, which can result in delayed mission timelines	3	2	Low	Mitigate (M)	↓ Decrease

Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
1. Cross-training personnel across multiple subsystems to ensure flexibility in task management 2. Prioritize mission tasks with high impact based on critical timelines	1. In-progress 2. In-progress	1. 10/10/25 2. 10/10/25	1. CDR 2. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 3 to 2 after implementing mitigation plans #1 and #2

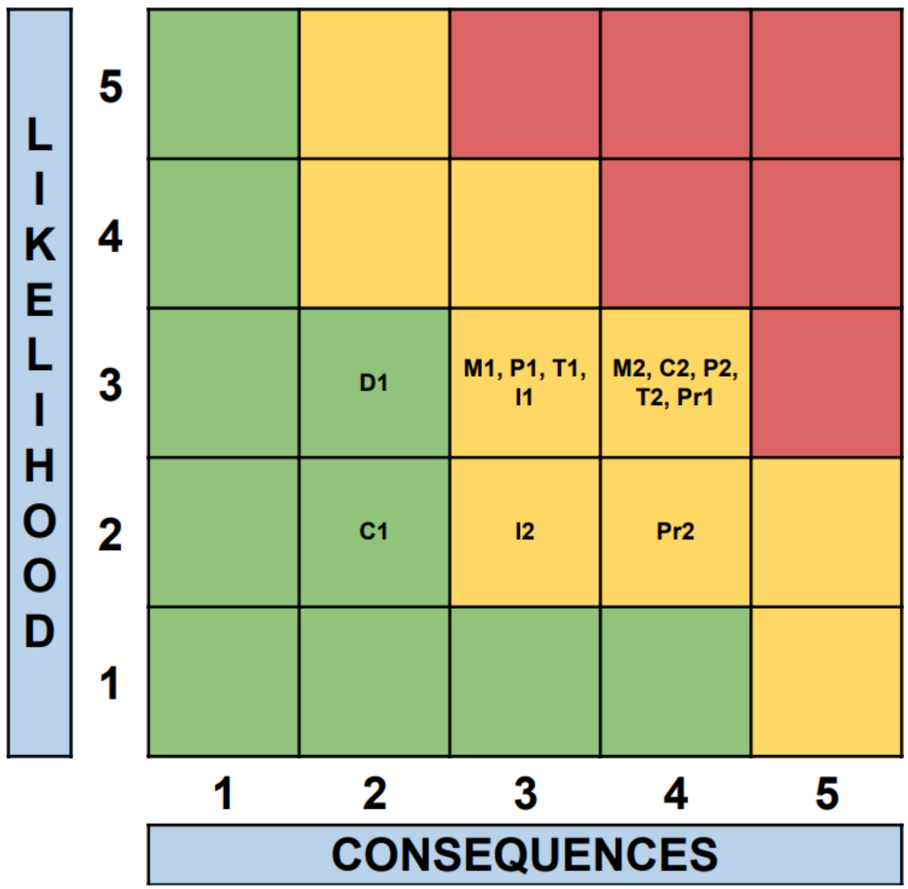


Figure 44: Risk Matrix

4.1.2 Failure Mode and Effect Analysis

The Failure Mode and Effect Analysis (FMEA) serves as a systematic approach to identifying, assessing, and mitigating potential risks associated with the Venus aerobot mission. Given the extreme environmental challenges posed by Venus' atmosphere like intense winds, corrosive particulates, high temperatures, and signal interference, the aerobot must be designed to withstand a variety of mechanical, electrical, and cybersecurity threats.

This analysis categorizes failure modes based on their severity, likelihood of occurrence, and detectability, resulting in a Risk Priority Number (RPN) that helps prioritize mitigation strategies. The most critical risks are those that threaten mission success by compromising spacecraft integrity, data collection, or operational functionality.

Among the highest-rated risks, vibration impact poses a serious threat to the aerobot's structural integrity due to Venus' high winds. If not properly addressed, excessive vibrations could lead to mechanical deconstruction, resulting in mission failure.This structural risk is being mitigated through improved fastening methods and tighter tolerances, however, once the aerobot has launched, there is no action that can be done to mitigate further deconstruction.

Cybersecurity threats also rank as a major concern, as the aerobot's data collection system could be vulnerable to cyberattacks or malware, potentially leading to data theft, loss of control, or mission compromise. Prevention strategies include real-time processing capabilities and the implementation of checksums which conduct Cyclic Redundancy Checks (CRCs) to ensure the integrity of the data. To prevent further cybersecurity breaches, rollback and failsafe frameworks have been put in place to add redundant systems to the CDH subsystem.

The power system faces a major risk although it is at a lower priority than the other two risks mentioned. Battery overheating due to Venus' extreme temperatures could lead to power loss and damage to peripheral components, compromising mission operations. To counteract this threat, the design incorporates redundant power distribution systems, low power mode, and voltage protection to prevent battery overheating from damaging other components. Redundant battery packs and solar panel arrays are also used as backup and redundant power systems.

Finally, the main risk with the programmatics subsystem is exceeding the mass constraint. Due to the DSS risk requiring a mission-wide descope, components had to be reconfigured to align with the new mass limits and the risk of existing components exceeding the allocated mass has increased. To mitigate this, mass calculations will be checked with multiple engineering personnel on the team and backup components will be evaluated in the case that a primary component is overweight. Throughout the mission, these mass calculations will be re-evaluated as components continue to be updated, with the hopes that meticulous analysis of the overall mass can ensure the mission stays within mass constraints.

Through this FMEA, the team has identified the most pressing risks and outlined key mitigation strategies to enhance the aerobot's resilience in Venus' harsh environment. Addressing these risks requires a combination of advanced materials, mechanical reinforcements, cybersecurity solutions, and thermal management techniques. By refining these countermeasures, the mission aims to improve system reliability, safeguard scientific data integrity, and maximize operational longevity. This risk assessment will serve as a dynamic tool, continuously informing engineering decisions throughout the aerobot’s design, testing, and implementation phases.

Table 39: Failure Mode and Effect Analysis

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Aerobot Chassis	Vibration Impact	Deconstruction of aerobot leading to failed mission	10	Venus' high winds	3	Self-locking screws, tight tolerances	3	90	No action can be taken once aerobot has launched
Data Collection	Cyberattacks/Malware	Data theft, loss of control of the spacecraft	9	Lack of software cybersecurity	6	Real-time processing, checksums, core Flight System selection	4	216	Rollback and failsafe frameworks
Power	Battery Overheating	Loss of power, damage to peripheral instruments	8	Venus' high atmospheric temperatures	5	Redundant power distribution systems, low power mode, voltage protection	2	80	Redundant battery packs, solar panels to limit battery usage
Programmatics	Exceeding Mass Limit	Delay or failure to launch	10	DSS risk requiring mass allocation and reconfiguration of components	4	Accurate mass calculations, alternative components with different weights	2	80	Subsystem-level mass reviews throughout mission lifecycle as components are updated

4.1.3 Personnel Hazards and Mitigations

As Team V.E.L.A.Z.Q.U.E.Z prepares to move into the manufacturing, integration, and testing phases of the Venus Aerobot mission, personnel safety becomes an essential operational priority. Although the mission does not involve direct human interaction with Venus, the development and assembly of flight hardware here on Earth presents numerous hazards that must be addressed through proactive planning, training, and procedural enforcement. These include mechanical, electrical, thermal, chemical, ergonomic, and psychological hazards, all of which must be mitigated to ensure the safety of team members and project success. The information in this section reflects NASA's Occupational Health Program and institutional lab safety best practices, in alignment with OSHA and ANSI guidelines (Dezfuli November, 2011) (Laboratories,Osha).

4.1.3.1 Machining and Manufacturing Hazards

The use of tools, machinery, and manufacturing spacecraft components introduces significant risks. During fabrication, personnel may encounter lathes, mills, drills presses, laser cutters, or 3D printers, all of which can cause physical injury.

Risks include lacerations from sharp tools, entanglement in moving machinery, burns from friction or heat based processes, and eye injury from debris or radiation exposure.

To mitigate these risks, all team members must undergo training on proper machine operation and wear Personal Protective Equipment (PPE) (Laboratories,Osha), including safety glasses, gloves, and enclosed emergency shut-ffs and lockout tagout (LOTO) protocols must be strictly followed. Workplaces will also maintain clear signage and restricted accesses during active manufacturing.

4.1.3.2 Electrical Hazards

Electrical work becomes increasingly dangerous during subsystem integration, especially when assembling power systems and Command and Data Handling (CDH) electronics.

Risks include electrical shock, burns from arc flashes, and potential fire hazards from improper wiring or overloading circuits, and integration of batteries such as EnerSys ABSL Li-ion batteries, which adds risks of thermal runaway or venting.

To mitigate these risks, only personnel trained in basic electrical safety and proper handling of lithium batteries will be authorized to perform electrical work. Proper PPE, such as rubber gloves, electrostatic discharge (ESD) wrist straps, and insulating mats, are required. Circuits will be tested on a grounded workstation and labeled clearly for voltage and current limits. Battery charging will occur in fire safe enclosures with ventilation (Laboratories,Osha).

4.1.3.3 Thermal Hazards

Thermal subsystems like TEMPCO flexible heat strips and Barium Sulphate coatings pose a variety of temperature related dangers during testing.

Risks include burns from surfaces, exposure to high temperatures from tools or ovens, and the risk of localized heating damaging adjacent systems or injuring personnel.

To mitigate these risks, all thermal testing is schooled under supervision with prior risk review. Infrared thermometers are used to verify temperature before handling, and insulated gloves and tools are required when interacting with heated elements. Test areas are isolated and marked clearly during operation. Personnel must complete hazard communication training (HAZCOM) regarding temperature sensitive components (Laboratories,Osha).

4.1.3.4 Chemical Hazards

Chemical exposure is another prominent risk during the mission integration and test (MIT) phase. This includes materials used for coatings, soldering, adhesives, and cleaning solvents.

Risks include chemical burns, inhalation of toxic fumes, allergic reactions, and eye damage.

To mitigate these risks, all chemicals will be labeled and stored according to their material safety data sheet requirements (MSDS) (Laboratories,Osha). Fume hoods, gloves, face shields, and safety goggles are required, and all work involving volatile compounds must be logged and supervised. Emergency showers and eyewash stations are checked weekly for accessibility and proper functioning.

4.1.3.5 Radiation and Laser Hazards

During testing, non-ionizing radiation such as infrared and ultraviolet light can be used to simulate planetary conditions or test sensors.

Risks include skin burns, retinal damage, or long-term eye degradation from UV/IR exposure or Class II/III laser systems.

To mitigate these risks, all optical testing environments are secured with warning signs, protective barriers, and strict access control. Laser goggles and shielding materials are provided. Team members must be trained in laser lab protocol and must never bypass interlock or operate systems alone (N.I.G.M.S).

4.1.3.6 Ergonomic and Physical Fatigue Hazards

Prolonged work sessions involving detailed electronics or heavy equipment pose ergonomic risks and fatigue related injury.

Risks include repetitive stress injuries, back strain, wrist and hand fatigue, and increased probability of human error due to mental or physical exhaustion.

To mitigate these risks, team members are encouraged to rotate tasks, use adjustable workstations, and take schooled breaks. Chairs, tools, and monitors are adjusted based on ergonomic principles. Stretching and wellness exercises are recommended, and time logs will help prevent overwork (Safety Education November, 2024).

4.1.3.7 Psychological and Team Stress Hazards

Collaborative projects under tight deadlines can lead to psychological strain, communication breakdown, and burnout.

Risks include decreased productivity, stress included illness, and interpersonal conflicts that impact mission performance.

To mitigate these risks, weekly wellness check-ins and access to institutional mental health resources are provided. Leadership encourages open communication, reasonable deadlines and a culture of mutual support and respect. Conflicts are mediated quickly, and no one is expected to compromise their well-being for project deadlines (OSHA BRIEF, 2013).

5 Activity Plan

5.1 Project Management Approach

The MCA team has carefully structured its personnel distribution to ensure the mission's success while adhering to budget constraints. Given the complexity of the mission and the need for expertise across multiple disciplines, personnel numbers will vary by phase to reflect mission priorities.

Table 40: Personnel Numbers and Costs

Phase	Scientists	Engineers	Technicians	Administration	Managers	Scientists Cost	Engineers Cost	Technicians Cost	Administration Cost	Managers Cost	Total Cost
A	10	6	0	0	3	800,000	480,000	0	0	360000	1640000
B	8	8	0	0	3	640,000	640,000	0	0	360000	1640000
C	10	15	30	5	4	800,000	12,000,000	1,800,000	300000	480000	18390000
D	15	15	30	5	4	12,000,000	12,000,000	1,800,000	300000	480000	23370000
E	6	10	4	2	3	480000	800000	240000	120000	360000	25370000
F	4	6	2	2	3	320000	480000	120000	120000	360000	26770000

The total estimated yearly personnel cost is $26,770,000. These figures were calculated from the Mission Budget personnel cost from the Mission Task document. The external personnel will be divided among essential mission teams to optimize efficiency and expertise allocation. The key system subteams of each mission team are:

1. **Engineering Team:** Designs, tests, and integrates mission hardware and software, including mechanical, thermal, power, and communications subsystems. Technicians are assigned to the Engineering team to assist with fabrication.
2. **Science Team**: Defines mission objectives, selects instrumentation, analyzes mission data, and ensures alignment with research goals. Additional scientists are assigned to the Science subteam to assist with science goals and instrumentation.
3. **Programmatics Team**: Manages the operational and financial aspects of the mission, ensuring the project stays on track regarding budget, schedule, and scope. This team handles risk management, resource allocation, and procurement while coordinating with stakeholders to keep the mission aligned with its objectives. Administration roles will be distributed to programmatics teams
4. **Management Team**: Includes the Project Manager, Deputy Project Manager, Lead Systems Engineer, and Chief Scientist. They oversee scheduling, budgeting, and inter-team coordination. Note:

Phases A-B: Concept & Preliminary Design

- These phases require a higher number of scientists (15 in Phase A, 12 in Phase B) to define mission objectives, select instrumentation, and develop early analysis models.
- A moderate number of engineers (5 in Phase A, 8 in Phase B) are needed to begin designing subsystems and defining technical requirements.
- No technicians are required at this stage since fabrication has not begun.
- Managers and administrative staff will oversee project development, budgeting, and coordination.

Phases C-D: Fabrication, Assembly, Integration & Testing

- Engineering and manufacturing take priority in these phases, requiring more engineers (10-12) and technicians (15 in Phase C, 12 in Phase D) to build and integrate components.
- Fewer scientists (8 in Phase C, 6 in Phase D) are needed as the focus shifts from conceptualization to implementation.
- Managers and administrative staff remain consistent to maintain scheduling, budgeting, and program coordination.

Phases E-F: Operations, Sustainment & Closeout

- The mission enters execution, requiring more engineers (15 in Phase E, 8 in Phase F) for system operations, troubleshooting, and data analysis.
- Scientists increase in Phase E (10 total) to analyze incoming data before tapering off in Phase F.

- Technicians decrease significantly (5 in Phase E, 2 in Phase F) as manufacturing and assembly end.
- Managers and administrative staff ensure mission success and efficient closeout.

