

Venus Aerobot Preliminary Design Review

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Table of Acronyms

Acronym List
ADV = Advisory AGL = Above Ground Level ATRIUM = AVO/UAF-GI = CCB = Change Control Board CCD = CDH = Command and Data Handling CER = Cost Estimate Relationships CFS = Core Flight System CH = Computer Hardware CNES-MICROSAT =

Acronym List

COTS = Commercially Available Off-the-Shelf
CP Series =
CPP = City Pair Program
CTBTO =
DAVINCI = Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DOD = Depth of Discharge
DR = Decommissioning Review
DRR = Disposal Readiness Review
EI = Electron Ionization
EL = Electrical
ESA = European Space Agency
EVA Film = Ethylene Vinyl Acetate Film
FMEA = Failure Mode and Effects Analysis
FRR = Flight Readiness Review
FY = Fiscal Year
GAO = Government Accountability Office
GEO = Geosynchronous Equatorial Orbit
GSA = U.S. General Services Administration
GSFC = Goddard Space Flight Center
IDC = Isolation Dynamics Corp.
IDE = Integrated Development Environment
ISS = International Space Station
ITAR = International Traffic in Arms Regulations
JAXA = Japan Aerospace Exploration Agency
JMARS = Java Mission-planning and Analysis for Remote Sensing
JPL = Jet Propulsion Laboratory
KDP = Key Decision Point
LEO = Low Earth Orbit
LRR = Launch Readiness Review
LIR = Longwave Infrared Camera
MCCET = Mission Concept Cost Estimating Tool
MCR = Mission Concept Review
MDR = Mission Definition Review
ME = Mechanical
MEO = Medium Earth Orbit
MFG =
N/A = Not Applicable
NASA = National Aeronautics and Space Administration
NETD = Noise Equivalent Temperature Difference
OH =
ORR = Operational Readiness Review
PAY = Payload
PDR = Preliminary Design Review
PT Series =
PTFE = Polytetrafluoroethylene
PVD =

Acronym List

PWR = Power
RAM = Random Access Memory
RFA = Request for Action
RTG = Radioisotope Thermoelectric Generator
RTOS = Real-time Operating System
SD Card =
SER =
SPICAM = UV Spectrometer
SR = System Requirements
SRR = System Requirements Review
STM = Science Traceability Matrix
SYS = System
TBD = To Be Determined
TEC = Thermoelectric Coolers
TH = Thermal
TMS Titanium =
TOF = Time of Flight
TOF-MS = Time of Flight Mass Spectrometer
TRL = Technology Readiness Level
UMBA = Uncooled Micro-Bolometer Array
US = United States
USD = United States Dollar
UTX Series =
UV = Ultraviolet

VERITAS = Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VIRTIS = Visible and Infrared Spectrometer
VIS = Vibration Isolation System

1. Mission Overview

1.1 Mission Statement

On this mission, a small, low-cost robotic aerobot system shall explore the extreme Venusian environment to advance understanding of the planet's atmospheric and geological evolution. This mission proposes the following two primary science goals: identifying biosignatures and chemical processes in Venus's atmosphere and investigating modern volcanic and tectonic activities. The mission shall navigate Venus's dense atmosphere, composed mostly of carbon dioxide at a supercritical state and clouds made of sulfuric acid, to investigate its biosignatures, chemical processes, and the potential impact of volcanic and tectonic activity on atmospheric composition. The scientific payload will contain instruments that will conduct in-situ atmospheric sampling and remote sensing of Venus's surface to analyze volcanic and tectonic

activities, resurfacing processes, and atmospheric interactions. Atmospheric instruments shall measure isotopic ratios, gases, and trace elements. Geological sensors will examine active volcanism on the surface, which could release gases that heavily influence atmospheric chemistry and Venus's climate evolution. The scientific instruments included for the mission are a Time-of-Flight Spectrometer, Infrasound Sensor, SPICAM UV Spectrometer, and longwave Infrared Camera. Some of the metrics these instruments will be getting include mass ranges in terms of atoms per mass unit (amu) of isotopic ratios. The mission will focus on the upper atmosphere above Maat Mons, the largest volcano on Venus, to ensure the detection of volcanic outgassing and its impact on atmospheric composition. While high-altitude winds may shift the aerobot's trajectory, its proximity to other volcanic features, such as the ultrawide Ozza Mons, provides alternative data collection sites to make sure that the mission's scientific returns are accomplished.

As a planet in a potentially habitable zone that was ravaged by runaway greenhouse heating, Venus plays a vital part in planetary climate studies. Investigating its active atmospheric processes, chemical composition, and volcanic activity provides insights into climate dynamics that directly relate to Earth's own atmospheric stability and ongoing climate change. Understanding Venus also helps to understand whether exoplanets in other galaxies in positions very similar to Venus and Earth could provide the right conditions to foster life. Studying Venus's climate evolution and atmospheric composition is essential for assessing the habitability of other worlds. This mission will enhance space exploration capabilities by mapping volcanic hotspots and identifying hazardous atmospheric conditions, paving the way for future Venus exploration missions. This mission promises a high scientific return at a reasonable cost, ensuring that taxpayer investments contribute meaningfully to planetary science, climate research, and the advancement of space exploration.

1.2 Science Traceability Matrix

Venus is often called Earth's uninhabitable twin, as its harsh surface and thick atmosphere filled with sulfuric acid make it a mysterious and hostile world. Studying Venus's atmosphere, volcanic activity, and chemical processes are key to understanding how planets evolve into potentially habitable environments, and how their climates change over time. The proposed mission is designed to address Decadal Question 6.4 from *Origins, Worlds and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*: "How do planetary surfaces and interiors influence and interact with their host atmospheres?" The mission's goal is to examine current geological activity, improve general understanding of the greenhouse effect, and search for signs of life, using cutting-edge spectrometry and remote sensing tools. This will allow scientists to explore the processes that shaped Venus's climate and might potentially unfold in Earth's future.

The proposed mission has outlined two main objectives: to look for possible signs of life and chemical reactions in Venus's atmosphere, and to determine if there is still volcanic or tectonic activity occurring on the planet today. Venus's atmosphere is chemically complex, containing mysterious ultraviolet-absorbing substances and signs of chemical imbalance that could point to ongoing photochemical reactions—or even early-stage processes related to life (Radke, 2023). The mission will trace specific isotopic ratios, like D to H, carbon-12 to carbon-13, and different forms of sulfur, as well as track gases such as CO₂, SO₂, OCS, PH₃, and other minor components in the atmosphere. A Time-of-Flight Mass Spectrometer will measure how these gases vary with altitude, while a UV Spectrometer will look for the unknown blocker of ultraviolet light in the 180 to 400 nanometer range. These measurements will offer insight into Venus's atmospheric chemistry and support a better understanding of climate behavior on Earth-like exoplanets. The second objective of this mission is to determine whether Venus remains geologically active, which could potentially reveal how its climate has shifted over time and whether those changes are still happening. Given that volcanoes on Venus are still active, they would be releasing gases like SO₂, H₂S, PH₃, and CO, modifying the planet's atmospheric chemistry and potentially affecting its greenhouse effect (Greaves et al., 2020). The aerostat on this mission will be fitted with a combination of instruments to investigate atmospheric and geological activity on Maat Mons, Venus's largest volcano. A UV Spectrometer is to be used to trace volcanic gases at various altitudes. An infrared camera will be used to spot heat from possible lava flows. Finally, an infrasound detector will be used to catch deep, low-frequency sounds linked to eruptions or shifts in the planet's crust. This mission will provide valuable information on how Venus's internal processes influence its atmosphere and affect its habitability over time. Understanding Venus's development will make it easier to discern how exoplanets create their atmospheres.

Table 1.1-01: Science Traceability Matrix table

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
“Decadal Question 6.4: How do planetary surfaces and interiors influence and interact with their host atmospheres?” - Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032	Determine potential biosignatures and chemical processes in Venus's atmosphere, including identifying the nature of the "unknown UV blockers," to provide evidence of the Greenhouse Effect	Identify composition of Isotopic Ratios: (D/H, ¹² C/ ¹³ C, ³² S/ ³³ S/ ³⁴ S) Compounds: (CO ₂ , SO ₂ , OCS, PH ₃ , and other trace gases) and any unidentified UV Blockers through Venus’s cloud layers.	Use a mass spectrometer to measure variations of biosignature gasses at different altitudes. As well as absorbance spectra in specific UV ranges, around 180 to 400 nm wavelength range.	Mass range (amu)	100-300 amu	1–5000 amu	Time - Of - Flight Mass Spectrometer	System shall carry instrumentation that will collect data
				Mass Resolving Power	≥500–1000 (FWHM)	5000-46000 (FWHM)		
				Sensitivity:	10 ⁻³ to 10 ⁻⁴ molecule s/cm ³	10 ⁻⁴ to 10 ⁻⁵ molecules /cm ³		
				Integration time:	≤1 s	≤1 s		System shall collect accurate scientific data on the atmosphere of Venus throughout it's operating period
	Determine if modern volcanic or tectonic activity is influencing Venus's atmosphere	Identify aerosol particle composition particularly SO ₂ , H ₂ S, CO, and other volcanic emissions as well as thermal anomalies	Measure and collect different SO ₂ , H ₂ S, CO, at different altitudes using UV and a mass spectrometer	Wavelength range:	180-400 nm	180-320 nm	SPICAM (Mars Express) UV Spectrometer	
				FOV/ Spatial resolution	~1°/≤1.5 km per vertical layer	FOV 0.5°/ Spatial resolution: vertical resolution of 1km		

		associated with active volcanism	in the 180 to 400 nm wavelength range as well.	Effective Area	~0.6 cm ² or better	0.6 cm ²		System shall study aerosol particles and chemical signatures of volcanic emissions
				Spectral resolution:	≤1.5 nm	1.5 nm		
				Wavelength range:	8-12 μm	8-12 μm	Longwave infrared Camera	System shall study acoustic indications of volcanic and tectonic activity
				Integration time:	≤1 s	16.7 milliseconds		
				NETD (Noise equivalent Temperature Difference)	≤0.3 K	0.3 K		
				Spatial resolution:	50 km per pixel	70 km per pixel		
				Wavelength detection range:	0.002-20 Hz	Full scale input range: 2000 Pa peak to peak	Infrasound detector (Chaparral Model 60-UHP2 Infrasound Sensor)	System shall study biosignatures and atmospheric chemical processes
				Frequency range	0.01-10 Hz	0.1 Hz – 40 Hz		
				Sensitivity:	45.13+/- 0.23 microV/Pa	0.01V/Pa at 1 Hz		
				Level of self-noise below 20 Hz	0.025 Pa at 1 Hz	0.025 Pa at 1 Hz		

1.3 Summary of Mission Location

The final mission location is the upper Venusian atmosphere above Maat Mons (8.0 ± 0.5 km elevation, 0.5°N 194.5°E), Venus's tallest volcano and a shield structure spanning 400 km in basal diameter. This volcanic complex features a summit caldera measuring 28×31 km with inner walls reaching 1.6 km depth, surrounded by radial dike swarms extending 1,500 km at 45° azimuthal intervals (average width 12-18 km). Situated in Atla Regio's tectonically active zone (strain rates $>10^{-17} \text{ s}^{-1}$), the site lies 800 km northwest of Ozza Mons (6.5 km elevation) within Venus' equatorial wind jet (60-90 m/s zonal velocities at 50-70 km altitude). This positioning enables cross-referencing with Magellan radar topography (120 m/pixel resolution) and VIRTIS mineralogical maps.

A 2023 analysis of Magellan SAR data revealed a 2.4 km^2 volcanic vent at 0.7°N 194.3°E that expanded to 4.8 km^2 within 8 months, with associated lava flows covering 34 km^2 (comparable to Kīlauea's 2018 35.5 km^2 eruption). The aerobot's Longwave Infrared Camera (LIR) will target these features with 70 km/pixel spatial resolution and 0.3K NETD sensitivity to detect thermal anomalies $\geq 5\text{K}$ above ambient 737K surface temperatures. Concurrently, the SPICAM UV Spectrometer (180-320 nm range, 1 km vertical resolution) will monitor SO_2 plumes at 0.1 ppm sensitivity, leveraging Venus' super rotating winds (96 m/s at 70 km) for atmospheric tracer analysis.

The operational altitude corridor (50-70 km, 0.9-2.5 bar pressure) optimizes instrument performance while maintaining 230-348K external temperatures compatible with the titanium hull's 400K thermal limit. This envelope permits detection of Maat Mons' summit features through 18-28 km thick cloud layers using LIR's 8-12 μm spectral band, which achieves 73% transmission efficiency in Venus' CO_2 -dominated atmosphere. Wind dispersion models predict SO_2 concentrations remain measurable (± 0.05 ppm) within 300 km of emission sources at 70 km altitude, ensuring redundant data collection despite potential 150 km horizontal drift during the 48-hour mission.

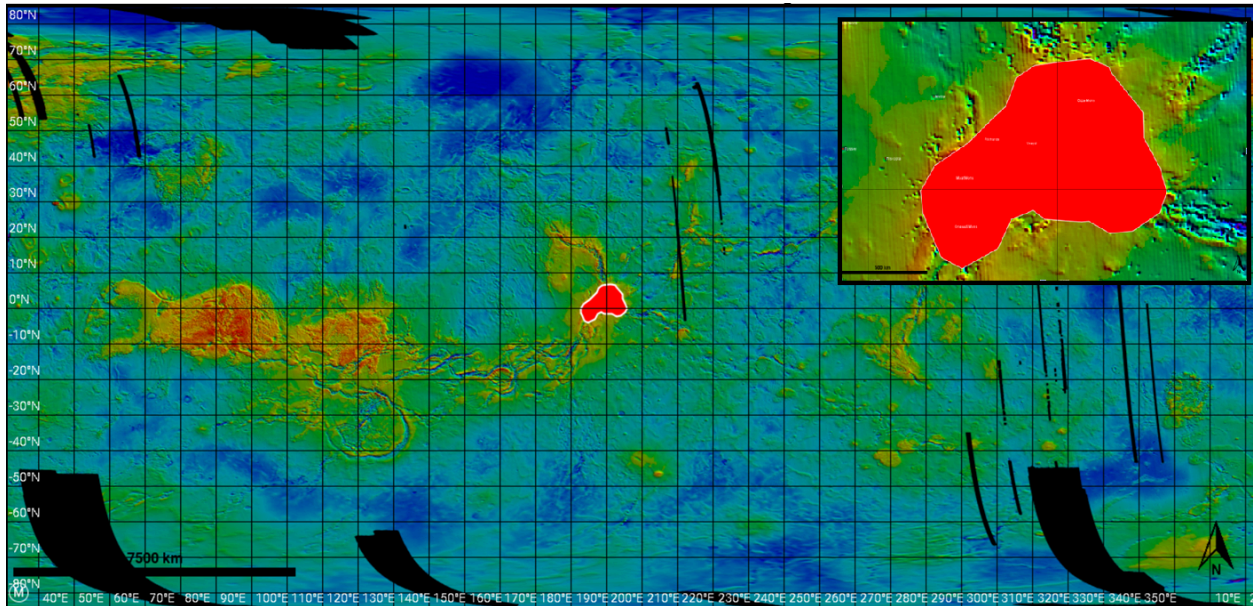


Fig 1.3-01: Image taken from JMARS software showing location of Maat and Ozza mons area highlighted. Shape layer: Venus Magellan Colorized Shaded relief. The map was generated using JMARS software, which provides detailed topographic and geological data to assist in mission planning.

1.4 Mission Requirements

Customer Constraints Description:

The Aerobot System will be designed to operate within the harsh Venusian environment for a minimum of 48 hours to conduct science investigations. The system will collect and transmit atmospheric and geological data to the Orbiter, providing a deeper understanding of the Venusian environment. To meet mission constraints, the system shall not exceed 50kg (SR-01) and shall not exceed the dimensions of 1m x 1m x 1m (SR-02) in order to integrate into the entire mission system.

To meet mission constraints, the aerobot shall not include a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof. While radioactive material overall for other spacecraft subsystems is permitted, it shall not exceed 5 grams in total.

To meet Scientific Decadal goals, the aerobot shall study the atmospheric composition of Venus and its volcanic and tectonic activity. This shall be accomplished through a variety of interacting subsystems, all of which shall also meet the constraints described within. The aerobot shall be designed around the Scientific and Decadal requirements outlined in the given Mission Task.

To meet budget constraints the system shall not exceed a budget of \$200M (SR-03) following NASA's Discovery Program requirements. The system shall be ready for integration by October 1, 2028 (SR-04) and shall be launch ready by March 1, 2029 (SR-05) to coordinate with the planned launch window. These constraints ensure the Aerobot System is both feasible and effective in its mission to enhance scientific understanding of Venus' environment.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
SR-01	Total mass of system shall not exceed 50 kg	System must launch and be able to transport successfully without weight limitations	Customer	-	Inspection	Met
SR-02	Dimensions shall not exceed 1m x 1m x 1m size	System must be able to be integrated with deployment and storage	Customer	-	Inspection	Met
SR-03	Budget shall not exceed more than \$200 million	System must fit within NASA Discovery Program budget	Customer	-	Analysis	Met
SR-04	System shall be ready for integration by October 1, 2028	System must align with mission timeline	Customer	-	Test	Met
SR-05	System shall be ready for launch by March 1, 2029	System must have coordination with launch window	Customer	-	Test	Met
SR-06	System shall not have a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof. Any radioactive material used for spacecraft systems shall not exceed a cumulative mass of 5g.	System must align with NASA guidance on prohibited materials	Customer	-	Analysis	Met
SYS-01	System shall be designed to withstand Venus' environmental conditions for 48 hours	System must survive environment to complete mission.	Customer	PWR-01, PWR-02, PWR-03 TH-01, SYS-03, ME-02	Test	Met
SYS-02	System shall communicate back and forth between to Orbiter	System must be able to transmit necessary commands and information to and from the orbiter	Customer	CDH-01,CDH-02	Test	Met

SYS-03	System shall remain powered and operational during descent to 48 hour descent to Venusian surface	System must have power necessary to run all onboard instruments operational for data collection during descent	SYS-01	-	Test	Met
SYS-04	System shall collect accurate scientific data on the atmosphere of Venus throughout it's operating period	System must collect scientific data on Venus	-	ME-01, ME-03	Analysis	Met
ME-01	System shall give necessary access to all subsystems	Instrumentation needs access to outside environment to function and collect data	SYS-04	-	Demonstration	Met
ME-02	System shall remain firmly attached to the balloon during descent	System must be whole to complete mission	SYS-01	-	Demonstration	Met
ME-03	System shall house all instruments	Protect instruments from Venus environment	SYS-04	-	Inspection	Met
PWR-01	The system shall power the aerobot's crucial components for the duration of 48 hours	The system must provide power for the instrumentation to collect meaningful data and recharge	SYS-04	PWR-05, PWR-06, PWR-07	Demonstration	PWR-01
PWR-02	Power shall withstand high temperatures on Venus	Power must survive for the whole duration of the mission	SYS-01		Test	PWR-02
PWR-03	The Power System shall be securely mounted	The system must be stable to reduce failure and survive for the duration of the mission	SYS-01		Test	PWR-03
PWR-04	Power systems must be corrosion-resistant	The power system must survive for the whole duration of the mission	SYS-01		Test	PWR-04
CDH-01	System shall deliver data at TBD frequency for TBD transfer windows	System must be able to relay data to orbiter	SYS-02	-	Analysis	Met
CDH-02	System shall store sufficient data during communication blackouts before transmissions to the	System must have an ability to store data incase of missed window or system blackout	SYS-02	-	Test	Met

	spacecraft					
CDH-03	System shall contain backups of itself in the event of damage or unexpected circumstances	CDH system completes data processing and storage for the entire Aerobot, to loose it would be catastrophic	SYS-04	-		Met
TH-01	System shall remain within safe operating temperatures	System internals (payload, CDH structure, etc) must be kept within a dedicated range of temperature	SYS-01	-	Demonstration	Met
PAY-01	System shall carry instrumentation that will collect data	System must have the right instruments to collect desired science	SYS-04	-	Demonstration	Met
PAY-02	System shall be securely mounted within the aerobot's superstructure	System must collect scientific data on Venus and insulate componentes from harm	SYS-04	-	Inspection	Met
PAY-03	System shall measure infrasound throughout the flight.	The investigation of volcanic and tectonic activity on the venusian surface was selected as a science objective for this mission	SYS-04	-	Inspection	Met
PAY-04	System shall record images of the Venusian atmosphere and surface throughout the flight	The investigation of volcanic and tectonic activity on the venusian surface was selected as a science objective for this mission	SYS-04	-	Analysis	Met
PAY-05	System shall record measurements of the atmospheric composition throughout the flight and search for gasses which would indicate volcanic or tectonic activity	The investigation of volcanic and tectonic activity on the venusian surface was selected as a science objective for this mission	SYS-04	-	Analysis	Met

PAY-06	System shall record measurements of the atmospheric composition throughout the flight and search for gasses which would indicate biological processes or provide clues as to the greenhouse effect on Venus	The investigation of biological processes and the greenhouse effect was selected as a science objective for this mission	SYS-04	-	Analysis	Met
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Table 1.4-01 - Mission Requirements table

1.5 Concept of Operations (ConOps)

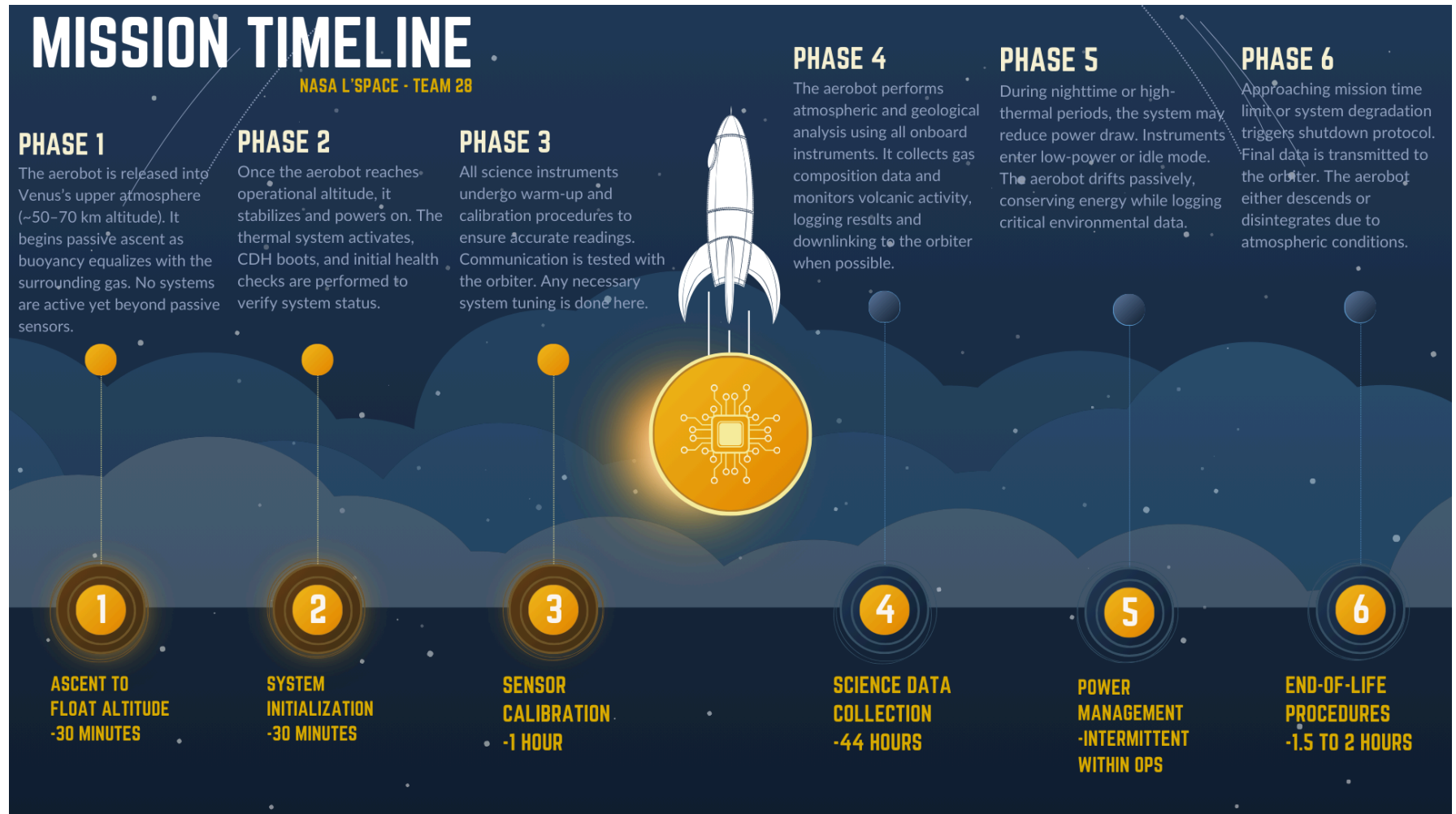


Figure 1.5-01 - (Mission Timeline Graphic)