Mission Organizational Structure

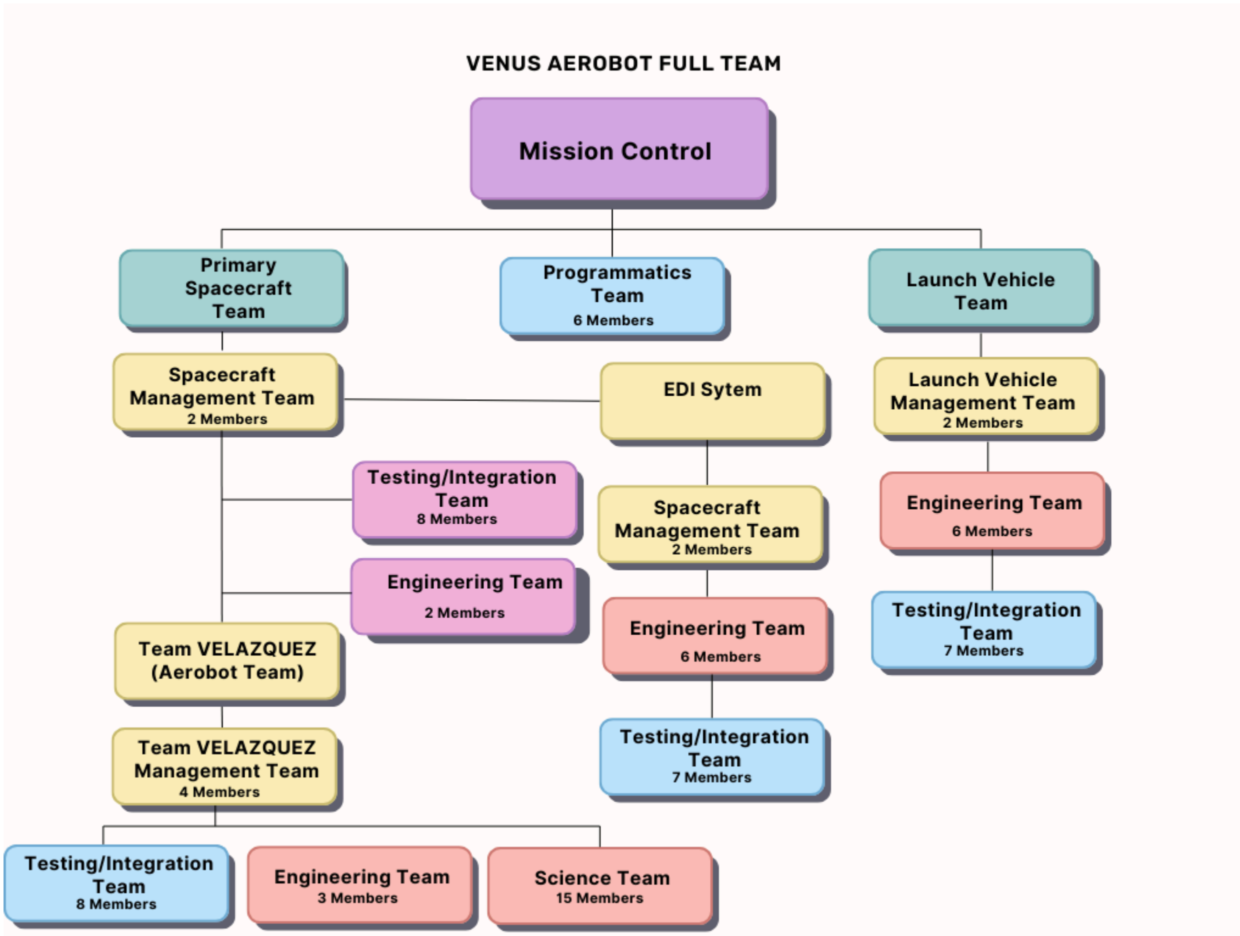


Figure 45: Full Team Organizational Chart

Aerobot System and Its Integration with Mission Teams

The Aerobot System, managed by Team V.E.L.A.Z.Q.U.E.Z, is a critical component of the mission, designed to carry out science operations within Venus' atmosphere. It relies on coordination with several other mission elements and external teams to ensure a successful descent, deployment, and operation within the planetary environment.

Interaction with Mission Systems and Teams

Launch Vehicle (Contractor)

- The Launch Vehicle contractor is responsible for delivering the entire mission payload into Earth orbit.
- The Aerobot System, housed within the EDI System, is integrated into the payload before launch. The MCA team collaborates with the contractor to ensure

proper structural, thermal, and vibrational constraints are met to prevent damage during launch.

Primary Spacecraft (Contractor)

- Once in Earth orbit, the Primary Spacecraft provides propulsion to carry all systems to Venus
- The Aerobot System remains dormant during transit, relying on the Primary Spacecraft for thermal control and power management. The MCA team ensures compatibility with the spacecraft’s power and communication systems, maintaining survival conditions until EDI System separation.
- After arrival at Venus, the Primary Spacecraft remains in orbit and acts as a relay for data transmission between the Aerobot System and Earth. The MCA Team must ensure the Aerobot’s communications system is aligned with the spacecraft’s relay capabilities.

EDI System (Contractor)

- The Entry, Descent, and Insertion (EDI) System houses the Aerobot System during transit. The contractor team designs the heat shield and parachute that will protect the Aerobot System during atmospheric entry.
- Upon separation from the Primary Spacecraft, the EDI System follows a controlled descent, slowing the payload before releasing the Aerobot at a predetermined altitude.
- The MCA team works closely with the contractor to ensure the Aerobot System is securely housed, properly deployed, and that descent parameters align with scientific objectives.

Descent Subsystem (Contractor)

- Attached to the Aerobot System, the Descent Subsystem consists of a helium-filled balloon that regulates the system's descent within the Venusian cloud layer.
- The MCA Team ensures that the Aerobot System properly interfaces with the Descent Subsystem, maintaining buoyancy and stability within the designated altitude range for scientific measurements.
- Additionally, the MCA team coordinates with the contractor to verify compatibility with the environmental conditions, ensuring the system remains operational during the mission's duration.

5.2.1 Schedule Basis of Estimate

5.2.1.1 Assumptions

The Schedule Basis of Estimate (BoE) outlines the scope, key decision points, assumptions, and phases for the Aerobot System project, ensuring cost estimates are informed by interdisciplinary expertise based on NASA guidelines. As the mission progresses, the BoE will be updated to reflect new data and risks. Guided by the NASA Decadal Question 6.4 (In Origins, Worlds, and life 2023, 247-251), this mission aims to study Venus’ atmosphere and surface, specifically, analyzing sulfuric acid cloud composition and the specific conditions for cloud precipitation to occur (Izraelevitz, n.d.).

In order to make the mission run smoothly, assumptions need to be made to know what is and what could happen. One of the most important assumptions the team made throughout the mission is the required margin needed which was added appropriately for each subtask.

Another big assumption that could potentially affect the whole mission schedule is any supply shortages or shipping delays. Since this is a discovery mission, supplies do prioritize solar system exploration (Bowman 2019), and shipping delays will be out of the team's control. Another minor assumption made in the mission was personnel turnover, which was based on the base salary of each position (scientists, engineers, technicians and management). Inflation and employee related expenses have also been put in consideration giving the team an estimation of expenses needed to cover from the overall budget.

5.2.1.2 Ground Rules

Assuming the mission has passed all key decision points prior, the team will continue to further control gates that NASA contains. Using fiscal years (FY) rather than calendar years (CY) to ensure alignment with government funding cycles and reporting requirements (Schedule Management 2020, 69). This approach supports a more accurate forecasting of budget and timelines. Following the constraints imposed by the customer, the mission's integration phase is targeted for completion by October 1, 2028, at Goddard Space Flight Facility in Greenbelt, MD. Choosing this place for its role in integrating systems for NASA (Adkins, 2019). Also, the vehicle is required to be ready for launch by March 1, 2029, from Cape Canaveral, FL. Cape Canaveral is the spot for the launch since Cape Canaveral and Kennedy Space Center are the primary launch sites for NASA. This is because of its close proximity to the equator which helps with the kinetic energy from take-off since the Earth rotates faster at the equator relative to the center (Amanda Barnett, 2024).

Beginning with the final design and fabrication at Phase C. During this phase, the aerobot's final system design along with its fabrication, assembly, and test of individual components should be completed. This phase is named the final design and fabrication of a NASA mission due to the combining of the final components of the system and mission. This contains the Critical Design Review (CDR) and the System Integration Review (SIR).

Phase D follows, encompassing assembly, integration, and testing. This begins immediately and runs through late 2028 to early 2029. The system shall be fully operational and ready for launch by the end of this point. Special attention is given to the Aerobot System to make sure its performance aligns with mission goals for science investigations. In this phase, the mission goes through the ORR and the MRR until it launches (Ryschkewitsch 2012, 27). Missing any of these deadlines or not getting the launch approval would necessitate waiting for the next favorable launch window, potentially delaying or even canceling the mission.

Entering Phase E, the team will enter into the launch operations on the first of March. Undergoing a Post Launch Assessment Review (PLAR). A quarter of the way into the Phase E, which is based on operations and sustainment, the mission shall undergo a Critical Events Readiness Review (Ryschkewitsch 2012, 112). After completion of the mission, it will be expected to go through a Post-Flight Assessment

Review and Decommissioning Review (DR). This phase focuses on operations, data collection, and ensuring the system completes its mission. Phase F is deemed to be the closeout of the mission and contains the Disposal Readiness Review (DRR). This gate is meant on how the team and system will dispose of itself, where here the system will burn up in the high temperatures in Venus.

5.2.1.3 Drivers

For phase C to be passed, the Aerobot System has to meet stated performance requirements within cost, schedule, and risks (Ryschkewitsch 2012, 108). An adequate margin of 10-15% is built in during this timeframe to handle potential integration issues and testing complications (Schedule Management 2020, 118-120). The Aerobot Subsystem, which will be responsible for the mission, and the other systems, will be managed by contractors within the industry, helping to streamline the development process while keeping oversight of the respective technologies The mission's total time of operation is a 48-hour operational window.

5.2.2 Mission Schedule

5.2.2.1 Introduction

The purpose of the schedule, presented by the Gantt chart, is to ensure timely mission execution from Phase C (Final Design & Fabrication) to Phase F (Closeout). The key milestones embedded in the Gantt Chart display the expected approvals, readiness, and major completions of the mission. Additionally, the milestones set the expectations of the schedule, ensuring certain actions are taken to fulfill the requirements of the mission. In order to mitigate the risk of mission incompletion as a result of delay, schedule margins are incorporated into the schedule to prevent such risks. Additionally, strict coordination among the science, engineering, and programmatic teams are enforced to minimize unnecessary delays. In matters of schedule development, NASA's Systems Engineering Processes and Requirements and NASA's Systems Engineering Handbook was utilized as a guide to reflect historical mission guidelines and practices to the Aerobot mission.

5.2.2.2 Phase C

Phase C will approximate a three year schedule, starting on June 2nd, 2025, to October 1st, 2028. Being the longest phase among all phases, this phase includes the manufacturing and procurement of the Aerobot system parts. Beginning with the first milestone of decision approval on how to approach the mission, all subteams following the approval begin on the design of the Aerobot system. All subteams are given approximately two months to finalize their design of the Aerobot system to ensure successful system performance and minimal complications. Similarly, the Critical Design Review will occupy one month of time for all subteams to detail the components of the Aerobot system and how they adapt to mission requirements and possible risks (Ryschkewitsch 2012, 108). Once the CDR is finalized, the team will reach another milestone where all subteams will thoroughly present the review for 5 days to guarantee approval and move forward with the mission (NASA 2011, 1). Following the milestone of CDR approval, preparation for fabrication and software commences (Deiss, 2019); CDR approval is a milestone because it allows for the continuation of the mission.

The Preparation for fabrication and software is another milestone for the team which will take nearly 14 months to make certain that the correct materials are fabricated for successful component functionality (NASA 2011, 29). Additionally, the allotted time is considered to avoid possible software errors that may affect the functionality of system components. Aside from preparing for the materials and software of the Aerobot system, time is taken to find suppliers that are able to manufacture and fabricate the required materials and software (Deiss, 2019). Determining the best fit suppliers for the required materials may grant reduction of cost and time for fabrication. Furthermore, determining secondary suppliers will be considered to ensure the continuation of fabrication if the primary suppliers are unavailable. Subsequent to the preparation, the production of assembly preparation will be allotted six months. During the six months, the suppliers will take the time to properly manufacture the required materials/software. Correspondingly, assembly preparation will begin among the engineering subteams to ensure assembly efficiency and effectiveness. After the six months of production and assembly preparation, three months will be given to all engineering subteams for integration and operational planning. At this point, the engineering subteams will prepare on how they will integrate the different components with one another, and how the components will be verified for functional use (testing, analysis, demonstration, or inspection).

For any unfortunate delays (primarily involving production delay), a nine month margin is allocated within the schedule for such delays. After integration and operational planning and any unfortunate delays, a new milestone is reached, in which the system is ready for integration. This will then be preceded by one month of labor for the final system integration with the participation of all subteams, in which the main body of the system will be constructed. Then, another month is necessary for all subteams to participate in the subsystem integration, making certain that all components from each subteam correctly and carefully integrate within one another. After the Aerobot system is completely built from the 2 months of integration, verification is required to ensure the system and all subsystems perform with sufficient functionality. Following the integration, verification of the Aerobot system is required to test, analyze, demonstrate, and inspect all components of the system and subsystems. This will take 15 days to appropriately verify the functionality of all components (Deiss, 2019).

A new milestone is reached after verifying the system and subsystem components, in which all subteams participate in the System Integration Review for a week to ensure all components of the system are integrated and functional (Ryschkewitsch 2012, 109-110). Phase C’s critical path without any delay will take 1,218 days with 280 total days added for margin.

Table 41: Gantt Chart Phase C

1	Manufacturing and Procurement		0%	6/2/25	10/1/28	1218	280
1.1	◆ Key Decision Point - C Approval	Programmatics	Not complete	6/2/25	6/2/25	1	
1.2	Finalizing Detailed System Design	All Subteams	Not complete	6/3/25	8/4/25	63	
1.3	CDR Draft Review	All Subteams	Not complete	8/5/25	9/5/25	32	
1.3.1	◆ CDR Presentation and Approval	All Subteams	Not complete	10/6/25	10/10/25	5	
1.4	◆ Prep for Fabrication & Software Dev	MECH, PWR, CDH	Not complete	10/20/25	12/28/26	435	
1.4.1	Production and Assembly Prep	MECH, THRM, PWR	Not complete	12/30/26	6/30/27	183	
1.5	Integration & Operational Planning	LSE All Subteams	Not complete	7/1/27	9/30/27	92	
1.6	◆ System Ready for Integration	All Subteams	Not complete	10/1/27	10/1/27	1	
1.6.1	Final System Integration	All Subteams	Not complete	10/5/27	11/2/27	27	
1.6.2	Subsystem Integration	All Subteams	Not complete	11/3/27	12/3/27	31	
1.6.3	Full System Verification	All Subteams	Not complete	12/4/27	12/18/27	15	
1.7	Schedule Margin			12/19/27	9/23/28	280	
1.8	◆System Integration Review	All Subteams	Not complete	9/24/28	10/1/28	8	

5.2.2.3 Phase D

Phase D will be an approximate five month schedule, starting on October 2nd, 2028, to February 28th, 2029. This phase will focus on the assembly, integration, and testing of the Aerobot system. Next, the CDH and mechanical subteams will take nine days to analyze the verification results of the Aerobot system to identify any errors within the components of the system (NASA 2011, 51-52).

Another milestone is reached, in which the programmatics team allocates thirteen days for the Operational Readiness Review, covering the contents that make each component fully functional and operational. A week is then taken to identify action items based on the ORR and resolve them. This time is needed so that all errors involved in the functionality of the system components are resolved effectively. For pre-launch checkouts/reviews, 10 days are needed for all subteams to prepare for and resolve any discrepancies that may interfere with the launch approval of the mission.

For any unfortunate delays (primarily involving the system verification process and analysis), a week margin is allocated within the schedule for such delays. Once the pre-launch checkouts are complete, the next milestone will be reached involving the MRR. This review will take 20 days and will examine tests, analyses, and determine if the system's readiness for a safe and successful launch. This review will examine and ensure that all flight and ground hardware, software, personnel, and procedures are operationally ready (Ryschkewitsch 2012, 100). Thus, from the pre-launch preparation and previous reviews, the milestone of launch approval is reached (taking one day), and operations and sustainment is ready to commence. Phase D's critical path without any delays will take 150 days with 89 total days added for margin.

Table 42: Gantt Chart Phase D

2	Assembly, Integration, and Testing		0%	10/2/28	2/28/29	150	89
2.1	Verification Results Analysis	CDH, MECH	Not complete	10/2/28	10/10/28	9	
2.2	◆Operational Readiness Review	PROGRAMMATICS	Not complete	10/11/28	10/23/28	13	
2.2.1	ORR Action Items Resolution	All Subteams	Not complete	10/24/28	10/31/28	8	
2.3	Pre-Launch Checkouts/Reviews	All Subteams	Not complete	11/1/28	11/10/28	10	
2.3.1	◆Mission Readiness Review	All Subteams	Not complete	11/11/28	11/30/28	20	
2.4	Schedule Margin			12/1/28	2/27/29	89	
2.5	◆ Launch Approval	All Subteams	Not complete	2/28/29	2/28/29	1	

5.2.2.4 Phase E

Phase E will approximate a seven month schedule, starting on March 1st, 2029, to October 5th, 2029. The first day of the phase is a milestone that marks the beginning of the launch operations, in which the transportation subteam sends the Aerobot to Venus. For the time between the launch and the next LCR, all the subteams will lead an outreach campaign talking and educating the public about the importance of this mission and how it will impact scientific and future missions.

Another milestone is reached following one month after the launch, where all subteams designate eleven days of their time to complete the LCR, Post Launch Assessment Review, to ensure all launch operations occurred smoothly with little to no error. Meanwhile, and immediately after the beginning of the launch operations, about 200 days (amount of time needed for the Aerobot to reach Venus) are assigned for cruise phase monitoring and system health checks (Ryschkewitsch 2012, 70). All subteams engage in cruise phase monitoring to assure smooth and strict arrival time to Venus, preventing and avoiding any obstacles that may come between transit. Likewise, All engineering subteams. Using the transponders and transceivers within the Aerobot system, routine system health checks will occur during the event of transit so that the Aerobot system is operational for data collection and mission goals (NASA 2011, 13).

Reaching the 200 days of expected transit, the team reaches the next milestone for the LCR, the CERR, taking three days to complete where the mission confirms the readiness to execute its critical activities during flight operation (Ryschkewitsch 2012, 113). After the team confirms the CERR, the Aerobot system will simultaneously be making its arrival on Venus, reaching the 12th milestone of the schedule. It is at this point where the mission is at its climax, the point in which all subteams prepared for data collection on Venus. Through the integration of CDH, mechanical, power, and thermal engineering applications, the Aerobot system takes two days to gather as much data as possible within the Venusian atmosphere. After the two days assigned for data collection, the Aerobot system will degrade from Venus' harsh environment and halt data collection. This is due to the environment in Venus where the extreme heat and acidic atmosphere make it hard for the aerobot to survive (In Origins, Worlds, and life 2023, 240-242).

The 13th milestone is reached, marking the end of the data collection once the Aerobot system can no longer collect data due to expected malfunction. At this time, the CDH and science subteams analyze the data collected on Venus through the Aerobot's transponder subsystem. The CDH and science subteams occupy two days for the preliminary data analysis in order to carefully review the results of the data and resolve any discrepancies found within the data. Then, all subteams designate a week of work for the next milestone, the DR, where the team assesses the readiness of the system for the safe decommissioning and disposal of the system (Ryschkewitsch 2012, 114). This is to detail the efficient and effective functionality of the Aerobot system during its time in Venus.

For any unfortunate delays (primarily involving launch and/or transit delay), an eight day margin is allocated within the schedule for such delays. Phase E's critical path without any delay will take 219 days already including a total of eight days for margin.

Table 43: Gantt Chart Phase E

3	Operations and Sustainment		0%	3/1/29	10/5/29	219	8
3.1	◆Launch Operations Begin (LRD)	Transportation Subsystem	Not complete	3/1/29	3/1/29	1	
3.2	Outreach campaigns	All Subteams	Not complete	3/1/29	4/1/29	31	
3.3	◆Post Launch Assesment Review	All Subteams	Not complete	4/1/29	4/12/29	11	
3.3.1	Cruise Phase Monitoring	All Subteams	Not complete	3/2/29	9/16/29	199	
3.3.2	System Health Checks	MECH, PWR, CDH, THRM	Not complete	3/2/29	9/16/29	199	
3.3.3	◆Critical Event Readiness Review	MECH, PWR, CDH, THRM	Not complete	9/13/29	9/16/29	3	
3.4	◆Venus Arrival	All Subteams	Not complete	9/17/29	9/17/29	1	
3.4.1	Venus Data Collection	All Subteams	Not complete	9/17/29	9/18/29	2	
3.4.2	◆ End of Data Collection	All Subteams	Not complete	9/18/29	9/18/29	1	
3.5	Preliminary Data Analysis	CDH, SCIENCE	Not complete	9/19/29	9/20/29	2	
3.6	◆Disposal Review	All Subteams	Not complete	9/21/29	9/27/29	7	
3.7	Schedule Margin			9/28/29	10/5/29	8	

5.2.2.5 Phase F

Phase F will approximate a 3 month schedule, starting on October 6th, 2029, to December 31st, 2029. An outreach section is scheduled during the closeout of the mission where it will show how the mission was executed and performed, noting though that data is still being collected and analyzed, the outreach will focus on performance of the Aerobot system and its concept of operations now based on its actual performance. Now reaching the second to last milestone, the DRR. This LCR confirms the readiness for the final disposal plan of the system assets (Deiss, 2019) which will take almost a month to complete.

Nearing the end of the mission, time is taken for all subteams to decommission for 2 weeks because work regarding the Aerobot system itself is no longer needed. Following the 2 weeks of commissioning, the science and programmatic teams perform data analysis on the data the Aerobot system collected in Venus' 60-70 km altitude. This process will take 15 days so that the science and pogrammtics team can carefully analyze how the data quantifies volcanic activity through thermal emission, and how the data quantifies volcanic outgassing by sulfur dioxide in the atmosphere. Once the data is analyzed, another 15 days is allotted for the CDH, science, and programmtics teams to archive the data. This amount of time is necessary for future reference on Venusian surface history, and to apply the archived data for further missions or research. Finally, the Final Mission Report is constructed by all subteams to complete in 16 days. This granted time is needed to thoroughly input the results of the data collected through the Aerobot system, and to detail the performance of the Aerobot system as a whole. In addition, the 16 days is required to cover how much the mission costed, how long it lasted, and what risks were involved within the mission.

For any unfortunate delays (primarily involving data analysis and the Final Mission Report), a 10 day margin is allocated within the schedule. The final milestone of the mission will be its closeout which is just another way of putting an official conclusion to this mission.

Table 44: Gantt Chart Phase F

4	Closeout		0%	10/6/29	12/31/29	87	10
4.1	Outreach	All Subteams	Not complete	10/6/29	10/15/29	9	
4.2	◆Disposal Readiness Review	All Subteams	Not complete	10/6/29	11/4/29	29	
4.2.1	Decommissioning	All Subteams	Not complete	10/22/29	11/4/29	14	
4.3	Data Analysis	SCIENCE, PROGRAMMATICS	Not complete	11/5/29	11/19/29	15	
4.4	Archiving Data	PROGRAMMATICS, SCIENCE, CDH	Not complete	11/20/29	12/4/29	15	
4.5	Final Mission Report	All Subteams	Not complete	12/5/29	12/20/29	16	
4.6	Schedule Margin			12/21/29	12/30/29	10	
4.7	◆ Closeout Completed	All Subteams	Not complete	12/31/29	12/31/29	1	

5.2.2.6 Conclusion

The margin of each phase was deduced by the severity of each event that occurred within each phase, involving approvals, reviews, transit time, integration, and verification. Furthermore, the margins were minorally influenced by the length of each phase, in which the longer the phase, the more margin it would be granted (NASA 2011, 45-46). The critical path of the entire mission schedule starts from June 2nd, 2025, to December 31st, 2029 (ultimately lasting a total of 1,673 days).

5.3 Budget

5.3.1 Budget Basis of Estimate

For the mission, the contractor has set a primary budget parameter of $200 million dollars. The total mission cost will be divided into facilities, outreach, travel, personnel, and direct costs (power, thermal, mechanical, communication/data handling, and payload). This serves as a general guideline for allocating funds within the mission (Table 1) (NASA, 2022). The $200 million limit encompasses all costs following the PDR, which include the life cycle costs from phases C to F. This budget does not include any of the expenses for the primary spacecraft or entry, descent, and 14 insertion. The budget will cover the scope of all science instruments (payload), as well as mechanical, electrical, command and data handling, communication, and thermal subsystems. A high level Work Breakdown Structure can be found in Figure 46. Within the $200 million dollars, a total personnel expense of $33 million is included. Personnel is expected to fluctuate from phase to phase to meet the demands of the mission.

Margin rates, to account for unexpected expenses, are given in assumptions. Stakeholders and contractors also set a ground rule that the mission concept must be functional in the actual environment of Venus. Systems testing must also be determined by the development team. Before transitioning to the next phase in the NASA Mission Life Cycle, a Key Decision Point will be held to determine project efficacy. If the decision is made to continue, later Key Decision Points (KDP) will be held, namely, C, D, and E, and travel costs will be accounted for. Cost model estimation tools will include but are not limited to: the NASA Mission Concept Cost Estimate Tool, the NASA Instrument Cost Model, the NASA Cost Analysis Data Requirement, Xometry, and the One NASA Cost Engineering tool (a web tool for estimating costs, schedules, and confidence levels).

Table 45: Cost Percentages per Category

Category	Percentage of Total Cost
Facilities	12%
Personnel	18%
Travel	1%
Outreach	1%
Payload	30%
Mechanical	30%
Power	10%
Thermal	5%
Comms/Data Handling	8%

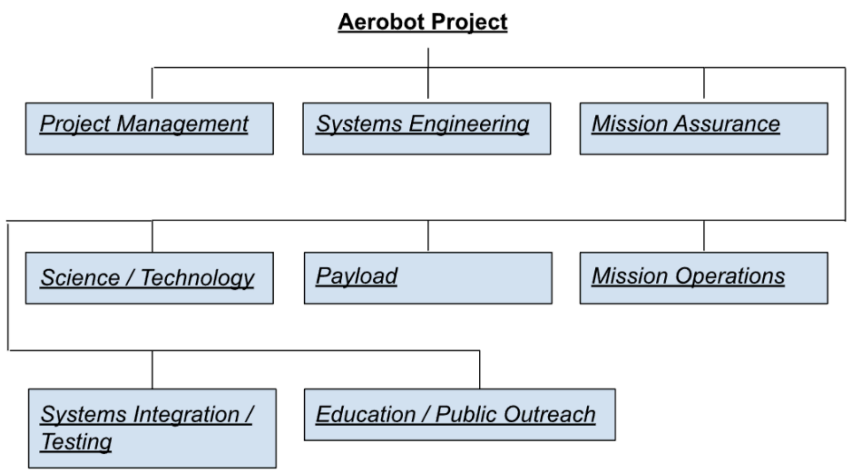


Figure 46: Breakdown Structure for Aerobot Project

Assumptions are defined as conditions the team assumes to be true in order to make decisions or estimate budgeting. The main budget assumption is the cost of inflation, where the rate (from 2004 dollars to 2024 dollars) is taken to be 165.74%. It is also to be assumed that the inflation rate for every future year is 2.6% per the NASA New Start Inflation Index (NASA, 2023).

In addition to budget constraints, it assumed that incidentals are bound to occur during the phases following the PDR, therefore, margins will be instilled to cover incidental expenses. There will be no cost-reduction instilled that will reduce the budget's set amount to increase profit.

For matters concerning the team, the salary budget component will cover more than the mission team personnel. It is assumed that other personnel expenses will be included in the salary budget component. Table 1 below shows the margin percentages by category. The Facilities and Administrative margin accounts for the indirect costs and overhead. The manufacturing margin is allocated for potential delays or supply chain issues. Total cost margin is used as a contingency to prevent overspending. And lastly, Employee Related Expenses (ERE) is used for costs related to personnel benefits.

Table 39: Margin Percentages by Category

Category	Margin Percentage
Facilities and Administrative	10%
Manufacturing	50%
Total Cost Margin	30%
ERE	28%

Drivers are taken to be non-negotiable constraints that remain fixed, regardless of other circumstances. The major cost drivers included within the budget involve weight, volume, quantity, personnel, and schedule. Mission parameters dictate the production of one main flight module (the Aerobot) including but not limited to 5 main engineering items. It is also mandatory that the payload contains no more than 5 kg of radioactive material. The aerobot must be ready for integration by October 1st, 2028 at the Goddard Space Flight Center. Then, the vehicle must be ready for launch by March 1st, 2029.

NASA cost estimates are shaped by the weight and volume of space systems, hardware and any other kind of complex design for the mission. The budget basis accounts for cost drivers over the course of 6 years and phases C through F. Direct costs include but are not limited to the following subsystems: mechanical, power, thermal control, communication and data handling, guidance, science instrumentation, and margins. Manufacturing and testing categories are also assigned wrap costs. Wrap costs are determined based on a cost estimation relationship (CER) and a schedule estimating relationship (SER).

1.10.3.3 Phases D–F (FY4–FY6): Integration, Operations, and Closeout

Drivers, Ground Rules, and Assumptions

- **Fabrication Complete:** Technicians are phased out after FY4, since manufacturing tasks wind down.
- **Increased Scientific Load:** Science personnel expand in FY5 and FY6 (15 each) to handle data analysis, operational monitoring, and anomaly investigation.
- **Engineering Taper:** Engineering staff drop from 15 in FY4 to 10 in FY5 and FY6, reflecting reduced hardware-focused tasks.
- **Administrative Stability:** Administration (5) and Management (4) remain consistent, ensuring oversight and continuity.

5.3.2 Total Mission Cost

Table 46: Budget Template

Additional Information

	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6
Science Personnel:	15	15	8	8	16	16
Engineering Personnel:	15	15	12	12	10	10
Technicians:	10	10	20	20	4	4
Administration Personnel:	4	4	4	4	4	4
Management Personnel:	6	6	6	6	6	6