The six flight phases of the aerobot, as marked in the above diagram, begin with deployment into the upper Venus atmosphere at altitudes between 50 and 70 km. The altitude range was selected because it is relatively stable in addition to having substantial scientific interest, particularly above Maat Mons where local volcanism has been inferred by recent observations.

Following release, the aerobot ascends and levels to float altitude passively. Primary systems are running low power with passive sensors for monitoring environmental conditions. Major systems are powered up at float altitude, for example, thermal control and the command and data handling (CDH) subsystem. Thermal control is maintained by thermoelectric coolers (TECs), controlling the internal state to ~ 300 K, while spring-loaded solar panels deploy using electromagnetic latches. Primary checks verify hardware operation and prepare the platform for science.

During the second phase, all of the scientific instruments are calibrated to make accurate measurements. Thermal equilibration protocols and alignment checks, particularly on the infrared imaging sensor and the gas sensors, are conducted. The Time-of-Flight Mass Spectrometer (TOF-MS) is vibrationally mounted on a Wire Rope Vibration Isolation System (VIS) and calibrated against a reference gas cell containing 500 ppm SO_2 . The UV Spectrometer aligns with aerosol-scattered atmospheric light paths and aerosol scattering corrected for, and The Longwave Infrared Camera (LIR) calibrates using its internal blackbody reference, viewing outward through a Germanium window coated with parylene. The atmospheric gases are sampled through PTFE tubing connected to an NMP 09 sample pump, which maintains a constant flow rate of ~ 0.65 L/min. System tuning is carried out here to ensure optimal performance under Venusian environmental conditions.

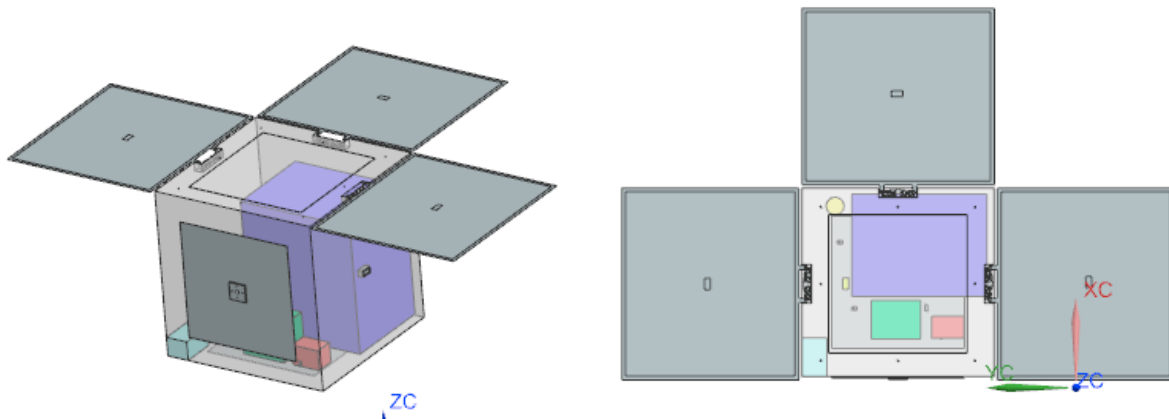
After calibration, the aerobot is in full scientific operation. Within a period of about 44 hours, sensors gather data on atmospheric composition, trace gas content, and geologic signatures. The payload is a UV Spectrometer, Mass Spectrometer, Infrasound Detector, and Longwave Infrared Camera. Sensors allow identification of target gases like CO_2 , SO_2 , and phosphine and seismic markers of volcanic activity. CDH redundancy allows onboard data to be compressed and buffered in blackout, and science continuity ensured until downlink resumes. The Germanium window enables the LIR to observe surface thermal anomalies, while the infrasound sensor continues passive detection of atmospheric wave signatures. Data are locally stored locally and downlinked periodically when line-of-sight with the orbiter is regained.

Under extreme thermal load or limited energy availability, the system powers down to power conservation mode. The instruments go to low-power or idle state and background monitoring that is critical to the science continues on. TECs and CDH components throttle back to reduce power usage, having only passive sensors active

while staying within safe thermal levels. The mode is entered on a periodic basis within the science cycle based on environmental needs.

When the mission approaches its planned end of life, shutdown is initiated. Data is transferred and the aerobot lands or structurally fails due to atmospheric stress. Shutdown may also be initiated by system degradation or internal flag conditions. The mission ends with the final data transmission, and structural failure may occur due to long-term thermal cycling or internal overpressure. Mission's end is the final data recovery opportunity and marks the end of the mission timeline.

1.6 Vehicle Design Summary



Figures 1.6-01/1.602 - (Assembly Isometric View and Top View)

The Aether Solaris aerobot is a balloon-launched robotic platform designed to operate in the upper atmosphere of Venus, between altitudes of 50 and 70 kilometers. The vehicle is buoyant by nature and is sustained at altitude by a superpressure helium balloon. The aerobot structure accommodates unbroken science operations for 48 hours, including instrument calibration, data acquisition, and power management.

The mechanical system of the aerobot is built around a titanium internal structure, selected for its strength-to-weight ratio and resistance to corrosion. The science payload is housed within this structure: a Time-of-Flight Mass Spectrometer (TOF-MS), UV Spectrometer (SPICAM), Longwave Infrared Camera (LIR), and an Infrasound Detector. External equipment is a parylene-coated Germanium window for thermal infrared imaging and PTFE tubing that allows gas intake for spectrometric analysis. Vibrational stability to TOF-MS is provided by a wire rope vibration isolation system.

The power system consists of 477 NeXt Triple Junction solar cells with a combined surface area of 2.84 m², which provide 75 watts of peak sunlight. An onboard energy storage of 236.8 Wh is served by a battery. Subsystems draw up to 90W during operation; solar generation (75W peak) is augmented with battery reserves and

strategic power cycling. Energy management is supplemented by thermal electric coolers (TECs) that regulate internal temperatures to ~ 300 K and radiator assemblies of 0.95 m^2 to dump heat loads in maximum operation.

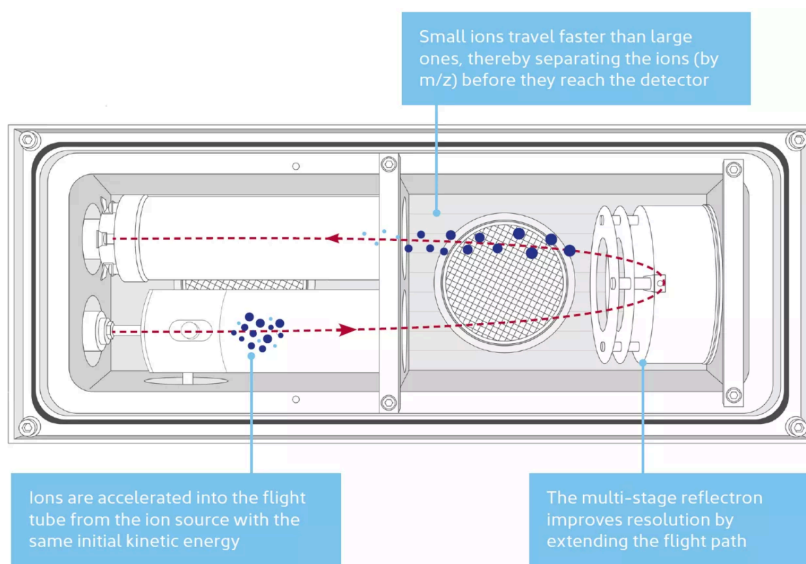
The entire dry mass of the aerobot is estimated at 15.42 kg and includes scientific payload, thermal control, power storage, and structure systems. Aluminum radiator panels each weigh 1.22 kg, and the solar panels contribute less than 1 kg collectively since they are ultra-light. The last balloon diameter is not specified in the document, although the frame and solar deployment geometry suggest a vehicle footprint of around 1 meter in diameter.

This spacecraft architecture balances environmental survivability and scientific capability. Thermal management, data redundancy, and low-mass design enable stable atmospheric sampling and imaging within a corrosive, high-temperature, and low-density environment. The aerobot will operate autonomously with triple-redundant Raspberry Pi Zero systems for command and data handling in order to maintain fault tolerance and storage of all collected data for later downlink to an orbiter when in line-of-sight. Critical systems like the sample pump include lightweight redundancy, while passive components like the VIS are mechanically fail-safe.

1.7 Science Instrumentation Summary

Time Of Flight Mass Spectrometer

A Time-of-Flight Mass Spectrometer (TOF-MS) is an instrument that is widely used to identify the composition of a sample by measuring the masses of its particles (SepSolve Analytical 2023). The way it works can be broken down to three main steps (Fig 1.7.1).



The principle of operation of a TOF mass spectrometer (in this case SepSolve's BenchTOF2). The path taken by the ions is shown by the dotted red line.

Figure 1.7.1 Schematic illustration of a Time-of-Flight Mass Spectrometer (TOF-MS), showing ionization of the sample, acceleration of ions through the flight tube, and multi-stage reflection principle. This configuration allows for identification of particle masses and chemical composition in complex mixtures. (Adapted from SepSolve Analytical, <https://www.sepsolve.com/techniques/what-is-tof-ms.aspx>)

First, the sample is converted into charged particles, ions, using an ionization source. For space missions, the most common method is electron ionization (EI), where a beam of electrons directed at the sample, breaks off electrons to create ions. After being ionized, the particles then accelerated into a long, empty flight tube. They all receive the same energy boost, but lighter ions travel faster and reach the end of the tube quicker than heavier ones. The time each ion takes to reach the end is recorded and used to calculate its mass. There is a detector at the end of the tube (an electron multiplier was not included in the illustration) that transcribes the arrival of each ion into an electrical signal. These signals are then analyzed to figure out the composition of the collected sample (de Hoffmann and Stroobant 2007; Arevalo et al. 2019). TOF-MS is especially useful in planetary exploration because it can analyze complex mixtures in a compact, reliable design that works in space. It is exceptionally well-suited to support the mission's goals of detecting biosignatures and analyzing atmospheric chemistry and volcanic activity on Venus. Since TOF-MS can achieve mass resolution ($m/\Delta m$) of 10,000–60,000, it allows to discriminate between molecules and isotopes with nearly identical masses (Arevalo et al. 2019). This will help to identify trace gases and isotopic ratios in Venus's atmosphere. For example, distinguishing between $^{12}\text{CO}_2$ and $^{13}\text{CO}_2$ or between SO_2 and H_2S will help understand both chemical processes and volcanic gas emissions. Also, TOF-MS has detection limits in the parts-per-billion (ppb) to parts-per-trillion (ppt) range, which can help to trace organics that could serve as potential biosignatures, such as phosphine (PH_3), methane (CH_4), or certain nitrogen- and sulfur-bearing compounds (Radke 2023). Given its rapid acquisition times, often on the order of microseconds to milliseconds per spectrum, TOF-MS makes it possible to continuously monitor the environment as the aerobot travels through Venus's

atmosphere. Its systems can also operate over a wide mass range, typically from 1 to 1,000 atomic mass units or higher, enabling the detection of both light gases and complex organic molecules (Arevalo et al. 2019). TOF-MS instruments have demonstrated functionality under low-pressure or corrosive environments when properly shielded. That makes them viable for usage through Venus's acidic and high-temperature upper atmosphere when paired with appropriate thermal and chemical protection.

SPICAM UV Spectrometer

Previously used for Mars exploration, SPICAM UV spectrometer was chosen for this mission for several reasons. Its compact size, relatively low mass, and dual-channel instrument design make it an excellent choice to complement Mass Spectrometer. SPICAM provides independent measurements of gas concentrations and their vertical distribution in addition to Mass Spectrometer results. Its UV channel operates within 180-320 nm range with the spectral resolution of 1.5 nm, using an intensified CCD (Charge-Coupled Device) detector, that measures the light absorption by atmospheric gases (Bertaux et al. 2006). The instrument works by detecting light (photons) hitting the CCD, which turns them into electrical charge. Then this charge, depending on how

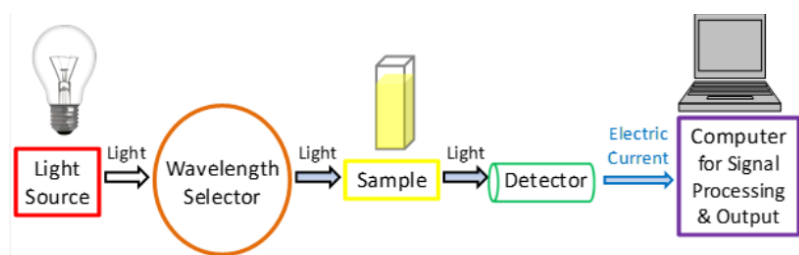


Figure 1.7.2 Simplified diagram of how SPICAM's UV-Vis spectrometer detects light: photons (light) pass through the atmosphere and hit a detector, where they are converted into electrical signals that indicate light intensity at different wavelengths. (Adapted from Tom 2021, <https://www.technologynetworks.com/analysis/articles/uv-vis-spectroscopy-principle-strengths-and-limitations-and-applications-349865>)

much light there is, accumulates into an array of cells called pixels (Figure 1.7.2) (Tom 2021). These charges are then read into sequence to be converted into a digital image that shows intensity of light at different wavelengths.

SPICAM will identify and quantify key atmospheric constituents, such as sulfur dioxide (SO₂), carbon dioxide (CO₂), ozone (O₃), and potential unknown UV absorbers (Royal Belgian Institute for Space Aeronomy 2025). It can operate in different observation modes, like nadir viewing, limb scanning and solar/stellar occultation, allowing for vertical profiling of atmospheric composition (Bertaux et al. 2006). Studying how the aerosols and various trace gasses are distributed will allow for characterizing photochemical processes of Venus's cloud layers. It also will add more clarity into understanding chemical imbalances that may indicate active volcanic activities or biosignature gases such as phosphine (PH₃).

Infrasound Detector

The Chaparral Model 60-UHP2 Infrasound Sensor can provide data on atmospheric dynamics, by detecting the infrasound that is generated by volcanic activity or an atmospheric disturbance. Despite its compact design (only 3.75in in diameter), it provides high-performance results in detecting low-frequency acoustic waves and that is what makes it so suitable for planetary exploration missions (Marcillo, Johnson, and Hart 2012). In combination with UV-spectrometer and mass spectrometer, the infrasound sensor will offer complementary data to satisfy science objectives for this mission. For example, while spectrometers can identify chemical compositions, the infrasound sensor can detect physical events like eruptions or atmospheric waves.

It operates within the frequency range of 0.1Hz to 40Hz, and has a sensitivity of 0.01 V/Pa at 1Hz, reaching a noise floor of 0.025 Pa at 1Hz. It can handle input pressures up to 2000Pa peak-to-peak (Chaparral Physics 2025). The way it works is by detecting pressure variations caused by low-frequency sound waves that are created from various natural (or anthropogenic) sources. In this case, the instrument will be detecting volcanic eruptions and atmospheric turbulence. This mechanical deflection is then converted into an electrical signal, allowing for the detection of very low-frequency sounds with high sensitivity and accuracy (Slad and Merchant 2016).

Longwave Infrared Camera (LIR)

The Longwave Infrared Camera (LIR) is a thermal imaging instrument that detects the natural heat emitted by Venus's upper cloud layers, specifically in the 8–12 μm wavelength range, which is the part of the spectrum where warm objects radiate the most energy (Taguchi et al. 2007). LIR captures the thermal energy that is radiated by the planet and it makes it ideal for observing Venus both during the day time and at night time. This instrument uses a micro-bolometer array which detects infrared radiation by sensing even tiniest changes in temperature which in its turn changes the electrical resistance in the sensor (Fukuhara et al. 2011). This change is measured and translated into an image showing temperature variations across the planet's atmosphere.

In this mission, LIR will focus on the upper cloud deck of Venus, approximately 65 km above the surface. At this altitude, the clouds are thick with sulfuric acid aerosols, and the temperature hovers around 230 K (Fukuhara et al. 2011). The goal is to continuously capture thermal images that will reveal how heat is distributed across the planet. This will support the scientific objective of understanding Venus's atmospheric processes, specifically the circulation patterns that drive Venus's infamous super-rotating winds. Previously those winds were observed to circle the planet in just a few days, far faster than the planet rotates (Lee et al. 2007). LIR data will also help detect dynamic features like gravity waves or transient thermal anomalies that could hint at volcanic activity below. When used in combination with the Time-of-Flight Mass Spectrometer (which identifies chemical species) and the SPICAM UV Spectrometer (which maps gas concentrations), LIR will add essential information on where the heat is rising or falling and suggest what processes might be causing it. It also will complement the results of the infrasound sensor. The infrasound detector picks up acoustic signals of volcanic eruptions or atmospheric turbulence, while LIR will simultaneously capture thermal signatures of these events, offering a fuller picture of Venus's dynamic environment.

1.8 Programmatic Summary

1.8.1 Team Introduction

Angel Rico-Madriz

Role(s): Project Manager

Major: Mechanical Engineering

University: Sacramento State University @ Sacramento, California

Location: Sacramento, California

Relevant Experiences: President of Cabrillo Aerospace Club, Vice President and Director of Professional Development of Sacramento State Chapter for the Society of Hispanic Professional Engineers. Previously participated in NCAS Mission 1.

Leo Wong

University: University of California, Berkeley

Location: Berkeley, CA

Relevant Experience: Incoming undergraduate student majoring in Statistics & Data Science. Experience in data analysis through R and Python, social media and product management, frontend development, software, rocketry building, and trading.

Yelyzaveta Ismatullayeva

University: University of Washington

Location: Seattle, WA

Relevant Experience: Graduate student in Remote Sensing lab at the Environmental Studies school, studying carbon stocks and policy. Experience in education, product management and cross-cultural communication.

Sequoia Boubion-McKay

Role: Lead Systems Engineer

University: Berkeley City College

Major: Computer Science & Engineering

Location: Berkeley, CA

Relevant Experience: Computer Science Tutoring Team Lead at Berkeley City College, Previous Data Engineering Intern, NASA NCAS Alumni, and certified in Data Analytics from University of California, Berkeley. Specialized in software engineering and data science with an emphasis in machine learning.

Angie Apolinar

Major: Cybersecurity and Information Assurance

University: Western Governors University

Relevant Experience: Professor's Assistant for Cybersecurity and Computer Science division, Cyber mentor, and NCAS Alumni. Experience in python scripting, CISCO networking, cloud security, event coordination and interpersonal communication.

Acony Lanford

Role(s): Scientist, Command and Data Handling Engineer

Major: Mechanical Engineering

University: Oregon State University

University Location: Oregon State University, Corvallis Oregon

Relevant Experiences: Undergraduate in Mechanical Engineering. Experience in robotics, CAD modeling, and project planning

Maya Looney

Role(s): Scientist, Editor in Chief

Major: Astrophysics and Planetary Science

University: University of California Berkeley, Berkeley CA

Relevant Experiences:

Radial Velocity Researcher for the Habitable Worlds Observatory NASA flagship mission (under Prof. Courtney Dressing)

Ramsden Fellow Researcher in Prof. Raymond Jeanloz's Planetary Interiors Group (Experimental)

Student Researcher for the Bureau of Ocean Energy Management

Lead Telescope Officer of the Undergraduate Astronomy Society

Christian Santori

Role(s): Program Analyst, Mechanical Engineering

University: University of Central Florida

Location: Orlando, FL

Relevant Experience: Undergraduate student in Mechanical Engineering with a focus on aerospace systems. Experience in CAD modeling, project management, and robotics.

Juan Rosas

Role(s): Mechanical Engineer, Thermal Engineer

University: University of California, Davis

Location: Davis, CA , Los Angeles, CA

Relevant Experience: Undergraduate student in Aerospace engineering with a focus on aerospace science. Experience in CAD modeling, robotics, coding in Java, Matlab and python and leadership.

Nicholas Rasoilo

Role(s): Thermal Engineer, Outreach Officer

University: University of California, Davis

Location: Davis, CA

Relevant Experience:

Sunny Nguyen

Role(s): Computer Hardware Engineer, Electrical Engineer

University: Cal Poly University: Pomona

Location: Pomona, CA

Relevant Experience:

Thiviru Pulukkuttige Don

University: San Jose State University

Location: San Jose, CA

Relevant Experience: Undergraduate student in Aerospace Engineering with a focus on aerospace systems. Experience with data processing in MATLAB, CAD modeling, and Aircraft design.