NASA L'SPACE Mission Concept Academy Budget - *V.E.L.A.Z.Q.U.E.Z*

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
PERSONNEL							
Science Personnel	$ 800,000	$ 820,800	$ 420,800	$ 431,200	$ 1,324,800	$ 1,356,000	$ 5,153,600
Engineering Personnel	$ 1,200,000	$ 1,231,200	$ 1,262,400	$ 1,293,600	$ 883,200	$ 904,000	$ 6,774,400
Technicians	$ 1,800,000	$ 1,846,800	$ 1,893,600	$ 1,940,400	$ -	$ -	$ 7,480,800
Administration Personnel	$ 300,000	$ 307,800	$ 315,600	$ 323,400	$ 331,200	$ 339,000	$ 1,917,000
Project Management	$ 480,000	$ 492,480	$ 504,960	$ 517,440	$ 529,920	$ 542,400	$ 3,067,200
Total Salaries	$ 4,580,000	$ 4,699,080	$ 4,397,360	$ 4,506,040	$ 3,069,120	$ 3,141,400	**$ 24,393,000**
Total ERE	$ 1,278,278	$ 1,311,513	$ 1,227,303	$ 1,257,636	$ 856,591	$ 876,765	**$ 6,808,086**
Personnel Margin	$ 585,828	$ 601,059	$ 562,466	$ 576,368	$ 392,571	$ 401,816	**$ 3,120,109**
TOTAL PERSONNEL	$ 6,444,106	$ 6,783,556	$ 6,508,860	$ 6,834,567	$ 4,767,384	$ 4,994,579	$ 36,333,051
TRAVEL							
Total Flights Cost	$ 110,000	$ 110,000	$ 110,000	$ 330,000	$ -	$ -	**$ 660,000**
Total Hotel Cost	$ 176,000	$ 176,000	$ 176,000	$ 528,000	$ -	$ -	**$ 1,056,000**
Total Transportation Cost	$ 5,500	$ 5,500	$ 5,500	$ 16,500	$ -	$ -	**$ 33,000**
Total Per Diem Cost	$ 22,000	$ 22,000	$ 22,000	$ 66,000	$ -	$ -	**$ 132,000**
Travel Margin	$ 5,600	$ 5,600	$ 5,600	$ 16,800	$ -	$ -	**$ 33,600**
Total Travel Costs	$ 319,100	$ 327,397	$ 335,693	$ 1,031,969	$ -	$ -	**$ 2,014,159**
OUTREACH							
Total Outreach Materials	$ 40,000	$ 40,000	$ 6,000	$ 6,000	$ 3,000	$ 3,000	**$ 98,000**
Total Outreach Venue Costs	$ 50,000	$ 50,000	$ 10,000	$ 10,000	$ -	$ -	**$ 120,000**
Total Outreach Travel Costs	$ 100,000	$ 100,000	$ 10,000	$ 10,000	$ 11,000	$ 11,000	**$ 242,000**
Total Outreach Services Costs	$ 10,000	$ 10,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	**$ 24,000**
Total Outreach Personnel Costs	$ 300,000	$ 300,000	$ 180,000	$ 180,000	$ 180,000	$ 180,000	**$ 1,320,000**
Outreach Margin	$ 50,000	$ 51,300	$ 21,700	$ 22,300	$ 17,222	$ 18,200	**$ 180,722**
Total Outreach Costs	$ 550,000	$ 565,634	$ 240,592	$ 247,185	$ 234,293	$ 240,916	**$ 2,078,621**
DIRECT COSTS							
Mechanical Subsystem	$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000	**$ 7,200,000**
Power Subsystem	$ 18,200,000	$ 18,200,000	$ 18,200,000	$ 18,200,000	$ 18,200,000	$ 18,200,000	**$ 109,200,000**
Thermal Control Subsystem	$ 900,000	$ 900,000	$ 900,000	$ 900,000	$ 900,000	$ 900,000	**$ 5,400,000**
Comms & Data Handling Subsystem	$ 3,800,000	$ 3,800,000	$ 3,800,000	$ 3,800,000	$ 3,800,000	$ 3,800,000	**$ 22,800,000**
Guidance, Nav, & Control Subsystem							**$ -**
Science Instrumentation	$ 36,800,000	$ 36,800,000	$ 36,800,000	$ 36,800,000	$ 36,800,000	$ 36,800,000	**$ 220,800,000**
Spacecraft Cost Margin	$ 30,450,000	$ 30,450,000	$ 30,450,000	$ 30,450,000	$ 30,450,000	$ 30,450,000	**$ 182,700,000**
Total Spacecraft Direct Costs	$ 91,350,000	$ 93,725,100	$ 96,100,200	$ 98,475,300	$ 100,850,400	$ 103,225,500	**$ 583,726,500**
Manufacturing Facility Cost							**$ -**
Test Facility Cost	$ 18,300,000	$ 18,300,000	$ 18,300,000	$ 18,300,000	$ 18,300,000	$ 18,300,000	**$ 109,800,000**
Facility Cost Margin	$ 1,830,000	$ 1,830,000	$ 1,830,000	$ 1,830,000	$ 1,830,000	$ 1,830,000	**$ 10,980,000**
Total Facilities Costs	$ 20,130,000	$ 20,653,380	$ 21,176,760	$ 21,700,140	$ 22,223,520	$ 22,746,900	**$ 128,630,700**
Total Direct Costs	$ 111,480,000	$ 114,378,480	$ 117,276,960	$ 120,175,440	$ 123,073,920	$ 125,972,400	**$ 712,357,200**
Total MTDC	$ 91,350,000	$ 93,725,100	$ 96,100,200	$ 98,475,300	$ 100,850,400	$ 103,225,500	**$ 583,726,500**
FINAL COST CALCULATIONS							
Total F&A	$ 6,090,000	$ 6,327,510	$ 6,565,020	$ 6,802,530	$ 7,040,040	$ 7,277,550	**$ 40,102,650**
Total Projected Cost	$ 124,883,206	$ 128,382,576	$ 130,927,126	$ 135,091,692	$ 135,115,637	$ 138,485,445	**$ 792,885,681**
Total Cost Margin	$ 32,921,428	$ 32,937,959	$ 32,869,766	$ 32,895,468	$ 32,689,793	$ 32,700,016	**$ 197,014,431**
	26.4%	25.7%	25.1%	24.4%	24.2%	23.6%	
Total Project Cost	$ 124,883,206	$ 128,382,576	$ 130,927,126	$ 135,091,692	$ 135,115,637	$ 138,485,445	**$ 792,885,681**

F&A %	10%	10%	10%	10%	10%	10%
ERE - Staff	28%	28%	28%	28%	28%	28%
Inflation Rate	0.0%	2.6%	5.2%	7.8%	10.4%	13.0%
Science Personnel Salary	$ 80,000					
Engineering Personnel Salary	$ 80,000					
Technicians Salary	$ 60,000					
Administration Personnel Salary	$ 60,000					
Project Management Salary	$ 120,000					

The budget of this mission is based on the customer constraints which is within the NASA discovery mission budget (Bowman 2019). The budget is first spread around the salaries for each role where it was established by the customer to be $80,000 for engineering and science personnel, $60,000 for the technicians and administration personnel, and lastly $120,000 for the management personnel. These salaries are set for the mission with inflation already included at different rates, and the employee related expenses staying at a fixed rate of 28%.

The cost estimate for personnel is a general breakdown of costs for each subsystem of the mission and the associated facilities costs. The costs for personnel were determined for each fiscal year as the different phases of the mission have different needs. The costs of personnel fluctuate throughout the phases since some personnel are needed more in certain phases than others.

Travel cost is all expenses by the team including but not limited to: flight, hotel, transportation, and per diem. Travel is $2,500 per person per week of travel used. Per diem was taken into consideration for travel to FI for hotel cost. The total cost in outreach converges towards $2,078,621. This includes all services for outreach personnel.

Overall, the team's final cost calculations overlook the total projected cost and cost margin at $989,900,112. The margin for this projected cost came to be $197,014,431.

5.3.3 Personnel Cost

5.3.3.1 Overview and Key Constraints

This section presents a comprehensive breakdown of the mission's personnel costs from Phases C through F, consistent with the L'SPACE Budget Template and the mission's $200 million cost cap. A total of $33 million has been allocated to personnel expenses, which covers:

- **Base Salaries:** $80k for science and engineering, $60k for technicians and administration, and $120k for management.
- **28% Employee Related Expense (ERE):** Applied exclusively to personnel salaries. This fringe factor *does not* apply to Travel, Outreach, or Direct Costs.
- **Inflation:** 0.0% in FY1, 2.6% in FY2, and 5.2% in FY3, following NASA's New Start Inflation Index.
- **Schedule and Risk Margin:** Additional staffing is built in to address shipping delays, staff turnover, and onboarding periods.

In addition to personnel costs, there are three other cost categories: Travel, Outreach, and Direct Costs. Since these categories are *non-labor* expenses, the 28% ERE factor does not apply to them. Their totals appear separately in the overall mission budget.

5.3.3.2 Phase C (FY1–FY3): Design, Fabrication, and Early Integration

Drivers, Ground Rules, and Assumptions

- **High Labor Intensity:** Phase C finalizes the aerobot design, requires rigorous subsystem test- ing, and addresses tight fabrication deadlines.
- **Margin for Turnover and Training:** The staff count includes extra technicians and engineers to mitigate potential personnel changes.
- **Shipping Delays and Supply Risks:** Higher staffing ensures fabrication

remains on schedule even if materials or components are delayed.

- **Customer Launch Readiness Date:** Meeting the assigned launch integration milestone is paramount, justifying a larger workforce than typical guidelines (30–50) might suggest.

Phase C's total staff of 64 (10 Science, 15 Engineering, 30 Technicians, 5 Administration, 4 Manage- ment) slightly exceeds standard guidelines, but is critical to meet the design and fabrication schedule. The base salaries and ERE produce the listed totals, with inflation factored in for FY2 and FY3.

Table 47: Personnel Costs

NASA L'SPACE Mission Concept Academy Budget - *V.E.L.A.Z.Q.U.E.Z*							
Mission Phase	**Phase C**	**Phase C**	**Phase C-D**	**Phase D**	**Phase E**	**Phase F**	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative Total**
PERSONNEL							
Science Personnel	$ 800,000	$ 820,800	$ 420,800	$ 431,200	$ 1,324,800	$ 1,356,000	$ 5,153,600
Engineering Personnel	$ 1,200,000	$ 1,231,200	$ 1,262,400	$ 1,293,600	$ 883,200	$ 904,000	$ 6,774,400
Technicians	$ 1,800,000	$ 1,846,800	$ 1,893,600	$ 1,940,400	$ -	$ -	$ 7,480,800
Administration Personnel	$ 300,000	$ 307,800	$ 315,600	$ 323,400	$ 331,200	$ 339,000	$ 1,917,000
Project Management	$ 480,000	$ 492,480	$ 504,960	$ 517,440	$ 529,920	$ 542,400	$ 3,067,200
Total Salaries	$ 4,580,000	$ 4,699,080	$ 4,397,360	$ 4,506,040	$ 3,069,120	$ 3,141,400	**$ 24,393,000**
Total ERE	$ 1,278,278	$ 1,311,513	$ 1,227,303	$ 1,257,636	$ 856,591	$ 876,765	**$ 6,808,086**
Personnel Margin	$ 585,828	$ 601,059	$ 562,466	$ 576,368	$ 392,571	$ 401,816	**$ 3,120,109**
TOTAL PERSONNEL	$ 6,444,106	$ 6,783,556	$ 6,508,860	$ 6,834,567	$ 4,767,384	$ 4,994,579	$ 36,333,051

Phase C’s total staff of 64 (10 Science, 15 Engineering, 30 Technicians, 5 Administration, 4 Management) slightly exceeds standard guidelines, but is critical to meet the design and fabrication schedule. The base salaries and ERE produce the listed totals, with inflation factored in for FY2 and FY3. The total across Phases D–F reaches $33,030,046 for personnel. This reflects the redeployment of staff from fabrication to science roles while maintaining administrative and managerial continuity. All salaries are subject to the 28% ERE and inflation, as shown in the table.

Other Cost Categories and Fringe Factor Application
Alongside personnel costs, the mission includes three additional cost categories:

- **Travel:** $50,000, $51,300, $68,161, $53,900 (cumulative $223,361).
- **Outreach:** $50,000, $51,300, $52,600, $53,900 (cumulative $207,800).
- **Direct Costs:** $1,148,813, $1,179,947, $10,520, $10,780 (cumulative $2,350,060).

Since these are non-labor expenses, the 28% ERE *does not* apply to them. Travel, outreach, and direct costs each follow their own assumptions regarding inflation or margin but remain separate from personnel fringe calculations. The resulting totals are integrated into the overall mission budget but are not subject to ERE.

5.3.3.4 Consistency with the Project Management Approach

The evolving staff requirements align with the Project Management Approach, which addresses:

- **Phase C Focus:** A robust workforce to finalize design and meet the customer launch readiness milestone.
- **Phases D–F Reallocation:** Technicians step back as manufacturing concludes, while scientists increase to manage in-flight operations and data.
- **Margin for Risk:** Turnover, shipping delays, and supply chain disruptions are mitigated by having additional staff, especially in Phase C and early Phase D.

This strategy ensures that the mission stays on schedule, addresses potential contingencies, and remains within the $200 million overall budget constraint, with $33 million specifically allocated to personnel. The fringe factor is *only* applied to direct labor salaries, whereas travel, outreach, and direct hardware or facility costs are accounted for separately.

5.3.3.5 Conclusion

By the close of Phase F, cumulative personnel costs amount to $33,030,046, reflecting the base salaries, ERE, and inflation for all roles. Although staff levels in Phases C and D exceed typical guidelines, these numbers are vital to safeguard the schedule and mitigate risks. Non-labor expenses (travel, outreach, direct costs) do not incur the 28% ERE and are tracked independently. This approach maintains rigorous adherence to the mission's cost cap, the Project Management Approach, and NASA's recognized cost-estimation methodologies.

5.3.4 Travel Budget

This section provides a thorough analysis of the travel costs associated with our mission. The travel budget covers expenses for morale trips, team meetings, and the journey to and from the launch site at Cape Canaveral, FL (Southwest Airlines 2024). Travel is organized into clearly defined mission phases (C, D, E, and F) across fiscal years, allowing for precise cost allocation and strategic planning.

The travel events include:

- **Mission Launch and Team Meetings:** Key personnel will travel to Cape Canaveral to observe the launch and attend essential pre- and post-launch meetings.
- **Additional Travel:** The budget also covers trips for site visits, including hardware construction and testing sites, as well as additional review meetings.
- **Travel Arrangements:**

Commercial Coach Flights: Utilizing government rates under the City Pair Program, with cost estimates based on high fares.

Lodging: One room per person at a partnered hotel (via Fedrooms) for the duration of each trip.

Ground Transportation: Group car rentals and local transport to accommodate varied schedules.

Meal Per Diem: Daily allowances per person based on U.S. General Services Administration (GSA) rates.

For this analysis, it was assumed that a complete travel event for the selected 15 key personnel costs $23,200. This estimate is based on the following components:

- **Flights:** $350 per person (round-trip) × 15 = $5,250
- **Lodging:** 15 rooms × 5 nights × $120 per night = $9,000
- **Ground Transportation:** 5 days × $50 = $250
- **Meal Per Diem:** 15 persons × 5 days × $60 per day = $4,500
- **Additional Travel Allowance:** Estimated for extra site visits = $3,200
- **Contingency Fund:** Lump sum for unforeseen expenses = $1,000

The mission is divided into four phases, with travel events allocated as follows:

- **Phase C:** Occurs over Fiscal Years (FY) 1, 2, and 3. One travel event per year.
- **Phases D, E, F:** All scheduled in FY4, with one travel event per phase.

The table below summarizes the travel cost allocation by mission phase and fiscal year:

Table 48: Travel Cost Allocation by Mission Phase and Fiscal Year

TRAVEL							
Mission Phase	**Phase C**	**Phase C**	**Phase C-D**	**Phase D**	**Phase E**	**Phase F**	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative Total**
Total Flights Cost	$ 110,000	$ 110,000	$ 110,000	$ 330,000	-	-	**$ 660,000**
Total Hotel Cost	$ 176,000	$ 176,000	$ 176,000	$ 528,000	-	-	**$ 1,056,000**
Total Transportation Cost	$ 5,500	$ 5,500	$ 5,500	$ 16,500	-	-	**$ 33,000**
Total Per Diem Cost	$ 22,000	$ 22,000	$ 22,000	$ 66,000	-	-	**$ 132,000**
Travel Margin	$ 5,600	$ 5,600	$ 5,600	$ 16,800	-	-	**$ 33,600**
Total Travel Costs	$ 319,100	$ 327,397	$ 335,693	$ 1,031,969	$ -	$ -	**$ 2,014,159**

The cost breakdown consists of:

- Phase C: Travel events are scheduled in FY1, FY2, and FY3, each incurring a cost of $23,200, totaling $69,600.
- Phases D, E, F: Each of these phases has one travel event in FY4, each costing $23,200.
- Yearly Totals: FY1, FY2, and FY3 each incur one travel event ($23,200 each), while FY4 includes three events ($23,200 × 3 = $69,600).
- Overall Total: The cumulative travel cost for all phases amounts to $139,200.

By carefully planning for flights, lodging, ground transportation, meal per diem, and additional travel events, the mission ensures that all key personnel can participate in critical meetings and site visits. The structured approach enables accurate cost allocation and robust contingency planning, ultimately contributing to the mission's overall operational readiness and success.

5.3.5 Outreach Cost

The outreach costs are all of the costs associated with the outreach efforts mentioned later in section 5.5. The outreach costs are separated into five categories and by each phase of the mission. These categories are materials, venue, travel, services, and personnel. These categories were picked based on generalizing the outreach costs per main categories.

The material costs include but are not limited to the costs of printing brochures and posters, branded merchandise, prizes for the competition, event supplies, VR headset, and digital and video production. The majority of these expenses will be incurred before the launch date in phases C and D. This is because that is when the main outreach efforts will occur, and most of the material costs post phase D will be video production and a few events. Branded merchandise will include items such as t-shirts and educational materials. Digital production costs include editing software, professional video equipment, and animations and infographics for social media and educational presentations. Educational materials not only help promote the mission but, "encouraged the students to ask more questions in class, which probably carried over into their other classes and benefited their academic studies" (Mcfadden 2011). These materials will benefit the team's ability of spreading the word to a specific audience as well.

The venue costs for outreach include the costs of renting out a venue for the various outreach events. Most of the venue rental is for the speakers and presentations. Venue costs also cover expenses such as audio and visual equipment and cleaning fees. There will be no venue costs post launch, as no in person events will be taking place. When given the opportunity to publicly address a wide audience, “allows researchers to communicate their research much faster and more widely than is possible through scientific journals or through textbooks” (Blasi 2007). Presentations are a crucial part of outreach.