Ethan Fernandez

University: California State University Fresno

Location: Fresno, CA

Relevant Experience: Undergraduate student in Electrical Engineering with focus on hardware design and power systems. Experience in Robotics, Software design, and Circuit design

Enter photos here if applicable:

- Angel:



- Christian:



- Yely

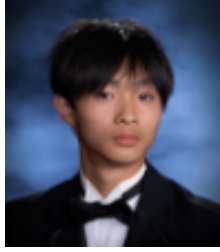


- Sequoia:



- Acony:





- Leo:



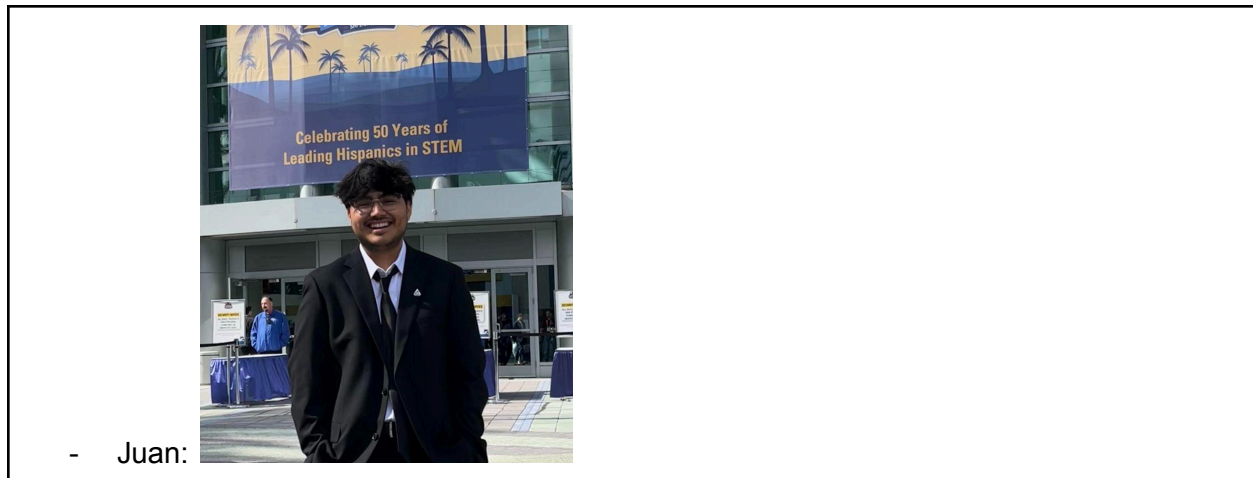
- Thiviru:



- Maya:



- Angie:



1.8.2 Team Management Overview

Team 28's organizational chart is depicted below with many individuals specializing in various fields. As stated before, Team 28 continues to handle the workload relatively well and has followed the team decision-making rules accordingly. No changes have been made to the original implementation of the delegation of workload. The decision-making process remains as a "consensus-based decision with fallback to majority vote". Critical, time sensitive decisions are still ultimately determined by the final decision of the project manager where discussion with other team leaders may be prominent. An instance of decision making which includes time-sensitive decisions is when the team leaders have determined to request an extension for a deliverable when advised by a mentor. The "Conflict Resolution Plan" has been working effectively, and the team continues to foster an open communication environment where concerns and disagreements are discussed in a professional manner. This plan has not been changed and is working in effect.

With an adequate amount of time going by since the team was formed, team leaders have observed that team members are able to gel and familiarize themselves with a team environment further as time goes on. Members regularly incorporate meeting times into their daily schedules and adjust accordingly if unpredictable events occur, during exam seasons, or spring breaks. Each respective discipline has scheduled meetings accordingly with their subteams. These non-general discipline meetings are managed by collaborating members when they see a mutually convenient time.

Moreover, although there have been no major challenges that the team has faced, during exam seasons, team members often face altered schedules. To overcome these time-constraint challenges, other team members have approached these challenges by putting in extra hours of work if necessary and vice versa when others are in their respective exam seasons or dealing with difficult situations. This also applies to breaks, which are listed in the schedule, to allow for proper planning. Internally, the team operates using a "buddy system" where individuals with similar roles work together on personal working documents in which they upload accordingly to the drive. This allows the entire team to track the progress of subsections and redelegate workload if

necessary. Before each deliverable is begun, a task chart document is also created to assign sections early on. Members vote on which tasks they would like to work on and switch if needed.

Team 28 has consequently set up frequent “When2Meet” announcements and have communicated through the team server to schedule brief check-in meetings. Meeting notes are also documented for tracking, simplicity, or organization purposes and to ensure that other team members are able to catch up on missed meetings, understand what tasks need to be completed, and answer any potential questions which all contribute to mitigating challenges.

This system has allowed Team 28 to be organized and accomplish fulfilling the academy’s mission task requirements for each deliverable. The team constantly checks the requirements tasked on given documents and compares them to the mission’s final goals and objectives. There have been no current changes to the system besides swapping general meeting times and meeting dates from Wednesday and Friday to only Friday as proposed in the SRR. This adjustment will allow team members to have more time for discipline-specific assignments as well as for researching materials. This will not only help members attend specific role meetings, discipline meetings, and collaborate with the team with more ease, but also allow individuals to manage their external workload more efficiently.

Nonetheless, potential future changes recommended to further increase the team’s chance of success after the team has discussed post-SRR and MDR suggestions to stabilize advantages and improvise disadvantages which includes: Updating the Gantt chart more often while assigning tasks and roles earlier, Having more frequent weekly science, programmatics, and engineering meetings, Clarifying meeting schedules, Improving drive organization, Following page count per section, and Better team cross-communication. Meanwhile, the advantages that the team shall continue include: Having good cross subteam communication, Coming together when needed, Quality content, and Shout-outs to team members! Action has been taken to mitigate the disadvantages experienced in the SRR and MDR as the team has created a rough draft of task assignments early on and has organized tasks on the L’SPACE-provided Gantt chart and Teamhood, a project and resource management Gantt chart system. Implemented plans in the future consist of keeping open communication involving scheduling, teamwork, and for tasks done, and to organize the Google drive and upload every working document or in other words, share working documents for easy and effortless cross-team communication.

Roles and Responsibilities Chart:

- Primary role is listed first for each member’s discipline.
- Secondary role disciplines listed afterward.

Tbl 1.5.1-01

Team Member	Discipline	Available Hours Dedicated

Angel Rico-Madriz	Team Leadership	10 - 14 hours per week
Leo Wong	Team Leadership, Programmatic	10+ hours per week
Yelyzaveta (Yely) Ismatullayeva	Team Leadership, Science	10 - 12 hours per week
Sequoia Boubion-McKay	Team Leadership, Engineering	6 - 10 hours per week
Christian Santori	Programmatic, Engineering	6 - 10 hours per week
Acony Lanford	Science, Engineering	8 - 10 hours per week
Juan Rosas	Engineering	6 - 10 hours per week
Angie Apolinar	Programmatic, Engineering	8 hours per week
Nicholas Rasoilo	Engineering, Programmatic	10 - 12 hours per week
Sunny Nguyen	Engineering	8 hours per week
Maya Looney	Science, Editor (Programmatic)	6 - 8 hours per week
Thiviru Don	Engineering	6 - 10 hours per week
Ethan Fernandez	Engineering, Programmatic	8 - 10 hours per week

Table 3

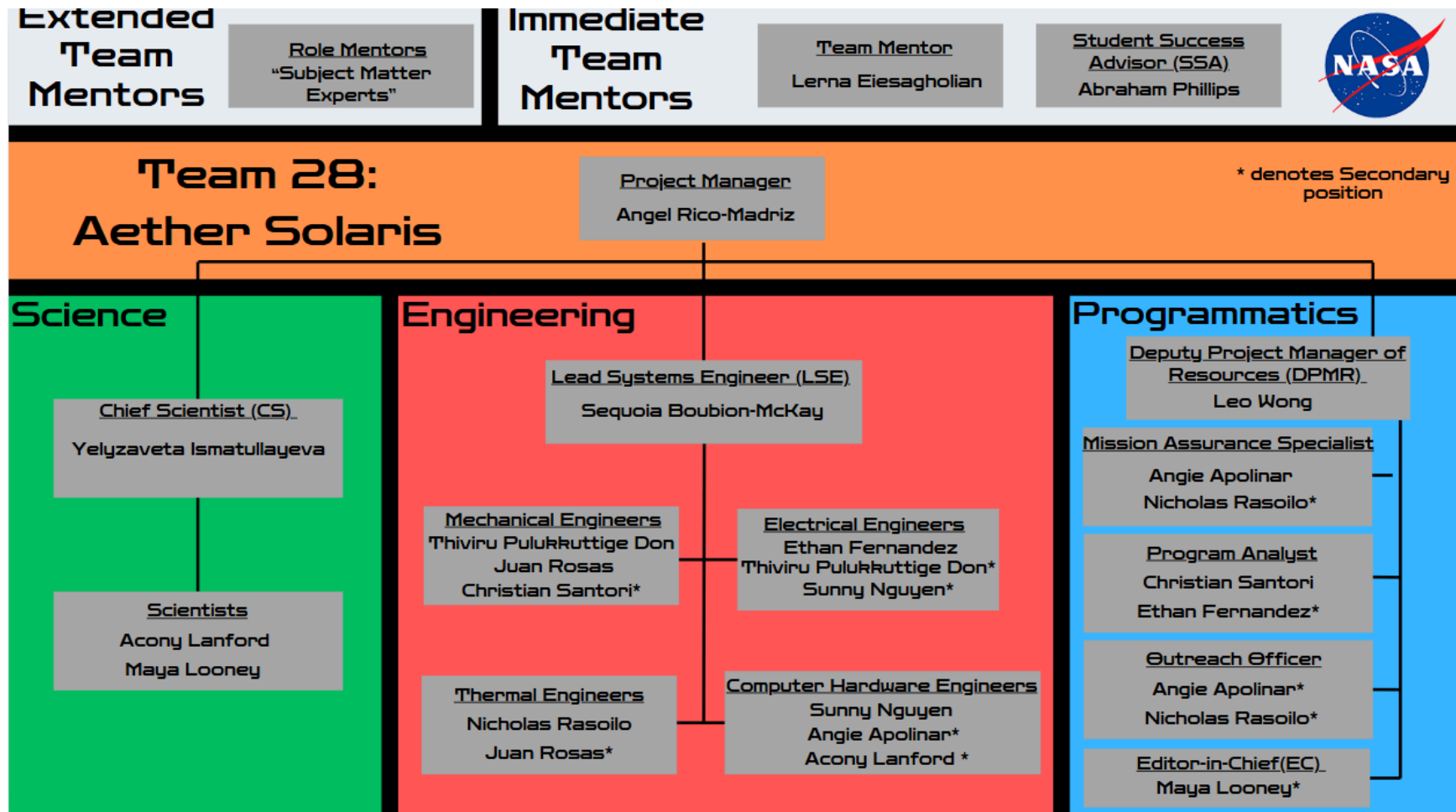


Figure 5: Team Organization Chart

1.8.3 Schedule Overview

High-level schedule with major milestones

- Phase C Starts - March 1, 2025
- Critical Design Review - May 1, 2025
- Complete Subsystem Assembly - June 1, 2027
- System Integration Review - December 1, 2027
- Thermal Vacuum and Environmental testing - November 1, 2028
- Operational Readiness Review (ORR) - December 1, 2028
- Flight Readiness Review (FRR) - December 15, 2028
- Launch Readiness Review (LRR) - January 14, 2029
- Launch Date - March 1, 2029
- Venus Arrival - September 1, 2029
- Science Operations Begin - September 29, 2029
- Mission closure - October 1, 2029

This updated mission schedule incorporates the revised scope of work from Phase B, extending the schedule by six months while maintaining the hard deadlines of October 1, 2028 (Final Design, Fabrication, and Assembly Completion) and March 1, 2029 (Launch Date). The table follows four distinct phases, C through F, with specific tasks and milestones ensuring timely progress.

1.8.4 Cost Overview

The mission has a budget cap of \$180M, \$20M short of the original \$200M. This \$20M has been reallocated towards the aerobot balloon contractor with an additional six months descoping this mission to begin testing early alongside assembly and manufacturing of each subsystem. This results in a final total mission cost of **\$174,171,081** allocated across five fiscal years. The Personnel total cost estimate is \$26,946,022, the Travel cost estimate is \$2,287,576, the Outreach cost estimate is \$458,387, and the Direct cost estimate is \$137,293,906. All cost estimates factor in a unique margin for each section. The budget estimate contains a small underrun which will remain as a contingency reserve that can be reallocated based on unforeseen

needs and costs as depicted in Fig1.8.4-01.