The travel costs include costs associated with transportation, accommodation, per diem, and shipping and logistics for the outreach team. The transportation costs are allocated for the plane tickets, car rentals, and public transportation for the outreach team. Accommodations are the costs for the outreach teams' hotels during their circuit. Per diem is a daily amount allotted to an individual team for daily food, which, per NASA travel recommendations, is, on average, $60 a day (NASA). The per diem rates, “provides the general rules for using a federal per diem rate to substantiate the amount of ordinary and necessary business expenses paid” (Schreiber 2018). Additionally, the shipping and logistics are the cost for moving the equipment from location to location and to events. With a total of 40-50 planned events The services costs include event coordination, media and production, catering, and security and safety.

Personnel costs are the costs for the wages and stipends of the outreach team, costs for temporary and part-time staff, and training and preparation costs. The costs for the wages of the team were determined from the (MCCET 2024). The salaries of the outreach personnel would be $60,000 for the outreach officers and $120,000 for the outreach manager. There will be three outreach officers and one outreach manager. After launch at the end of phase D, there will be less need for outreach and the team will be reduced to one outreach officer and one manager.

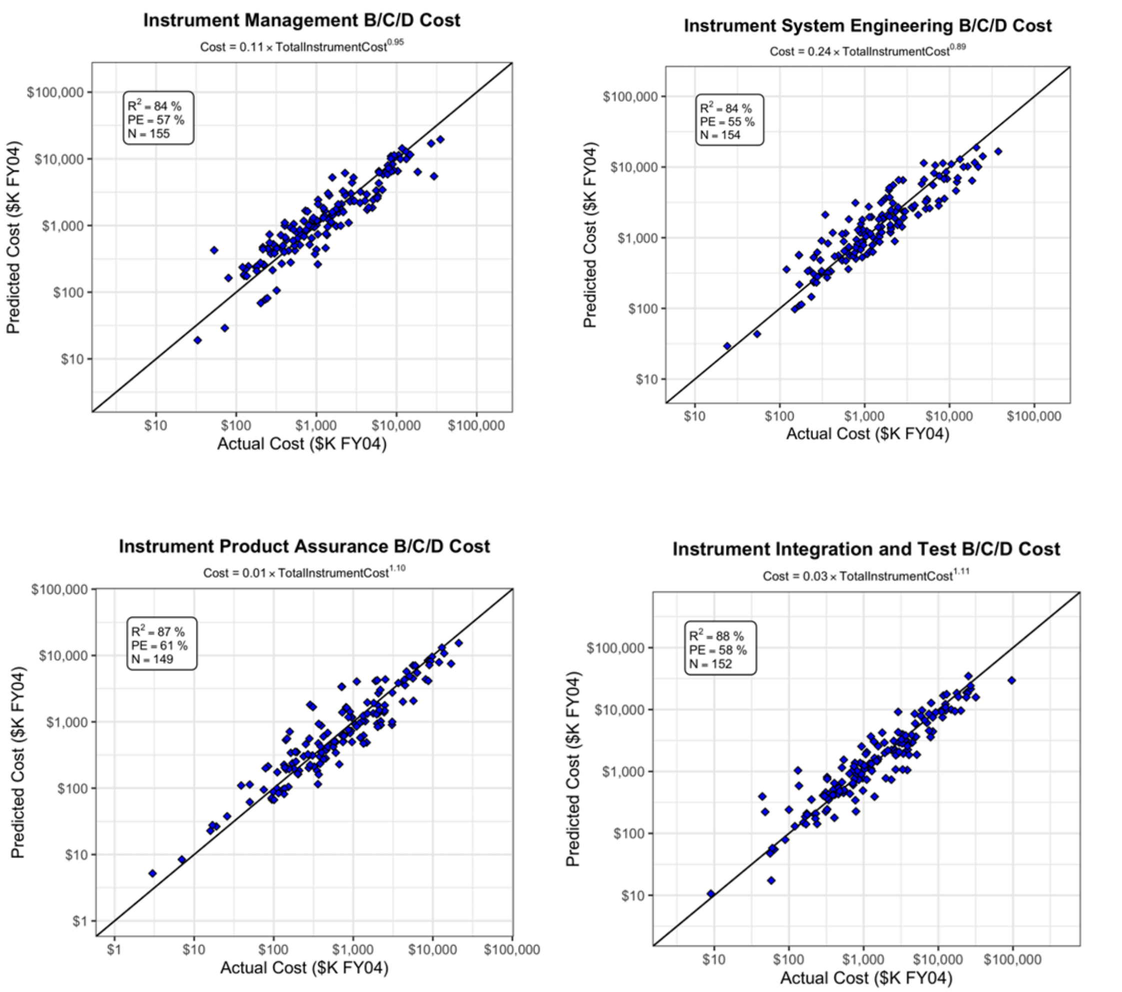
Table 49: Breakdown of the outreach costs

OUTREACH							
Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
Total Outreach Materials	$ 40,000	$ 40,000	$ 6,000	$ 6,000	$ 3,000	$ 3,000	**$ 98,000**
Total Outreach Venue Costs	$ 50,000	$ 50,000	$ 10,000	$ 10,000	$ -	$ -	**$ 120,000**
Total Outreach Travel Costs	$ 100,000	$ 100,000	$ 10,000	$ 10,000	$ 11,000	$ 11,000	**$ 242,000**
Total Outreach Services Costs	$ 10,000	$ 10,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	**$ 24,000**
Total Outreach Personnel Costs	$ 300,000	$ 300,000	$ 180,000	$ 180,000	$ 180,000	$ 180,000	**$ 1,320,000**
Outreach Margin	$ 50,000	$ 51,300	$ 21,700	$ 22,300	$ 17,222	$ 18,200	**$ 180,722**
Total Outreach Costs	$ 550,000	$ 565,634	$ 240,592	$ 247,185	$ 234,293	$ 240,916	**$ 2,078,621**

5.3.6 Direct Costs

General Direct Cost Approach

Team V.E.L.A.Z.Q.U.E.Z has chosen to primarily use the NASA Instrument Cost Model (NICM) tool to establish Cost Estimating Relationships (CERs). For subcomponents that lack pre-established cost models, such as the Power Subsystem, a cost model derived from an analogous mission will be applied to the subcomponent. Cost analogies offer quicker methods of establishing CERs but may oftentimes rely on very few data points (NASA 2015) and thus will also only be used on subcomponents that have no available parametric costs but have strong similarities to historical missions. The obtained values from these models will then be accounted for based on the year the tool came out (parametric) or the year the cost figures were published (analogous). Finally, wrap costs (**tables []-[]**) will be added according to the cost curves as derived from the NASA Instrument Cost Model (NICM) version 9c, which is used by the Mission Concept Cost Estimation Tool (MCCET). Facility costs per subsystem and margins will be outlined in the final subsections, with a budget table for summary.



Figures 47-50: Wrap Cost Estimating Relationships used by NICM 9c, derived from data points (blue points) across different types of instruments from different labs like JPL, JHU APL, GSFC, and many other system contractors (Mrozinsky 2023).

Mechanical Subsystem

The Mechanical Subsystem is responsible for all structural and material components that make up the Aerobot. This includes bolts, fasteners, actuators, cable claddings, anti-corrosive material coatings, as well as the chassis of the Aerobot itself.

For the parametric cost models, all subcomponents were included in the mass parameter. The Mechanical Subsystem Model CER was used to model the total costs for nuts, bolts, fasteners, cable protection, and the chassis itself (NICM 2020). Each mass value and power value is derived from the SRR.

Table 50: Mechanical Subsystem CER

Mechanical Subsystem CER		
Subcomponents	**Cost Model**	**Final Value**
Anti-corrosive powder coat, Inconel Cables, cable claddings, bolts, nuts, fasteners, Aerobot Chassis	219 * MechMass^0.41 * TotalMaxPwr^0.52	520.19

All values from the NICM-derived Cost Estimating Relationships (CER) template were accounted for from 2004.

$ 520 in 2004 will be worth $887 in 2025

This is an average inflation rate of **2.59%** and cumulative inflation of **70.53%**.

The costs after inflation are multiplied by 1000 to obtain the total (before wraps).

Total Cost before wraps (nearest $100,000): $900,000

Finally, wrap costs are calculated, each according to NICM 9c cost models detailed in table 46.

Table 51: Mechanical Wrap Costs

Wrap Costs	Cost Estimate
Management Costs	$50,000.00
Systems Engineering Costs	$50,000.00
Product Assurance Costs	$40,000.00
Integration & Test Costs	$120,000.00
Final manufacturing cost per unit (manufacturing + wraps)	**$1,200,000.00**

Power Subsystem

The Power Subsystem handles all flow, distribution, and sourcing of electricity within the Aerobot system, whether for general power supply (Fixed power to run the different subcomponents) or modulated current (For components like actuators, heaters, and antennas that require variable power). It achieves this through multiple solar panels, an 800W battery, and a power distribution array board.

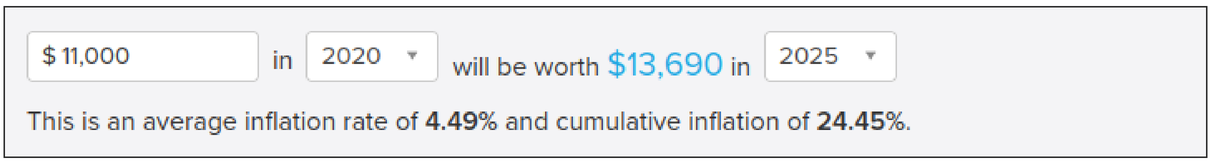
The NICM does not include any parametric CERs for the Power Subsystem, and will have to be estimated by cost analogies. The Venus Express mission includes the use of similar components in its Power Subsystem, namely using a 1200W Battery, power distribution boards, and solar panels capable of a total power of 450 W (NSSDC 2005-045A). These missions will thus be used by the team to estimate analogous costs. The Venus Express missions are estimated to have cost $110 Million with (https://www.space.com/18363-venus-express.html) ~10% of this cost attributed to their

Power Subsystems excluding margins and wraps. (https://www.nasa.gov/ocfo/ppc-corner/nasa-cost-estimating-handbook-ceh/).

Table 52: Power Subsystem Cost Analogies

Power Subsystem Cost Analogies		
Subcomponents	**Derived Mission**	**Cost**
800W Battery, Solar Panels, Power Distribution Board	Venus Express	$11,000,000

This value is accounted for inflation from the year of the source's publication when it reported the cost, 2020.



Multiplying this value by 1000 gives us the final total cost before wraps.

Total Cost before wraps (nearest $100,000): $13,700,000

Finally, wrap costs are calculated, each according to NICM 9c cost models detailed in table 48.

Table 53: Power Subsystem Wrap Costs

Wrap Costs	Cost Estimate
Management Costs	$660,000.00
Systems Engineering Costs	$540,000.00
Product Assurance Costs	$710,000.00
Integration & Test Costs	$2,510,000.00
Final manufacturing cost per unit (manufacturing + wraps)	**$18,200,000.00**

CDH Subsystem

While the CDH Subsystem consists of open source software and flight control systems, vital hardware components need to be manufactured and purchased for functional operation. This incorporates the use of an On-board Computer integrated with the flight control software bundle core Flight System and a data recorder, as well as a transceiver and three antennas that handle the communications of the Aerobot.

Of the subsystems, the CDH Subsystem has the most application-dependent specifications. Most components will be modeled parametrically and under two categories, one for electronics subcomponents (antennas, etc.) and one for software subcomponents (onboard computer, data recorders).

Because the CDH Subsystem consists of components modeled by two different parametric models, each subcomponent is classified under either software or electronic components (NICM 2020). The differentiation was determined by its proximity to data-handling processes. Because the onboard computer and the Data Recorder are directly responsible for software and data control, these two were modeled by the software CER, whereas the antennas were modeled under electronics. Each mass value is derived from the SRR.

Table 54: CDH Subsystem CER

CDH Subsystem CER		
Subcomponents	**Cost Model**	**Final Value**
Antennas	1516 * ElecMass^0.74	1249.40
On-board Computer, Data Recorder, Transceiver	236 * ElecMass^0.69	425.40

All values from the NICM-derived Cost Estimating Relationships (CER) template were accounted for from 2004.

The cost after inflation is multiplied by 1000 to obtain the total (before wraps).

<u>Total Cost before wraps (nearest $100,000):</u> $2,900,000

Finally, wrap costs are calculated, each according to NICM 9c cost models detailed in table 50.

Table 55: CDH Wrap Costs

Wrap Costs	Cost Estimate
Management Costs	$150,000.00
Systems Engineering Costs	$140,000.00
Product Assurance Costs	$130,000.00
Integration & Test Costs	$450,000.00
Final manufacturing cost per unit (manufacturing + wraps)	**$3,800,000.00**

Thermal Subsystem

The Thermal Subsystem encompasses material coating, radiators, and active heaters for both cooling and heating functions essential to keeping the Aerobot and its subsystems within stable operating temperatures. A delicate balance between passive elements as well as active elements is needed to strike a balance between effectiveness and cost.

Version 9c of the NICM includes a parametric CER for Thermal/Fluids Subsystems and will thus be used to derive the Thermal Subsystem cost. It is worth noting that the Barium Sulphate-Alcohol mixture was assumed to have negligible weight.

Table 56: Thermal Subsystem CER

Thermal Subsystem CER		
Subcomponents	**Cost Model**	**Final Value**
Barium Sulphate with Polyvinyl Alcohol Coating, Flexible Strip Heaters	642 * ThermMass^0.62	394.60

Inflation is accounted for from 2004, the year of version 9c of the NICM. The cost after inflation is multiplied by 1000 to obtain the total (before wraps).

$ 395 in 2004 will be worth $674 in 2025

This is an average inflation rate of **2.59%** and cumulative inflation of **70.53%**.

<u>Total Cost before wraps (nearest $100,000):</u> $700,000

Table 57: Thermal Wrap Costs

Wrap Costs	Cost Estimate
Management Costs	$40,000.00
Systems Engineering Costs	$40,000.00
Product Assurance Costs	$30,000.00
Integration & Test Costs	$90,000.00
Final manufacturing cost per unit (manufacturing + wraps)	**$900,000.00**

Payload/Instrumentation Subsystem

The science payload includes three main instruments for fulfilling science objectives. The first is a UV/VIS Spectrometer operational within 170-320 nm wavelengths, with an integration time of ~1 second and spatial resolution of 0.5 nm. The second is an infrared radiometer, mainly used for thermal emissivity in the 0.1-2 mm range, capable of 1s integration time and 0.01 micron spatial resolution. Lastly, a dust and radiance tool that covers dust and sand scattering in the 170-900 nm range, with integration times of 1s and a spatial resolution of 0.1 nm, rounds off the team's mission objective.

The nature of payload subcomponents is incredibly volatile and varies across every mission. For example, integration time on the spectrometers and radiometers may vary by an order ~10^{-3} if it were to be used in a different mission (Wetzel 2024). Thus, only parametric cost models will be used to derive costs for the Payload and Instrumentation Subsystem, as detailed below.

For the payload's three instruments, each can be classified clearly under one of the instrument types as listed by the NICM System Model CERs (NICM 2020). The spectrometer and dust and radiance tool, covering optical wavelengths of 170-320 nm and 170-900 nm to quantify data, can be categorized as optical planetary instruments. The infrared radiometer, on the other hand, covering 0.1-2 mm thermal emissivity readings, captures wavelengths much closer to the micrometer and sub-millimeter range, clearly classifying it as a microwave instrument. Its passive recording style, without the need for sending out its own signals, further puts it under the category of a Passive Microwave Instrument.

Each mass value and power value is derived from the SRR. The design life of the optical instruments is borrowed from their parent instruments, which are the SPICAV/SOIR instrument for the spectrometer and the MEDA Dust Tool for the Dust and Radiance Tool. The SPICAV/SOIR had a design life of 8 years (Trompet et al. 2016), and the MEDA was designed for an operational life of around 34 months, equivalent to 2.83 years (NASA 2025).