Budget Allocation

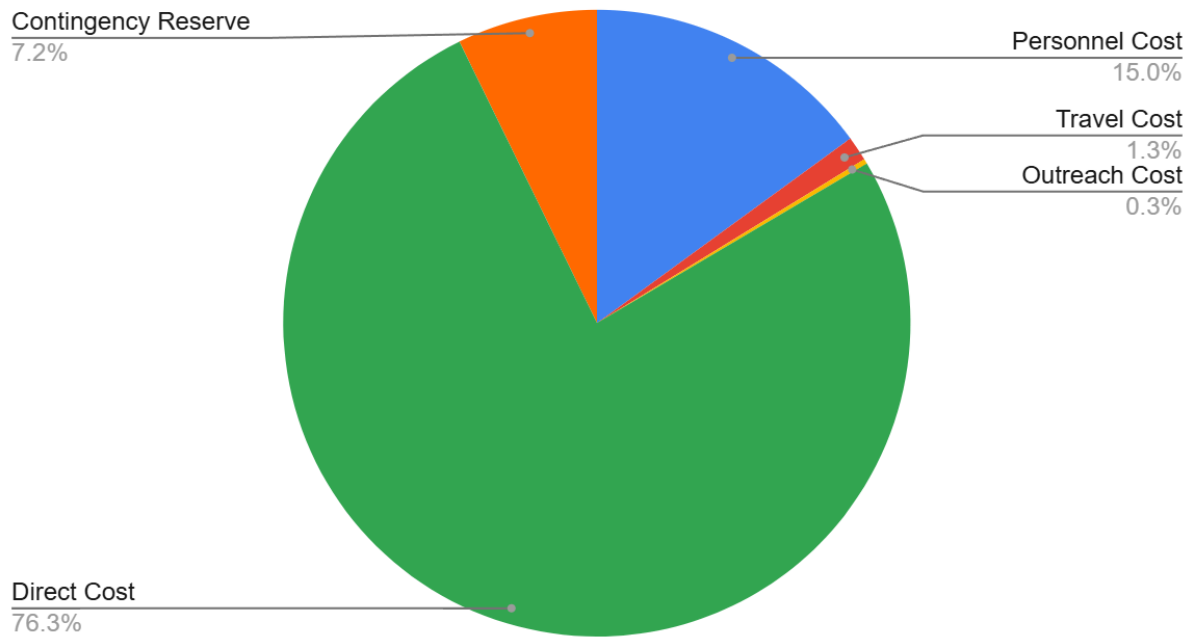


Fig6

2. Overall Vehicle and System Design

2.1 Spacecraft Overview

1.5.1 Spacecraft Overview

The spacecraft is designed to operate in Venus' atmosphere, carrying scientific instruments to collect atmospheric data during a 48-hour descent mission. The spacecraft consists of five primary subsystems: Mechanical, Power, Command & Data Handling (CDH), Thermal, and Science Instrumentation. Each subsystem is engineered to meet mission requirements while ensuring structural integrity, power efficiency, thermal regulation, and data communication.

Mechanical Subsystem

The mechanical subsystem provides the structural framework for the spacecraft and houses the scientific instruments. It includes a time-of-flight mass spectrometer, infrasound sensor, UV spectrometer, longwave infrared camera, a titanium structure, and a sampling pump. A vibration isolation system ensures stable instrument operation. A magnet latch and spring actuated solar panel frame deployment is implemented to allow power generation. A Germanium window is cutout and placed allowing longwave infrared camera to collect data.

Power Subsystem

The spacecraft is powered by battery-based energy storage, designed to sustain all onboard systems for at least 48 hours of descent operation. The power system must provide sufficient energy for science payloads, CDH, and communication systems while minimizing heat generation.

Command & Data Handling (CDH) Subsystem

The CDH subsystem consists of three Raspberry Pi Zeros, responsible for processing data from scientific instruments and relaying it to the orbiter. It ensures real-time data collection and implements data storage protocols to mitigate the effects of communication blackouts.

Thermal Subsystem

Operating within Venus' harsh atmospheric conditions, the spacecraft requires a thermal subsystem to regulate heat and protect sensitive instruments. The system includes thermoelectric coolers (TECs) and potentially additional passive or active cooling solutions to maintain operational stability.

Science Instrumentation

The spacecraft carries four primary instruments to study Venus' atmosphere:

- Time-of-Flight Mass Spectrometer (TRL 5) – Analyzes chemical composition.
- Infrasound Detector (TRL 5) – Captures low-frequency atmospheric waves.
- UV Spectrometer (TRL 6-7) – Measures UV radiation absorption.
- Longwave Infrared Camera (TRL 6-7) – Detects thermal emissions.

These instruments work in tandem to collect high-fidelity scientific data, advancing the understanding of Venusian atmospheric dynamics

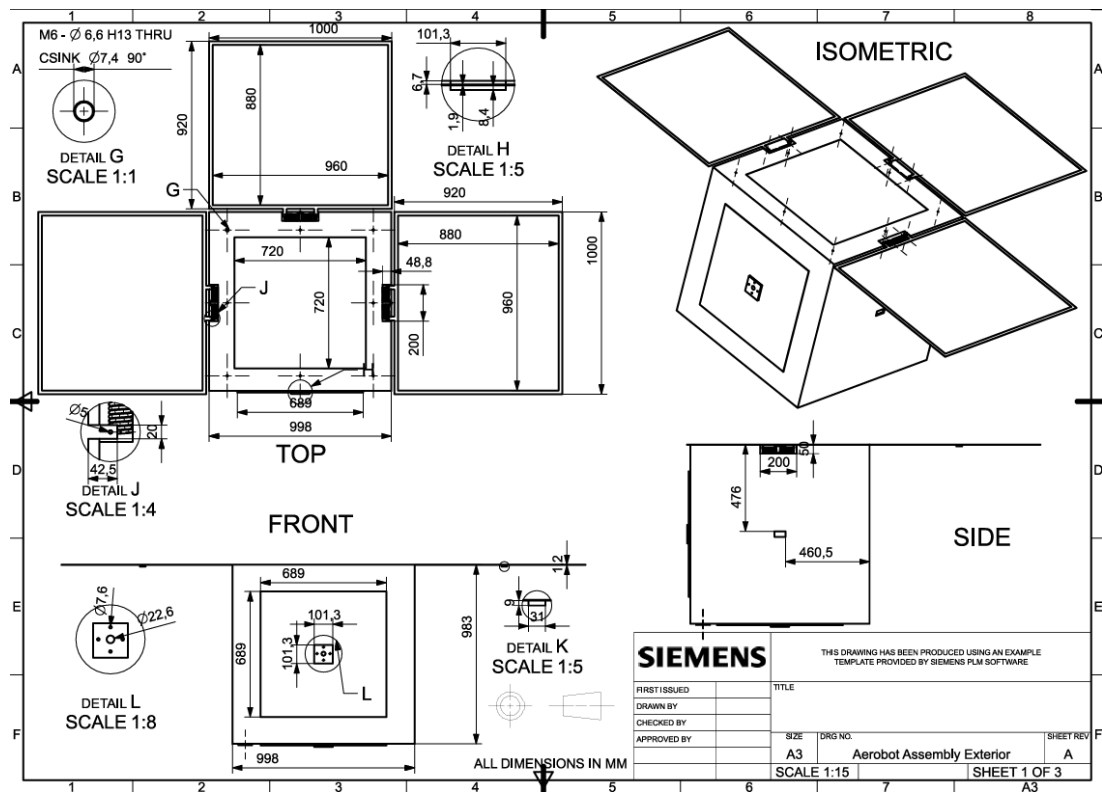


Fig 2.1 - 1

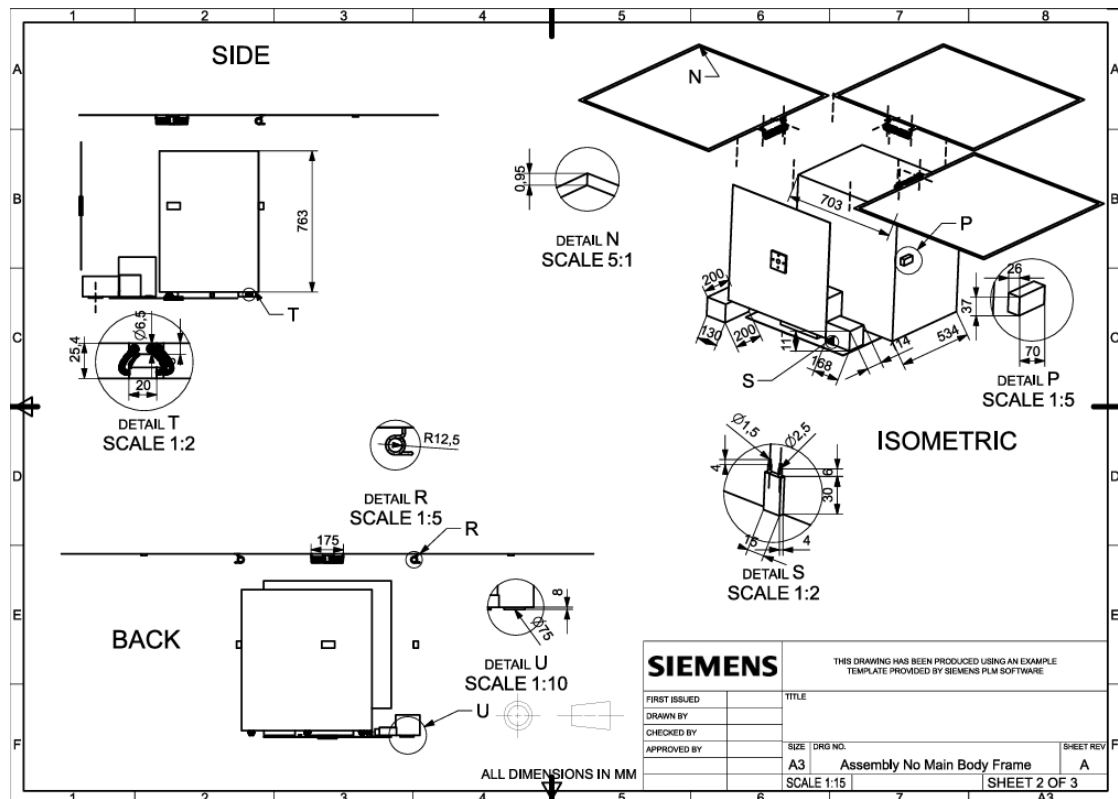


Fig 2.1 - 2

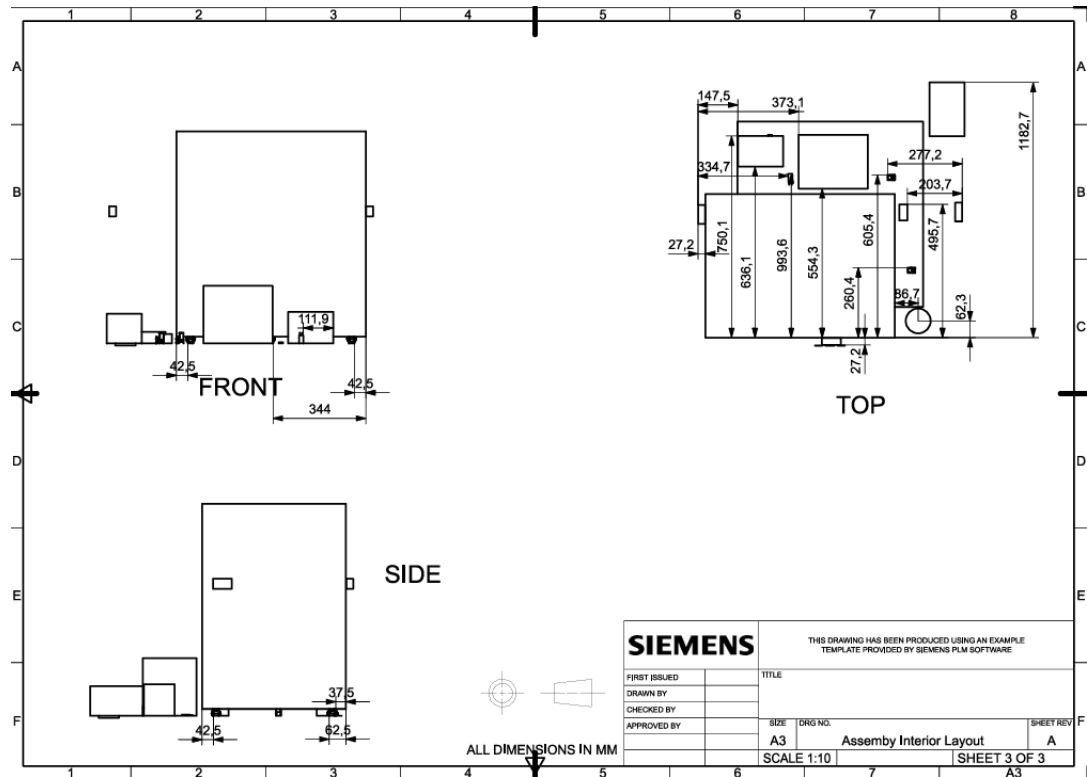


Fig 2.1-3

Table 2.1 -01

Subsystem	Mass(kg)	Power (W)	Dimensions(mm x mm x mm) or (diameter mm x mm)
Mechanical	10.23	3.56	3x[1000x920x1.2], 2x[27.5x19.8x39.4], [75mm diameter x8mm], 3x[20x20x25.2], 3x[35x37x70], 6x[1000x1000x.304]
Electrical	2.05	0	[114x168x117], 3x[880x960x.09], [720x720x.09]
CDH	.027	2.25	[65x30x35]
Thermal	7.51	34.4	2x[690x690x17], 2x[15x40x4] 6x[1000x1000x.304]
Payload	24.9	77.15	[534x763x703], [214x200x257], [200x130x110], [92.5mm diameter x42.9mm]

2.1.1 Mechanical Subsystem Overview

The mechanical subsystem provides the structural framework for the spacecraft and houses the scientific instruments. It includes a time-of-flight mass spectrometer, infrasound sensor, UV spectrometer, longwave infrared camera, a titanium structure, and a sampling pump. A wire rope vibration isolation system will be implemented onto the time of flight mass spectrometer. This will dampen vibrations occurring to the instrument to ensure functionality and accurate measurements. Three wire rope isolators will be used underneath the instrument which will be secured to the titanium frame of the aerobot. Additionally, the mechanical subsystem provides functionality for the instruments. The UV and time-of-flight spectrometers require active sampling from the outside environment. The mechanical subsystem will provide an access port connected to a sample pump that will be able to sample the outside Venusian atmosphere for the instruments to take data. The power subsystem requires a mechanical deployment mechanism for the solar panels to deploy at the start of the mission. The deployment will involve a spring loaded and electromagnetic latch actuated system. The solar panels themselves will be held in grade 5 aluminum to ensure durability throughout the mission and the spring will be made out of Hastalloy coated in parylene. This will provide resistance to high temperatures and chemicals along with a durable and high force spring. There will also be a Germanium window to allow the Longwave Infrared Camera to collect data. This Germanium window will be held in place with adhesive and will also be coated in parylene to protect it from sulfuric acid. Germanium is picked due to its effectiveness with Longwave Infrared Camera and allows them to take meaningful data about the temperature gratings and infrared emissions.

2.1.1.1 Mechanical Subsystem Requirements

Table 2.1.1-01

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met
ME-01	System shall give access to collect data	Instrumentation needs access to outside environment to function and collect data	SYS-04	ME-02 ME-08 ME-10	Demonstration	Met
ME-02	Systems access panels shall position itself to ensure quality measurements	System must be able to relay reliable data to orbiter	ME-01		Test	Met
ME-03	System shall remain firmly attached to the balloon during descent	System must be whole to complete mission	SYS-01		Demonstration	Met
ME-04	System shall house all instruments	Protect instruments from Venus environment	SYS-04	ME-05 ME-08	Inspection	Met
ME-05	The spectrometer shall be securely mounted with a vibration isolation system (VIS) to ensure stable measurements.	System must be stable enough to take usable measurements	ME-04	ME-06 ME-07	Inspection	Met
ME-06	The mounted VIS system shall withstand different forces	The mount must survive different forces	ME-05		Test	Met
ME-07	The attachment points shall be compatible with the Aerobot's main structure	The mount and access panel both need to integrate with current design	ME-05		Inspection	Met
ME-08	The access panel shall maintain a sealed environment when closed to prevent atmospheric exposure	The instrumentation must be kept safe when not in use	SYS-01	ME-10	Test	Met

Narrative

The mechanical subsystem of the aerobot was designed to withstand extreme conditions, have structural support, and absorb the needed information that the system would sample. These lower level requirements were adapted and derived from the overall system requirements and focused on the mechanical sub section.

To start, one of the system's top priorities was to allow access for the scientific tools being used by the system to absorb the samples. Then those samples gathered must be promptly transferred to allow it to be turned into data. It must have the ability to suck in a sample of the atmosphere and analyze it to turn it into usable data. This access area will have to be sealed so that it won't be exposed to the outside environment and be prone to damage. This will ensure all scientific instruments will be safe and secured.

The mechanical subsystem must also be capable of giving visual access to components that are required to "see" the outside environment. Furthermore, the mechanical subsystem is responsible for the moving deployments that are necessary after the aerobot has launched.

Another aspect of this system is the inner structure and the material that will protect the inner part of the aerobot. The titanium inner structure will surround the inside of the aerobot and be the interior protection for the system. It will consist of 6 panels to protect and house all the instruments and other assemblies as well. This must be a strong structure to ensure no damage happens to the inner systems.

2.1.1.2 Mechanical Sub-Assembly Overview

Wire Rope Vibration Isolation System (VIS)

The Vibration Isolation System (VIS), selected for the ToF Mass Spectrometer, will be three IDC SM3-070-A wire rope isolators from Isolations Dynamics Corp. (IDC). They will be arranged in a triangular configuration underneath the ToF Mass Spectrometer and bolted to the titanium frame of the aerobot. Each isolator can support 5.5-6 kg matching the 16.5kg of the ToF Mass Spectrometer and the combined mass of the VIS is 0.024kg. The VIS provides enough mechanical coupling and passive vibration control without needing to be powered or lubricated.

Within this configuration, the VIS provides six degrees of freedom vibration damping and a natural frequency range of 5-7 Hz with a damping ratio of 15-20%. This is ideal for mitigating vibrations from both launch and planet entry. The VIS cables are made of 300-series stainless steel and attached to aluminum housing. They are both rated for vacuum use and thermal temperatures from -185°C to 260°C, which is ideal for mission-defined altitudes. The VIS plays a key role in the integrity of the ToF Mass Spectrometer while keeping with the size, mass, and environmental constraints of the aerobot. All considered the Wire Rope VIS rests at a TRL 6 with COTS hardware that is already tested and validated in relevant environments, but lacks mission specific flight qualification. Further testing will raise this to TRL 7.

Sample Pump

The Sample Pump selected for the mission is the NMP 09 Sample Pump which is a COTS component by KNF Group. The Sample Pump will be used to transfer the

outside atmosphere into the ToF Mass Spectrometer and UV spectrometer so they can take data about Venus. The Sample Pump itself is very light and weighs around 23 grams and has a power draw of .7 watts. The flow rate of the pump is .65 l/min which is enough for a spectrometer. If the flow rate is too high, the spectrometers would be less accurate in collecting data and a slow and stable introduction of the sample gives optimal readings. The flowrate itself can also be varied to meet an optimal result which can be decided after testing. It has already been taken into consideration changes in atmospheric pressure on Venus. Since the atmospheric pressure around 50-70km on Venus will be similar or higher to the pressure on Earth, the flow rate of the pump either does not change or increase due to higher pressure difference at the inlet which means there will not be a risk of losing flow rate.

The pump will be connected to the outside atmosphere using a Teflon PTFE tubing. Teflon PTFE tubing is resistant to high temperatures and also very resistant to the sulfuric acid that is contained in the atmosphere. To keep the seal airtight a compression ring will be used. The compression ring itself also needs to be attached to one of the panels on the hull and be airtight along with corrosion-resistant. A titanium compression ring will be used to solve these issues. The exterior of the aerobot will be made out of titanium, with both the exterior and compression ring being made of the same material, TIG welding can be used to ensure the compression ring is inserted and kept airtight. Having a small cut out on the side of the aerobot for the compression ring, the compression ring can be inserted and welded into place. Furthermore, since the compression ring is made of titanium, it will be able to resist the sulfuric acid and high temperature of Venus's atmosphere.

The NMP 09 pump is chemical resistant, and has an operating ambient and permissible media temperature of 40 °C. However, the manufacturer stated the temperature rating can be increased upon request and so the pump will be requested to have 70 °C of permissible media. On top of being chemical resistant, the NMP 09 has excellent reliability and durability along with being able to be installed in any position. To securely attach the Sample Pump to the inside of the Aerobot, the sample pump can either be welded into place at the metal sections of the pump, or be glued into place using FM 680-1 adhesive since the sample pump itself is very light. The NMP 09 pump demonstrates the requirements needed to operate on the Venus Atmosphere due to its chemical resistance, temperature rating, speed controllability, and being able to be worked in any position. With all of this considered the Sample Pump will have a TRL of 6 with COTS hardware that is already tested and validated in relevant environments, but lacks mission's specific qualification. With testing the Sample Pump can be raised to TRL 7.

Titanium for Inside of System

The material that was chosen for the inside part of the system was the titanium sheet that's .012" thick and is grade 5. This is a proven type of titanium that has been used in past aerospace applications and will protect the system in an excellent way. This titanium will surround the aerobot's six sides and be the responsible material for blocking the harsh environment of Venus from the inner components. Each side of the aerobot should add to 4.11 kg which perfectly fits within the weight constraints the team has to keep in mind while designing the aerobot. The titanium has been proven to give

enough protection from heat and radiation that will be presented onto the aerobot. Due to the altitude we will be at, and the pressure being presented the titanium will successfully hold.

With an incredible strength to weight ratio, this type of titanium will have the perfect mix of strength, lightness and will allow minimization of mass for this mission. Titanium is also very resistant to corrosion and can withstand harsh environments like the atmosphere of Venus. The acidic nature and toxicity that will be presented on the aerobot will not affect it in any harsh way because of the titanium's ability to withstand that. We will be traveling throughout the Venusian atmosphere, starting from an altitude that somewhat mimics Earth-like temperature conditions but as we travel further down the temperature will rise. However this won't be an issue because this grade of titanium can withstand those temperatures and will be able to work in temperatures as high as 400 degrees celsius. Going back to the weight efficient aspect, the titanium chosen is .012" thick so that is where the perfect balance between weight and durability comes from. These sheets are all that will be needed for this short mission as long duration didn't need to be considered.

Venus also has immense radiation that had to be considered when thinking of which material to use for the aerobot. However, titanium has great effectiveness in blocking and protecting the system from this radiation. This material will be able to reflect and absorb the radiation which will protect the inner instruments like the ToF mass spectrometer and more. Due to its previous use in other aerospace applications, this has a TRL of 8 and won't need further testing.

Solar Panel Holding and Deployment

The frame to hold the solar panels will be made out of titanium, the same material used for the exterior of the aerobot. The exterior of the aerobot contains grade 5 titanium, and 0.05-inch-thick sheets of titanium will be needed for the solar panel frame. These sheets will be machined to have the necessary shape to hold the solar cells. When undeployed, the solar panel frames will be parallel and flush with the sides of the aerobot walls, and all frames will be within the 1 m³ requirement. The main section of the frame will be .92m x 1000m, and on the top will be two tabs extending out that are .0425m x .02m each. The thickness of the tab and outer parts of the frame is 1.2mm, while the center has an .88m x .960m section with .95mm milled out, leaving .25 mm thickness. This will make the weight of a single frame 1.359kg. The total thickness of a solar cell is only 0.1397mm, and the coverglass thickness can range from 0.0762 to 0.762mm. A coverglass of .3mm will be used for the coverglass as this gives tolerance for other layers and components for the solar cell frame.