Table 58: Payload Subsystem CER

Payload Subsystem CER		
Subcomponents	**Cost Model**	**Final Value**
UV/VIS Spectrometer	392 * TotalMass^0.45 * TotalMaxPwr^0.49 * DsgnLife^0.32	5377.14
Infrared Radiometer	1,686 * TotalMass^0.39 * TotalMaxPwr^0.38	6592.41
Dust and Radiance Tool	392 * TotalMass^0.45 * TotalMaxPwr^0.49 * DsgnLife^0.32	4140.95

All values from the NICM-derived Cost Estimating Relationships (CER) template were accounted for from 2004.

$ 16,110 in 2004 will be worth $27,472 in 2025

This is an average inflation rate of **2.59%** and cumulative inflation of **70.53%**.

<u>Total Cost before wraps (nearest $100,000):</u> $27,500,000

Finally, wrap costs are calculated, each according to NICM 9c cost models detailed in table 54.

Table 59: Payload Wrap Costs

Wrap Costs	Cost Estimate

Management Costs	$1,280,000.00
Systems Engineering Costs	$1,000,000.00
Product Assurance Costs	$1,520,000.00
Integration & Test Costs	$5,430,000.00
Final manufacturing cost per unit (manufacturing + wraps)	**$36,800,000.00**

Manufacturing, Testing, & Assembling

Besides costs that go directly into the Aerobot's multiple subsystems, costs for manufacturing and testing facilities also have to be accounted for.

For primary testing, analysis, and demonstration of the various subcomponents, subsystems, and system, the team has chosen to conduct testing at the Glenn Research Center, with dedicated resources to optimal Thermal Vacuum (TVAC), Electromagnetic Interference (EMI), Vibration Testing (VIBE), and integrated environments under its Space Environments Complex (NASA 2022).

Finally, the team plans to assemble the system at a facility that can provide precise, decontaminated, and industry-standard system assembly, vital to ensure mission goals while upholding considerations as detailed by Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 (The National Academies Press 2023). Marshall Space Flight Center's Michoud Assembly Facility offers the most suitable facilities for assembly requirements while offering additional support in materials and labor (NASA 2025).

As per the mission's System Requirements Review, testing in TVAC, EMI, and VIBE environments, as well as miscellaneous ambient testing, is required to properly gauge environmental capabilities under conditions similar to Venus' 50-70 km atmosphere. Additionally, sterile and decontaminated environments, as well as trained technicians and professionals, are needed to assemble a launch-ready Aerobot.

This involves weeks to months of both cleanroom and non-cleanroom facilities, 24/7 testing staff, and numerous equipment and fixtures, with an estimated ~30% of the overall instrument cost allocated to testing expenditure (Mission Concept Cost Estimate Tool 2025).

A general breakdown, following the Mission Concept Cost Estimate Tool's guidelines, can be found below in table **[fill in]** for the costs associated with each section covered under Manufacturing, Testing, and Assembling. Cleanroom facilities cost from $25-50k a month, for which up to 4 months can be taken when including TVAC, EMI, VIBE, and ambient testing, as well as cleanroom assembly. Staff that work 24/7 is required for TVAC, EMI, and ambient testing (MCCET 2025) and must also be reimbursed. The rest of the cost is distributed to the cost of equipment like fixtures that ensure proper and accurate testing.

The weights for TVAC EMI VIBE and Ambient were chosen as 0.5, 0.25, 0.125, and 0.125, respectively, adding up to 30%. These weights were allotted in this manner due to TVAC and EMI's longer durations and heavy cleanroom use and VIBE and Ambient's shorter durations without cleanroom necessity. Each subsystem's estimated facility cost is displayed below.

Table 60: Mechanical Subsystem Test Facility Cost

Mechanical Subsystem Test Facility Cost	Cost Estimate
TVAC	$180,000.00
EMI	$90,000.00
VIBE	$50,000.00
Ambient	$50,000.00
Final testing facility cost per unit	**$400,000.00**

Table 61: Power Subsystem Test Facility Cost

Power Subsystem Test Facility Cost	Cost Estimate
TVAC	$2,730,000.00
EMI	$1,370,000.00
VIBE	$680,000.00
Ambient	$680,000.00
Final testing facility cost per unit	**$5,500,000.00**

Table 62: CDH Subsystem Test Facility Cost

CDH Subsystem Test Facility Cost	Cost Estimate
TVAC	$570,000.00
EMI	$290,000.00
VIBE	$140,000.00
Ambient	$140,000.00
Final testing facility cost per unit	**$1,100,000.00**

Table 63: Thermal Subsystem Test Facility Cost

Thermal Subsystem Test Facility Cost	Cost Estimate
TVAC	$140,000.00
EMI	$70,000.00
VIBE	$30,000.00
Ambient	$30,000.00
Final testing facility cost per unit	**$300,000.00**

Table 64: Payload Subsystem Test Facility Cost

Payload Subsystem Test Facility Cost	Cost Estimate
TVAC	$5,520,000.00

EMI	$2,760,000.00
VIBE	$1,380,000.00
Ambient	$1,380,000.00
Final testing facility cost per unit	**$11,000,000.00**

Margin

Finally, margin will be added to both facility costs and direct spacecraft costs. A spacecraft cost margin of 50% will be included as a standard PDR value for design changes. Facilities & Administrative Cost (F&A) margin will be calculated at 10% the total facility costs, accounting for overhead and other indirect costs.

Spacecraft Margin: $30,450,000

F&A Margin: $1,830,000

Total Direct Costs Budget

The total direct cost is obtained by totalling all direct costs as well as their included margins, outlined below in table form.

Table 65: Direct Costs

DIRECT COSTS							
Mechanical Subsystem	$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000	**$ 7,200,000**
Power Subsystem	$ 18,200,000	$ 18,200,000	$ 18,200,000	$ 18,200,000	$ 18,200,000	$ 18,200,000	**$ 109,200,000**
Thermal Control Subsystem	$ 900,000	$ 900,000	$ 900,000	$ 900,000	$ 900,000	$ 900,000	**$ 5,400,000**
CDH Subsystem	$ 3,800,000	$ 3,800,000	$ 3,800,000	$ 3,800,000	$ 3,800,000	$ 3,800,000	**$ 22,800,000**
Science Instrumentation	$ 36,800,000	$ 36,800,000	$ 36,800,000	$ 36,800,000	$ 36,800,000	$ 36,800,000	**$ 220,800,000**
Spacecraft Cost Margin	$ 30,450,000	$ 30,450,000	$ 30,450,000	$ 30,450,000	$ 30,450,000	$ 30,450,000	**$ 182,700,000**
Total Spacecraft Direct Costs	$ 91,350,000	$ 93,725,100	$ 96,100,200	$ 98,475,300	$ 100,850,400	$ 103,225,500	**$ 583,726,500**
Test Facility Cost	$ 18,300,000	$ 18,300,000	$ 18,300,000	$ 18,300,000	$ 18,300,000	$ 18,300,000	**$ 109,800,000**
Facility Cost Margin	$ 1,830,000	$ 1,830,000	$ 1,830,000	$ 1,830,000	$ 1,830,000	$ 1,830,000	**$ 10,980,000**
Total Facilities Costs	$ 20,130,000	$ 20,653,380	$ 21,176,760	$ 21,700,140	$ 22,223,520	$ 22,746,900	**$ 128,630,700**
Total Direct Costs	$ 111,480,000	$ 114,378,480	$ 117,276,960	$ 120,175,440	$ 123,073,920	$ 125,972,400	**$ 712,357,200**
Total MTDC	$ 91,350,000	$ 93,725,100	$ 96,100,200	$ 98,475,300	$ 100,850,400	$ 103,225,500	**$ 583,726,500**

5.4 Scope Management

5.4.1. Change Control Management

There are two types of changes that the team must be aware of throughout the mission. Those two types of changes are external change requests which come from the customer and internal change requests which come from other members within the team. Any change requests that come from the customer are typically indisputable since the customer is the one that makes this entire mission possible. Bigger changes that are requested externally are typically discussed with the entire team during the weekly all-team meeting. Because these changes tend to affect the majority of the mission, it is important that every person hears about the change and gets to input their opinion on how best to address it. Smaller changes that are requested internally do not need to be discussed with the entire team unless it affects the entire mission. For these decisions, discussions happen on a subteam specific basis and it is the subteam leaders' responsibility to relay any relevant information to other leaders. Subsystem leads are responsible for tracking and documenting changes and communicating that to their subteam leads. The subteam leads are then responsible for communicating any changes that affect other subteams to those leaders and all subteam leads are responsible for communicating changes with the project manager. By following this flow down, pertinent information can get communicated effectively, while minimizing the amount of superfluous information passed between subteams.

Regarding decision making within subteams, each subteam meets once a week at a minimum to discuss updates from the past week, plans moving into the next week, and any changes that need to be addressed. These meetings are dedicated to the most important information that needs to be relayed in order to maximize and respect other people's time. The team leads are also responsible for checking in throughout the week to make sure everyone is staying on track and the team as a whole is prepared for the upcoming milestones.

When determining the priority level of decisions that need to happen, the highest priority will go to the decision that has the biggest effect on the mission. If, for example, there was a dispute between a decision for an instrument that if not made, could result in a loss of functionality of the instrument, and a decision regarding the CDH subsystem that would not affect the data being collected but if approved, could make the data collection process slightly easier, the instrumentation would take priority because loss of functionality has higher risks than ease of data collection.

Change requests are also something that will be utilized if necessary, but the goal for the team is to not have to complete change requests if possible. Change requests must happen for any internal changes that need to happen that have already been baselined in the mission. This involves submitting a change request form and, if necessary, setting up a Change Control Board (CCB), which is a meeting with stakeholders and relevant Subject Matter Experts (SMEs) to present the change request and provide justification as to why it is important to the mission. In order to reduce the probability for submitting a change request form, ensuring full understanding from every team member of deliverable instructions and feedback is of the utmost importance so the team does not pursue a pathway that might end up needing to be revised later down the line. Tangible steps to achieve this include every member reading through deliverable instruction documents thoroughly and taking notes where necessary as well as reviewing all feedback given from mentors and noting any important external changes that need to be addressed in future deliverables.

Date Submitted (double click cell)	Subsystem	Previous Description	What change is occuring	Reason for Change	Member	Date Effective	Communicated to rest of team?
							☐
							☐

Figure 51: Change Control Tracker

In order for the team to stay organized and communicate changes between subteams effectively, a comprehensive change tracker has been created (Figure 51). This change tracker outlines when a change was initiated, by whom the change was initiated, what the previous item was and what it was changed to, the reason for the change, as well as the date it became finalized, and whether it was communicated to the rest of the team yet. This change tracker, coupled with the master task document that was created will help the team stay organized with decision-making and tasks completed along with subsystem changes. This change tracker will also help manage any Request for Actions (RFAs) and Advisory (ADV) changes proposed by the stakeholders and can ensure that each RFA and ADV gets addressed in a timely manner.

RFAs are unnegotiable directives that must be addressed before advancing to the next review while ADVs are recommendations for improvement and are evaluated for feasibility and value. Each team member is responsible for reviewing the RFAs and ADVs for their respective section and implementing those changes into future deliverables. An example of ways RFAs and ADVs have been accounted for has been through the use of a personal checklist. Each RFA or ADV gets put in the form of a list item and is checked off once it is complete. This keeps the section author accountable for each change and ensures nothing is missed when implementing feedback. These changes reflect the team's ability to take external feedback seriously and turn it into meaningful improvements.

5.4.2 Scope Control Management

When the scope of a project changes, the first things that often get affected are schedule and cost. Schedule is the most important thing to keep in mind, especially with spacecraft launches, because if an aspect of the project falls behind, it risks jeopardizing the mission and wasting time and money trying to get it back on track. In descoping a project, requirements and objectives are often shifted due to limited resources. It often involves limiting objectives so the project can stay within a certain timeline or budget (Feather, Cornford, and Hicks 2003). Increasing scope is a rarer occurrence and could often be attributed to receiving more funding or in a less ideal scenario, a lack of initial project objectives which will require the scope to increase later in the project. In either case, the team must be prepared to shift resources and components to accommodate for the scope change.

<u>5.4.2.1 Budget Descope</u>

In the event of a descope, the team has several alternative solutions to ensure the project stays within budget constraints. One large contributor to budget and schedule is testing. The team plans to analyze the verification and validation methods used for different component assemblies and reduce complexity where necessary. Testing is often the most ideal way to validate and verify a system but it is also the most expensive and time consuming. To conserve budget and scheduling, each subassembly plans to scale down the verification and validation method from testing to analysis or inspection if possible, leaving the testing procedures to subassemblies that require testing for full functionality. Procurement methods also play a large role in budget and schedule constraints. Outsourcing components can get very expensive and lead times can often be extensive and unpredictable. To mitigate this, the team plans to have multiple procurement sources available for each subassembly with varying prices and lead times. This will allow component manufacturing to still be fulfilled but with a flexible timeline and cost. Finally, to ensure every component stays within budget, when estimating costs, there will be at least a 30% overestimation margin in order to account for any unexpected shipping or other associated costs.

5.4.2.2 Schedule Descope

Since scheduling is such a big factor in testing and launch procedures, schedule compression is often an effective method of keeping a project on schedule even if certain parts of the project might be behind schedule. Fast-tracking and project crashing are two effective methods for schedule compression. Fast-tracking is often the first choice and it involves tasks being completed simultaneously for maximum time efficiency (Laoyan 2025). This works well for this project since the aerobot system is already divided into different subteams. The only risk that comes with this method is increased errors that could come from doing multiple tasks at once.

In the instance that the scope must be increased due to an unexpected increase in funding, the team plans to use extra funding towards more advanced instrumentation and higher quality materials. Extra funding can also go towards personnel costs and extra travel that the team deems necessary for testing purposes. If science objectives needed to be honed due to a lack of initial project objectives, the budget margins can give the team a little cushion if new instruments needed to be selected or other materials procured.

5.4.2.3 Life cycle time and trade-offs

The team's response to scope change differs depending on where it occurs in the mission life cycle. Early in the life cycle, phases A-B, the team has the most flexibility as requirements are still being refined and component decisions are preliminary. This is the ideal time to absorb additional scope or make the scoping decisions with minimal technical debt.

By phase C (design finalization), the scoping becomes more difficult as designs have been baselined and allocated resources are more fixed. Changes here require detailed analysis and strong justification to avoid disrupting team workflows or integration planning.

In phase D-E (integration, testing, and operations), scope changes are extremely high risk. At this stage, only critical technical scopes or essential performance upgrades should be considered. Changes during late stages are expected to go through a full change control board (CCB) review and require approval.

No matter the timing, scope decisions are always filtered through a mission priority lens. If a change compromises science, return core functionality, or system safety, it is rejected. If it enhances performance while maintaining control of cost and schedule, it is evaluated with structured trade analysis and if approved, integrated into an updated scope baseline.

5.5 Outreach Summary

This section will cover everything about informing the public about the mission and its goals (NASA 2022). It is essential to ensure public awareness of the mission's progress and achievements, as it is funded by a federal agency and, therefore, accountable to the taxpayers who support it. This means that the public's perception of the mission is critical to receiving funding for future programs. The outreach team is also responsible for educating youth about their doings, in hopes that they will pursue a career in that field, and become the next generation of NASA engineers and scientists. Through targeted community engagement and educational initiatives, the outreach team aims to bridge the gap between the complex mission objectives and public understanding. The outreach plan outlines the strategies that will be used to reach diverse audiences, including K-12 students, undergraduate and graduate students, and the general public. The goal is to build lasting enthusiasm and engagement with the mission, highlighting its value to both the scientific community and the general public.

5.3.1 Outreach for K-12

The first target audience is students in grades K-12. Finding students who are passionate and/or fascinated with space and planetary science is where the science community can benefit the most. Engaging younger audiences is crucial for inspiring future scientists, engineers, and space enthusiasts. This plan will include interactive, hands-on experiences that facilitate learning and engagement.

The younger generation is easily intrigued by hands-on activities and physical demonstrations, so that will be the main focus of outreach for them. To maximize engagement among students in grades 6-12, one of the main strategies will be the implementation of a nationwide essay competition. A competition for participants to write an essay about various space-related topics. These topics will be carefully curated by the NASA team to inspire curiosity about space exploration. Separated by grade, students will have the opportunity to submit essays from a variety of prompts to compete for cash prizes. This competition serves not only as an incentive for students to engage with the mission, but also for them to research past missions and learn about the development of space exploration, and the great discoveries and innovations made by NASA. Schools will see this as an opportunity for students to challenge themselves academically, which helps promote competition. The competition will be promoted widely throughout schools, social media, and local outreach events to ensure a broad and diverse network of participants. Parents of participating students will likely have a positive response to this effort, creating a positive connotation with the mission and further solidifying the public's trust of the program.

Similarly, for students in grades K-5, a national art competition will take place. Like the essay competition, it will be centered around space themes. To appeal to a younger age group, in lieu of cash prizes, prizes will consist of items like science-related toys for children to continue their science fascinations and to foster a generation of curious minds. The visual arts nature will help nurture an interest in science and space exploration.

5.3.2 Outreach for College/University

The second target audience is students enrolled in colleges and universities; this effort varies from the former because most students in higher education have decided what they want to pursue as a career. This means that outreach efforts for students in higher education should aim to get those who are already pursuing scientific or engineering careers to want to work in the space or planetary field. This will be done by traveling to college campuses around the nation and setting up workshops, talks, and booths to make college students aware of the mission. If done effectively, this can create enthusiasm about a career in space, making the job market more competitive and allowing NASA to receive the best of the best.

In the coming months of the launch, a group of outreach personnel will begin a circuit, traveling to college campuses nationwide to create anticipation for the launch and garner the interest of those in higher education. This circuit will consist of the team setting up workshops, participating in career fairs, and guest panels and discussions. A total of ten of the nation's top science universities will be visited.

The interactive workshops will allow students to get a sense of what it's like to work on the mission. They will also include sessions for skill development, such as resume workshops and/or technical classes. Another workshop that will be implemented is a project showcase. Similar to the writing and drawing competitions of the lower age groups, a project competition will be held to see who can build the best all-around system that would prove beneficial to our mission. The competition will have cash prizes for participants and allow them to become familiar with the goals of the mission and what goes into the development of the system. Career fairs are another way for NASA to find top recruits and gather the best people for the job. Guest speakers are an opportunity to get the men and women behind the scenes of the mission to be able to speak to an audience and effectively disseminate important information about the program and what goes into the success of the mission and why the public plays a big part in that.

5.3.3 Outreach for General Public

The last area of the public that the team aims to engage with is the general public. This means visiting community centers and public institutions to try to reach the underserved communities. Public seminars and events at libraries, etc., will be vital to reaching the general public. Social media is also a big area of interest that the team will spend a lot of time on. All of the groups aforementioned have a strong presence on social media, so showing mission updates and other content can get a large group of people engaged.

An attraction that will garner a lot of interest from all ages is a VR (virtual reality) experience that allows families to have a 360-degree view of the Venus surface (NASA 2024). This exhibit will travel the circuit with the team to every stop they make, engaging crowds and intriguing the public about a mission to Venus. The VR experience will be complemented by informational displays and guided explanations from team members, who will be available to discuss and answer any technical questions that may arise. This dynamic and educational experience will serve as both an outreach highlight and an invaluable platform for communicating the mission's core objectives.

Outreach to the general public will be a critical component of promoting the mission and ensuring widespread awareness and support. The main objective is to effectively convey the mission objectives, significance, and progress through engaging initiatives.

5.3.4 Outreach Strategies

One of the central outreach strategies will involve a robust digital presence. A strong social media presence is key in this day and age to having the largest impact on the public. This will include regular updates about the mission through various social media platforms, interactive content such as mission facts, short docuseries, and live Q&A sessions with mission experts.

Although platform-specific media will need to be created, as social media is too nuanced for a single-faceted approach. The team will utilize X for real-time updates, mission milestones, and event announcements. Live posts can also be made during mission events to keep followers engaged and bought into mission success. Instagram will serve to post visually appealing content, like mission renderings or infographics about mission progress. Instagram Stories will be used for short mission facts and outreach event reminders. Facebook will allow the team to post in-depth articles, event announcements, and event recaps. YouTube is where documentary-style content, interviews, and educational content related to mission technology and scientific goals will be posted. It will also be used to stream live events and lectures. TikTok is an application where short, engaging videos do well and help break down complex concepts into digestible segments. Collaboration with creators is also an area that will be utilized to expand the reach of the outreach. LinkedIn will be used for professional updates about mission progress, research papers, and technical presentations. Altogether, social media is an outlet that must be made use of for maximum outreach.

In addition to that, the team will conduct public presentations at community centers, libraries, and museums, inviting the public to join and learn about the mission goals. These events will also include public lectures featuring mission scientists and engineers who know the ins and outs of the mission. They will delve into the mission's scientific objectives and the challenges of a mission to Venus. These lectures will also be live-streamed to broaden the audience.

By employing this multi-faceted approach to public engagement, the outreach team can maximize the public's awareness of the mission and ensure that it reaches a broad and diverse audience.

The success of the outreach will be measured analytically to provide feedback for future missions. The main metrics for success of the outreach efforts will include: attendance numbers at events, engagement metrics from social media and online platforms, and feedback from the participants and community partners. Data collection used to quantify these metrics will be from surveys and questionnaires distributed during and after events, and also by social media analytics. Regular assessment of the outreach strategies will take place to improve the process. Adjustments may be justified based on feedback and engagement data that is collected.

5.3.5 Conclusion

As a NASA-funded mission, public perception is critical to maintaining support and securing future funding. Therefore, outreach efforts are designed to build public awareness and inspire the next generation of engineers and scientists through educational initiatives. The outreach strategy targets three main audiences: K-12 students, college students, and the general public. For K-12 students, the plan emphasizes hands-on, interactive experiences to stimulate interest in space science. Initiatives include a nationwide essay competition for grades 6-12 and a drawing competition for grades K-5. These activities encourage students to explore space-related topics creatively and academically while fostering a connection to NASA's mission. For college students, the plan focuses on fostering professional interest in space exploration and related careers. Outreach efforts will include workshops, guest lectures, career fairs, and project competitions at college campuses. The goal of the outreach team is to have at least 10 university visits and 20-30 miscellaneous events (Seminars, workshops, and public events). The objective is to inspire students already pursuing STEM fields to consider careers in space exploration. Additionally, the use of interactive activities, like a VR experience simulating the Venus surface, will enhance engagement and build enthusiasm. For the general public, the outreach will prioritize accessibility and community involvement. Traveling exhibits, public lectures, and partnerships with local community centers will ensure diverse community representation. A robust social media strategy will also play a key role in maintaining public interest, utilizing platform-specific content to maximize outreach. Real-time updates, interactive Q&As, and multimedia content will help build sustained engagement across different demographics. The outreach plan will be continuously assessed through attendance metrics, social media engagement, and feedback from participants. Data collected will guide improvements to maximize the mission's outreach impact, ensuring the mission remains transparent and inclusive while fostering public enthusiasm for space exploration.

6 Conclusion

The Preliminary Design Review serves as a key checkpoint that analyzes and mitigates risk that stems from the Mission Concept. Additionally, the PDR baselines more technical aspects of the scientific area of the mission specifically pertaining to science instrumentation. Our mission is to deploy an Aerobot system into the atmosphere of Venus to conduct scientific investigations at specific altitudes. The Aerobot carries all essential subsystems including power, communications, thermal control, mechanical structure, and data handling. It will be delivered by a descent system that ensures a controlled entry and steady operation in the Venusian cloud layer. The system is designed to support a science payload selected by the team and maintain stability and data transmission throughout the mission duration.

Looking ahead, our team is focused on preparing for the Critical Design Review. This includes detailed subsystem design reviews, finalizing interface documentation, and ensuring that each component meets the mission requirements. One key change request under consideration is the integration of a new spectrometer that can withstand the temperature ranges present in the Venusian atmosphere. We aim to evaluate this alternative to improve the reliability and longevity of the science instrumentation payload. Additionally, the team will expand its outreach strategy by launching a mission-focused social media, organizing STEM workshops with high schools, and pursuing opportunities to present at student career fairs. For the Critical Design Review, we plan to demonstrate that our design is ready for fabrication and implementation, with validated performance and risk mitigation strategies in place.

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Declaration of Generative AI and AI-assisted technologies in the writing process (No page limit)

- Teams must disclose the use of generative AI and AI-assisted technologies in the writing process by adding a statement at the end of their deliverable, before the References/Bibliography. The statement should read similarly to this:
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- *Science Direct on Artificial Intelligence*

Appendix A: Risk Log

Risk ID #	WBS Element	Risk Owner	Category	Time frame	Risk Title	Risk Statement	L	C	Rating	Approach	Trend	Mitigation Plans	Status of Mitigation Plans	Trigger Date	Trigger Event	Closure Date	Closure Event	Status Updates
M1	1.1 Ingress Contamination	Mech. Engineer	Scope	Medium Term	Ingress Contamination	Given that Venus experiences high winds that carry dust and particles through the atmosphere, there is a possibility of the dust breaching the aerobot's exterior adversely impacting the interior components, which can result in possible damages to instrumentation, payload, and data transmission.	3	3	Moderate	Mitigate (M)	↓ Decrease	1. Tight tolerances between interfacing parts as well as sealant materials like silicone rubber to fill an gaps or cracks to prevent any debris and particles entering the aerobot	1. In-progress	1. 04/21/25	1. PDR	2/28/2029	Project PDR	(03/31/25): The risk's L was changed from 4 to 3 after implementing mitigation plan #1
M2	1.2 Vibration Impact	Mech. Engineer	Scope	Short Term	Vibration Impact	Given that Venus' atmosphere experiences high winds and turbulent conditions, there is a possibility of the aerobot experiencing extreme vibrational motion, adversely impacting the structural integrity and mechanical connections, which can result in a possible deconstruction of the aerobot mid-flight.	3	4	Moderate	Mitigate (M)	↓ Decrease	1. Tight tolerances and connection components like self-locking screws to reduce risk of chassis components shaking loose	1. In-progress	1. 04/21/25	1. PDR	2/28/2029	Project PDR	(03/31/25): The risk's C was changed from 5 to 4 after implementing mitigation plan #1
C1	2.1 Noise/Interference	CDH Engineer	Scope	Medium Term	Noise/interference	Given that Venus' atmosphere experiences high winds and turbulent conditions, there is a possibility of the aerobot experiencing extreme vibrational motion adversely impacting the data collected by the instruments, which can result in high amounts of noise in the data rendering results useless.	2	2	Low	Mitigate (M)	↓ Decrease	1. Signal processing techniques like low-pass digital filtering and utilizing low-power mode if turbulence becomes too extreme 2. Checksums used in core Flight System to detect any faults in data by	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(03/31/25): The risk's L and C were changed from 4 to 3 after implementing mitigation plan #1 (04/20/25): The risk's L and C were changed from 3 to 2 after implementing mitigation plan #2

												conducting Cyclic Redundancy Checks (CRCs)						
C2	2.2 Cyberattacks/ Malware	CDH Engineer	Scope	Medium Term	Cyberattacks/ Malware	Given that NASA discovery missions are uncovering new information about foreign planetary bodies, there is a possibility of a cyberattack on the aerobot's data collection system adversely impacting the integrity of the space mission and breaching confidential contracts, which can result in the potential nullification of the space mission, data theft, or loss of control of the spacecraft.	3	4	Moderate	Mitigate (M)	↓ Decrease	1. Selecting a software that has real-time capabilities to allow for faster updates as well as built-in cybersecurity measures. 2. Core Flight System (cFS) is selected for interfacing with rest of subassemblies	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(03/31/25): The risk's L was changed from 4 to 3 and C from 5 to 4 after implementing mitigation plan #1
P1	3.1 Solar Panel Degredation	Electrical Engineer	Scope	Short Term	Solar Panel Degradation	Given that Venus has extreme surface temperatures and a thick, heat-tapping atmosphere, there is a possibility of solar panel degradation adversely impacting power generation efficiency, which can result in insufficient energy supply for systems.	3	3	Moderate	Mitigate (M)	↓ Decrease	1. Redundant power distribution systems including high-efficiency solar cells so there will be a backup in case one system fails 2. Separate solar panels in parallel to create isolated power tracking and battery charging circuits so one failed panel does not affect the rest 3. Voltage protection so lithium-ion battery voltage stays within functional range and protects battery health	1. Complete 2. In-progress 3. In-progress	1. 04/21/25 2. 10/10/25 3. 10/10/25	1. PDR 2. CDR 3. CDR	2/28/2029	Project PDR	(03/31/25): The risk's L was changed from 4 to 3 after implementing mitigation plan #1 (04/20/25): The risk's C was changed from 4 to 3 after implementing mitigation plans #2 and #3

P2	3.2 Battery Thermal Runaway	Electrical Engineer	Scope	Short Term	Battery Thermal Runaway	Given that Venus' high temperatures can cause excessive heat buildup, there is a possibility of battery runaway adversely impacting the power storage system, which can result in total power loss and mission failure.	3	4	Moderate	Mitigate (M)	↓ Decrease	1. Redundant power distribution systems including high-efficiency solar cells so there will be a backup in case one system fails 2. Low power mode to focus power towards essential subsystems 3. Voltage protection systems to protect battery in case of overvoltage or undervoltage	1. Complete 2. In-progress 3. In-progress	1. 04/21/25 2. 10/10/25 3. 10/10/25	1. PDR 2. CDR 3. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 5 to 4 after implementing mitigation plans #2 and #3
T1	4.1 Material Breakdown	Thermal Engineer	Scope	Medium Term	Material Breakdown in Fluctuating Temperatures	Given that Venus' extreme temperature fluctuations in high altitudes can degrade materials over time, there is a possibility of insulation failure adversely impacting internal components, which can result in overheating or underheating and permanent damage to critical electronics.	3	3	Moderate	Mitigate (M)	↓ Decrease	1. Multi-layered insulation (MLI), high-temperature resistant materials, high-temperature coatings. 2. Multiple heat strips to account for extreme temperature fluctuations and thermal sensors to control heat strip activation	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 4 to 3 after implementing mitigation plan #2
T2	4.2 Radiator Inefficiency	Thermal Engineer	Scope	Short Term	Radiator Inefficiency	Given that Venus' dense atmosphere reduces the effectiveness of radiative cooling, there is a possibility of heat accumulation adversely impacting thermal regulation, which can result in overheating and systems failure.	3	4	Moderate	Close (C)	Closed	N/A	N/A	N/A	N/A	N/A	N/A	This risk was removed due to descope

I1	5.1 Data Corruption	Scientist	Scope	Medium Term	Data Corruption	Given that radiation levels on Venus are much higher than on Earth, there is a possibility that the increased radiation exposure might affect data collection and storage methods, adversely impacting the quality of data received, which can result in corrupted data upon landing.	3	3	Moderate	Mitigate (M)	↓ Decrease	1. Multiple backup sources and redundant backup systems to ensure data continues being collected even if one system fails 2. Checksums used in core Flight System to detect any faults in data by conducting Cyclic Redundancy Checks (CRCs)	1. Complete 2. In-progress	1. 04/21/25 2. 10/10/25	1. PDR 2. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 4 to 3 after implementing mitigation plan #2
I2	5.2 Insufficient Data Collection	Scientist	Scope	Medium Term	Insufficient data collection	Given that Venus' atmosphere experiences high winds, there is a possibility that the turbulent conditions might interfere with the sensors' ability to collect data, adversely impacting the amount of data collected over the 36 hour time window, which can result in a lack of data for analysis upon landing.	2	3	Moderate	Mitigate (M)	→ Neutral	1. Extensive testing procedures to ensure instruments can collect data for entire flight period as well as environment testing to ensure instruments can withstand Venus' extreme environment	1. In-progress	1. 10/10/25	1. CDR	2/28/2029	Project PDR	-
Pr1	6.1 Mass Limit	Programmatics	Schedule/Scope	Medium Term	Mass Limit	Given that the new DSS risk requires a mass reallocation, there is a possibility of existing components exceeding the new mass constraint, adversely impacting the mission requirements, which can result in a delayed or failed launch.	3	4	Moderate	Mitigate (M)	↓ Decrease	1. Research viable components at different mass limits and be extra diligent at checking mass calculations to ensure all numbers are as accurate as possible.	1. In-progress	1. 10/10/25	1. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 5 to 4 after implementing mitigation plans #1

Pr2	6.2 Cost Limit	Programmatics	Cost/Scope	Medium Term	Cost Limit	Given that the mission to Venus has a strict cost limit, there is a possibility of exceeding the allocated budget due to unforeseen technical challenges or scope changes, which can result in the need for reallocation of funds, delaying project timelines, or compromising mission objectives.	2	4	Moderate	Mitigate (M)	↓ Decrease	1. Employing overestimation margins of at least 30% to account for variability in lead times and procurement costs.	1. In-progress	1. 10/10/25	1. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 5 to 4 after implementing mitigation plans #2
D1	7.1 Resource Shortage	Descope	Cost/Scope	Medium Term	Resource Shortage	Given that the new DSS risk requires a descope to mission subsystems, there is a possibility of needing to reallocate resources, adversely impacting the amount of personnel associated with this mission, which can result in delayed mission timelines	3	2	Low	Mitigate (M)	↓ Decrease	1. Cross-training personnel across multiple subsystems to ensure flexibility in task management 2. Prioritize mission tasks with high impact based on critical timelines	1. In-progress 2. In-progress	1. 10/10/25 2. 10/10/25	1. CDR 2. CDR	2/28/2029	Project PDR	(04/20/25): The risk's C was changed from 3 to 2 after implementing mitigation plans #1 and #2

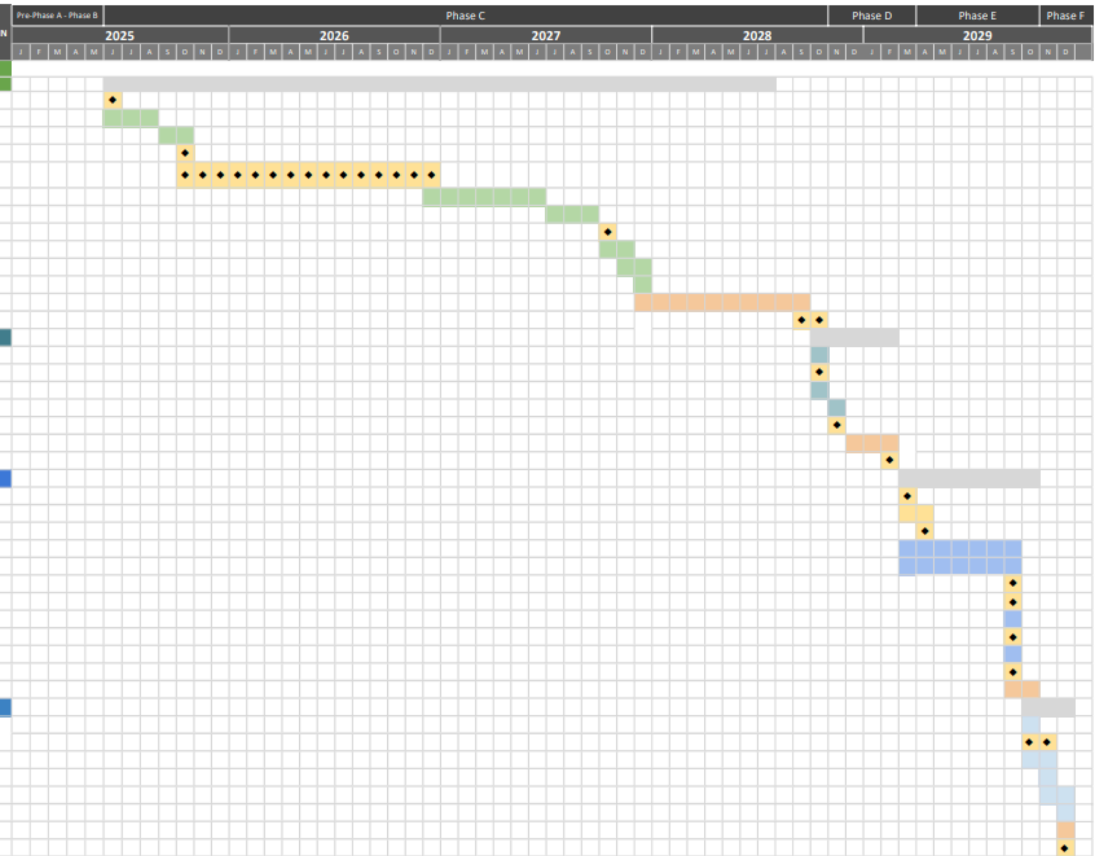
Appendix B: Gantt Chart

Project V.E.L.A.Z.Q.U.E.Z

Team 23

Project Team Members: Angel Guerrero, Briseyda Loescher, Carter Garrett, Daxx Delucchi, Eduardo Beltran, Emily Castro, Ethan T, Grace Kirk, James Rivera, Luis Marquez, Matthew Zhu, Shehan Rajapakse

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	Manufacturing and Procurement		0%	6/2/25	10/1/28	1218	280
1.1	◆ Key Decision Point - C Approval	Programmatics	Not complete	6/2/25	6/2/25	1	
1.2	Finalizing Detailed System Design	All Subteams	Not complete	6/3/25	8/4/25	63	
1.3	CDR Draft Review	All Subteams	Not complete	8/5/25	9/5/25	32	
1.3.1	◆ CDR Presentation and Approval	All Subteams	Not complete	10/6/25	10/10/25	5	
1.4	◆ Prep for Fabrication & Software Dev	MECH, PWR, CDH	Not complete	10/20/25	12/28/26	435	
1.4.1	Production and Assembly Prep	MECH, THRM, PWR	Not complete	12/30/26	6/30/27	183	
1.5	Integration & Operational Planning	LSE All Subteams	Not complete	7/1/27	9/30/27	92	
1.6	◆ System Ready for Integration	All Subteams	Not complete	10/1/27	10/1/27	1	
1.6.1	Final System Integration	All Subteams	Not complete	10/5/27	11/2/27	27	
1.6.2	Subsystem Integration	All Subteams	Not complete	11/3/27	12/3/27	31	
1.6.3	Full System Verification	All Subteams	Not complete	12/4/27	12/18/27	15	
1.7	Schedule Margin			12/19/27	9/23/28	280	
1.8	◆System Integration Review	All Subteams	Not complete	9/24/28	10/1/28	8	
2	Assembly, Integration, and Testing		0%	10/2/28	2/28/29	150	89
2.1	Verification Results Analysis	CDH, MECH	Not complete	10/2/28	10/10/28	9	
2.2	◆Operational Readiness Review	PROGRAMMATICS	Not complete	10/11/28	10/23/28	13	
2.2.1	ORR Action Items Resolution	All Subteams	Not complete	10/24/28	10/31/28	8	
2.3	Pre-Launch Checkouts/Reviews	All Subteams	Not complete	11/1/28	11/10/28	10	
2.3.1	◆Mission Readiness Review	All Subteams	Not complete	11/11/28	11/30/28	20	
2.4	Schedule Margin			12/1/28	2/27/29	89	
2.5	◆ Launch Approval	All Subteams	Not complete	2/28/29	2/28/29	1	
3	Operations and Sustainment		0%	3/1/29	10/5/29	219	8
3.1	◆Launch Operations Begin (LRD)	Transportation Subsystem	Not complete	3/1/29	3/1/29	1	
3.2	Outreach campaigns	All Subteams	Not complete	3/1/29	4/1/29	31	
3.3	◆Post Launch Assesment Review	All Subteams	Not complete	4/1/29	4/12/29	11	
3.3.1	Cruise Phase Monitoring	All Subteams	Not complete	3/2/29	9/16/29	199	
3.3.2	System Health Checks	MECH, PWR, CDH, THRM	Not complete	3/2/29	9/16/29	199	
3.3.3	◆Critical Event Readiness Review	MECH, PWR, CDH, THRM	Not complete	9/13/29	9/16/29	3	
3.4	◆Venus Arrival	All Subteams	Not complete	9/17/29	9/17/29	1	
3.4.1	Venus Data Collection	All Subteams	Not complete	9/17/29	9/18/29	2	
3.4.2	◆ End of Data Collection	All Subteams	Not complete	9/18/29	9/18/29	1	
3.5	Preliminary Data Analysis	CDH, SCIENCE	Not complete	9/19/29	9/20/29	2	
3.6	◆Disposal Review	All Subteams	Not complete	9/21/29	9/27/29	7	
3.7	Schedule Margin			9/28/29	10/5/29	8	
4	Closeout		0%	10/6/29	12/31/29	87	10
4.1	Outreach	All Subteams	Not complete	10/6/29	10/15/29	9	
4.2	◆Disposal Readiness Review	All Subteams	Not complete	10/6/29	11/4/29	29	
4.2.1	Decommissioning	All Subteams	Not complete	10/22/29	11/4/29	14	
4.3	Data Analysis	SCIENCE, PROGRAMMATICS	Not complete	11/5/29	11/19/29	15	
4.4	Archiving Data	PROGRAMMATICS, SCIENCE, CDH	Not complete	11/20/29	12/4/29	15	
4.5	Final Mission Report	All Subteams	Not complete	12/5/29	12/20/29	16	
4.6	Schedule Margin			12/21/29	12/30/29	10	
4.7	◆ Closeout Completed	All Subteams	Not complete	12/31/29	12/31/29	1	



Appendix C: CDH Subsystem Calculations

Calculations for derived values in data storage log periods, orbiter transmission gain, and duration of data relay windows detailed in the CDH Subsystem are outlined below.

250 discrete storage logs were chosen as a middle ground between data size and redundancy. Note that this value is only a minimum requirement, and storage logs may be more frequent if resources allow.

$$\frac{36 \text{ hours}}{250 \text{ discrete logs}} = 8.6 \text{ minutes per log}$$

The signal attenuation due to Venus' atmosphere at Ka-band frequencies (which is the frequency the ISARA operates at) is listed at 0.025 dB/km at an altitude above 50 km. Based on this, a gain of 3.75 dB is required for a complete signal to reach the orbiter, for a distance of 150 km between the orbiter (assumed to be 200 km at Low-Venus Orbit) and the Aerobot's altitude of 50 km during data transmission (defined in the ConOps).

$$0.025 \ \mathbf{dB/km} \times 150 \ \mathbf{km} = 3.75 \ \mathbf{dB}$$

In order to calculate the effective window duration for communication and data relay, the beamwidth for 3.75 dB must be obtained. However, without detailed experimental methods or manufacturer specifications, the 5 dB beamwidth is difficult to obtain. Thus, the half power beamwidth (HPBW, or 3 dB beamwidth) is sufficient to approximate the 3.75 dB beamwidth (Ulaby, Ravaioli 2023). An expression for HPBW can be easily obtained (Ulaby, Ravaioli 2023):

$$HPBW = \sqrt{\Omega_p} \quad \text{(for a symmetrical beam)}$$

Where Ω_p is the pattern solid angle of the antenna, representing the amount of area on a unit sphere subtended by the coverage of the antenna's radiation power. This can be defined directly from the gain of the ISARA, where 33.5 dB ≈ 2240.

$$\Omega_p = \frac{4\pi}{G/\eta} = \frac{4\pi}{2240/0.25} \simeq 0.0014 \text{ (steradians)}$$

$$\therefore HPBW = \sqrt{0.0014} = 0.037 \text{ (radians)}$$

Above, η is the radiation efficiency of the antenna, defined as 25% in the ISARA specifications (Hodges et al. 2015). The HPBW, in radians, can then be divided by 2π to obtain the fraction of travel where the orbiter is within transmission coverage.

$$\frac{0.037}{2\pi} = 0.0059$$

$$0.0059 \times 90 \text{ min} = 0.53 \text{ min} \simeq 32 \text{ seconds}$$

Finally, multiplying by 90 minutes, the window for communication comes out to approximately 32 seconds.

Appendix D: Thermal Subsystem Calculations

Table []: Calculations for Hot Case with TCS

Hot Case with TCS		
Heat Transfer	**Equation**	**Know Variables per Equation**
Q_solar	2780 * 1.633 * 0.99 = 4509.25 W	solar_flux = 2780 W/m^2 SA = 1.633 m^2 a = 0.99
Q_internal	300 W (constant)	N/A
Q_radiation	4(0.01 * 5.67E-08 * 1.633 * (300^4 - 400^4)) = -64.82 W	e = 0.01 σ = 5.67E-08 SA = 1.633 m^2 T_sys = 300 K T_atm = 400 K
Q_albedo	1.633 * 0.76 * 2601.3 = 3228.68 W	SA = 1.633 m^2 albedo = 0.76 solar_irr = 2601.3 W/m^2
Q_planetshine	0.01 * 5.67E-08 * 1.633 * (300^4 - 737^4) = -265.59 W	e = 0.01 σ = 5.67E-08 SA = 1.633 m^2 T_sys = 300 K T_sur = 737 K
Q_convection	4(6.216 * 1 * (737 - 400)) = -8378.86 W	h = 6.216 T_sur = 737 K T_atm = 400 K
Q_in	265.59 + 3228.68 + 4509.25 + 300 = 8303.62 W	|Q_planetshine| = 265.59 W |Q_albedo| = 3228.68 W |Q_solar| = 4509.25 W |Q_internal| = 300 W
Q_out	8378.86 + 64.82 = 8443.68 W	|Q_Convection| = 8378.86 W |Q_rdiation| = 64.82 W
Q_net	(8303.62 + 140) - 8443.68 ~ 0 W	Q_in = 8303.62 W htrs = 140 W Q_out = 8443.68 W

Table []: Calculations for Cold Case with TCS

Cold Case with TCS		
Heat Transfer	**Equation**	**Know Variables per Equation**
Q_solar	0 * 1.633 * 0.99 = 0 W	solar_flux = 0 W/m^2 SA = 1.633 m^2 a = 0.99
Q_internal	300 W (constant)	N/A
Q_radiation	4(0.01 * 5.67E-08 * 1.633 * (300^4 - 330^4)) = -13.92 W	e = 0.01 σ = 5.67E-08 SA = 1.633 m^2 T_sys = 300 K T_atm = 330 K
Q_albedo	1.633 * 0 * 2601.3 = 0 W	SA = 1.633 m^2 albedo = 0 solar_irr = 2601.3 W/m^2
Q_planetshine	0.01 * 5.67E-08 * 1.633 * (300^4 - 300^4) = 0 W	e = 0.01 σ = 5.67E-08 SA = 1.633 m^2 T_sys = 300 K T_sur = 300 K
Q_convection	4(6.216 * 1 * (300 - 330)) = 585.83 W	h = 6.216 T_sur = 300 K T_atm = 330 K
Q_in	0 + 0 + 0 + 300 = 300 W	|Q_planetshine| = 0 W |Q_albedo| = 0 W |Q_solar| = 0 W |Q_internal| = 300 W
Q_out	585.83 + 13.92 = 599.75 W	|Q_Convection| = 585.83 W |Q_rdiation| = 13.92 W
Q_net	(300 + 300) - 599.75 ~ 0 W	Q_in = 300 W htrs = 300 W Q_out = 599.75 W

Appendix E: Power Subsystem Calculations
Maximum descent/ascent time = (upper altitude - lower altitude)/(descent/ascent velocity) = (70km - 50km)/(5m/s) = 4000s = ~1hr 7min

Solar panel total area = 0.98m * 0.82m = 0.8036m^2

Total solar panel power generation = solar panel area * Venus solar constant * solar panel efficiency = 0.8036m^2 * 2622W/m^2 * 30% = 632.11 watts

Battery capacity = mass of batteries used * specific energy of battery = 4kg * 200W/kg = 800W

Data sending phase: 61.3W + 340W + 44W + 0.5 (DSS) = 445.8W

Battery charging phase: 49W (CDH) + 340W (thermal) + 0.5 (DSS) = 389.5W

Descent and ascend (will take about an half an hour): 49W (CDH) + 340W (thermal) + 10.5W (DSS) = 399.5W

Science cycle (slightly less than an hour): 44W (Science) + 49W (CDH) + 340W (thermal) + 0.5 (DSS) = 433.5W

Left over power to charge battery = 632.11W - 389.5W = 242.61W

Time to charge battery = battery capacity / power charging = 800 / 242.61 = ~3.3 hours