On the tabs at the end of the frames, a hole will be cut out on each for the ends of a torsion spring to be welded onto the frame. The torsion spring will be made out of hastelloy due to its being strong and having a high spring force with high corrosion resistance, and temperature resistance. The spring will be a double torsion spring, where it will have a center that will be connected to the aerobot frame with titanium clamps. The torsion spring will have two ends that will be free to move, and the spring will be configured such that pulling the ends down will load the spring. The ends of the spring will be circular and slot into the holes on the solar panel

frame. The torsion spring can have an inner diameter of 30 to 35mm and a maximum length of up to 200mm. The wire thickness can vary from 5 to 10mm. Using these values, MW Components can manufacture multiple torsion springs at once to be tested. These values can be later verified by doing tests with the solar panel frame and latch, depending on how much it weighs, how much force is needed to load the spring, and how fast the spring launches. The torsion spring should be a double torsion spring, as this gives two connection points onto the solar panel frame, which will halve the strain on the material at the contact point. The connection to the solar panel frame can be done with FM 680-1 adhesive, and having two washer-like tabs of hastelloy on either end welded to the spring. Welding the ends of the hastelloy spring directly to the titanium solar panel frame might be possible, but it is challenging and can be risky, leading to the material being weakened, so this approach is avoided. For further protection, the spring itself and the connections can be coated in parylene to protect them from the sulfuric acid in the Venusian atmosphere. Parylene is very effective to use against sulfuric acid and prevent components from corrosion.

FM 680-1 is used as the main adhesive for this mission due to how strong it is under harsh conditions. FM 680-1, when used to connect to flat surfaces, was able to withstand 1.2 ksi of shear strength at 700 degrees F and can withstand 3 ksi at 75 degrees F, making it incredibly effective (Collins 2005). The mechanism used to keep the spring loaded and the solar panel frame undeployed, an electromagnetic latch will be used. The electromagnetic latch used is the E-941SA-80Q from Seco-Larm and has a 36 kg holding force, which will be more than enough since a single frame weighs 1.359kg. An electromagnet has two components: the armature plate, which is a metallic plate that will be attached to the solar panel frame, and an electromagnet that will be inside the aerobot and will receive power. The armature plate can be placed on the back of the solar panel frame with FM 680-1 adhesive. To account for the protrusion of the armature plate and to allow for the solar panel frame to be undeployed and sit flush with the surface of the aerobot exterior, a cutout of the shape of the armature plate will be made on the walls of the aerobot. This means when the solar panel frame is closed and undeployed, the Armature Plate slots into the aerobot, and inside the aerobot, the electromagnet can come into contact with the armature plate and be powered to hold it in place. This means to deploy the solar panel frame and remove the load on the spring, the electromagnet needs to be powered off, which will detach the armature plate, making the frame fly up to its deployed position. The electromagnet has a larger surface area than the armature plate, so it is able to cover the cutout to protect the interior instruments from the environmental hazards. FM 680-1 adhesive can be used around the electromagnet to secure it around the cutout, and parylene can be coated on the exterior to protect it from sulfuric acid. The operating temperature of the electromagnet is 55 °C, which is lower than the maximum expected temperature on Venus at 50km of 70 °C in the atmosphere. However, the electromagnet will be launched at the very beginning of the mission, and so the solar panel can be deployed before reaching 50 km or the higher temperature regions. Using silver vaporized thermal coating on the electromagnet is a further possibility, but it could impact performance, so this needs to be tested before implementing.

There will be 3 solar panel frames, meaning there will need to be 3 springs and electromagnetic locks. Three 200x50x50 cutouts will be made along the edges of the top face. In those slots, the springs will be attached, and the solar panels with the electromagnetic latch will be attached so the solar panels sit flush with the walls of the aerobot. The top surface of the aerobot will also have an indent that is .95mm deep, but the thickness of the panel will still be the same thickness of .012" as the rest of the aerobot exterior. This means on the inside, there will be a .95mm protrusion. The area of this indent is 720mm by 720 mm, and this will be used to fit additional solar panels. No deployment is necessary for this since it will be placed directly on the top surface of the aerobot.

Germanium Window

The longwave Infrared camera needs to see the outside environment to be able to collect data. However, a simple glass window will not work on the longwave infrared camera due to reflection caused by the glass, which will make it unable to collect data. To give visual access to the outside environment, a Germanium glass pane will be used. Germanium is already used when developing the lenses for longwave infrared cameras and is ideal for infrared applications. The Germanium window will be acquired from Endum Optics. To hold the lens in place, the material used for the exterior of the aerobot will be rolled so it will be able to go around the germanium lens. This will be a hollow cylinder-like shape that can be welded onto the exterior of the aerobot. Then, using the FM 680-1, the germanium window can be slotted in the connection and held in place. The size of the lens is not fully determined, so as an overestimate, a larger window will be used. The diameter of the lens is 75mm, and the thickness of the lens is 8mm. This will result in a weight of 0.06 grams. The window will be placed on the bottom of the aerobot to ensure the Longwave Infrared Camera can take meaningful data of the thermal patterns. A thickness of 8 was chosen to decrease the durability of the window. The diameter can be changed once correct measurements are taken of the Longwave Infrared Camera.

2.1.1.3 Mechanical Subsystem Recovery and Redundancy Plans

Wire Rope Vibration Isolation System (VIS)

The VIS does not include a redundant amount of isolators because they are already inherently passive and fairly robust. Each wire rope isolator used is made from corrosion-resistant material, and they have no moving or electronic parts that could fail. The simplicity, high durability, and space-proven materials of the VIS reduce the likelihood of failure to a great extent. Additionally, due to the weight and volume constraints of the aerobot, it would be impractical to increase VIS count redundancy as adding more isolators would increase the complexity, mass, and space taken up if there were to be a failure in structure or performance of the VIS the configuration still provides load-sharing and stability. Minor degradation would not compromise the overall integrity of the payload support since the ToF Mass Spectrometer has a low center of mass and is lightweight, the other isolators would continue to give mechanical support and some damping. Even in the event of system failure, the VIS is structurally bolted to the titanium frame of the aerobot

adding a layer of mechanical redundancy by making sure the ToF Mass Spectrometer is still firmly attached even with loss of vibration isolation. This mechanical redundancy ultimately allows a steady degradation in case of failure. That said the VIS is not mission-critical in the same way that other instruments and power systems are so it is decided that there will be no additional wire rope VIS included and mechanical redundancy is factored into the configuration and material choice of the subassembly.

Sample Pump

The Sample Pump itself is a small component and is built to be very durable. The pump will work in any orientation and the temperature rating will suffice to withstand the environment on Venus. The pump itself is also made to be chemical resistant. However, the part itself is a COTS component and the chemical resistance itself isn't given in a measurable quantity. This means there is no way to know how resistant the pump is and if it will truly be able to withstand the chemicals in Venus's Atmosphere without doing proper testing. With this being said, it is still assumed that the pump has a low chance of failure due to its durability and chemical resistance, but there is still a chance of the Sample Pump degrading resulting in system failure which would be detrimental to the mission. The pump samples the outside environment into the ToF and UV spectrometers allowing crucial data to be collected. If the sample pump fails then the mission requirement of taking data about the Venus atmosphere will not be possible. Sample pump redundancy is implemented to mitigate the risks of a failing sample pump. The sample pump is a very small component, only weighing 27 grams. Due to this low weight, having a back-up pump for each spectrometer for redundancy will help mitigate the risk of losing sample data of the environment. Furthermore, with how light the sample pump is, the pump itself can simply be connected to the interior structure using an adhesive. Using FM 680-1 adhesive will allow the pump to be securely attached and not get damaged due to movements from deployment or high winds in the Venus atmosphere. Additionally, having the sample pump securely attached also mitigates the risk of tubing detaching from the sample pump itself.

Titanium for Inside of System

The titanium for the inside of the system doesn't really have a normal, or traditional type of redundancy plan compared to other components. This isn't like an electronic component that will have a backup system running in case the primary fails. Instead the inside structure will be fully surrounded by the titanium material and will be a passive structural component. The material goes above the needed requirements for radiation protection, strength, weight efficiency, and corrosion resistance. This is all built in safety factors that help and allow the risk factor for failure to be low. It's basically a structural overdesign to ensure the material won't fail in the atmosphere it's presented. Therefore, because of this low risk of failure, there isn't a need for a physical backup. The material will show its priority of reliability through its performance and proven aerospace use.

As for recovery, in the event of damage or cracking happening to the titanium material, there wouldn't be much worry for the mission. The titanium shielding will surround the inner system from all six sides of the aerobot and the panels should hold and have solid integrity. It is unlikely that there will be significant damage or

corrosion to the material to the point where a recovery system is needed. The titanium is also easily replaceable if there was any damage found before launch. However, throughout the mission there is no recovery needed nor is there recovery possible which isn't an issue because the titanium will be able to perfectly hold the atmosphere and environment for a 2 day mission. The titanium structure is very reliable, and will not need normal recovery for this subsystem.

Solar Panel Holding and Deployment

The main deployment will not have any redundancy due to it being impractical. The solar panel frame being made out of titanium makes it very strong and durable along with the torsion spring being tested to make sure it meets the required specifications. Furthermore, the spring is made from a hastelloy which is very durable and Parylene will be used to protect it from corrosion. There is no practical way to implement a secondary solar panel deployment system and due to how secure the frame and spring are this seems unnecessary. The electromagnetic latch does not need a redundant component since it will only be used at the very beginning of the mission. After the solar panels have launched, the electromagnetic latch can fall off or break and it would not impact the objective of the mission since the solar panels will not be undeploying. The chances of the electromagnetic latch failing is very low since it is active for such a short period of time and just powers off for deployment which will happen as soon as the aerobot reaches its starting position.

Germanium Window

There will be no redundancy for the Germanium Window. This is because it is only in Longwave Infrared Camera, and this camera only has one lens. With there being no practical way to make the camera swap to a different window in case of failure, only one Germanium Window will be used. Additionally, Germanium is ideal for Infrared applications that deal with rugged optics. To protect the Window from sulfuric acid, parylene will be used since it is a non-reflective coating and will not affect the Longwave Infrared Camera's ability to collect data while protecting it from sulfuric acid.

2.1.1.4 Mechanical Subsystem Manufacturing and Procurement Plans

Wire Rope Vibration Isolation System (VIS)

Supplier: Isolation Dynamics Corp. (IDC) (COTS)

Backup Supplier: Enedine (COTS)

Narrative: IDC was chosen as the primary supplier for the VIS because of the COTS wire rope isolators that they provide, which are proven in aerospace and defense applications. This ensures reliability in the VIS's ability to mitigate vibrations for the ToF Mass Spectrometer. The products provided by IDC meet spaceflight-grade requirements and offer multi-axis damping, which can be customized as needed. The secondary supplier chosen is Enedine for similar reasons, though with fewer COTS options. However, due to their expertise in vibration isolation in aerospace applications.

They could provide a reliable alternative that can be customized that will still meet mission requirements.

The expected lead time for a Wire Rope VIS from IDC is 6-10 weeks according to industry standards.

The expected lead time for a Wire Rope VIS from Enedine is 6-10 weeks according to industry standards.

Sample Pump

Supplier: KNF Group (COTS)

Backup Supplier: Cole-Parmer (COTS)

Narrative: KNF Group was chosen as the primary supplier for the sample pump as it is a COTS component and they are original developers and manufacturers of the pump. The pump itself meets all the necessary requirements for this mission, the permissible temperature is slightly low, but the manufacturer stated the value can be increased upon request, since only a 10C increase is needed it can be assumed that this request is achievable. KNF Group specializes in the development, design, production, and distribution of diaphragm pumps for handling gases and liquids. They have had experience working with pumps for space applications such as making an advanced closed-loop system for the ISS. The backup supplier chosen is Cole-Parmer since they have experience with manufacturing and supplying various lab equipment pieces and have been doing so along with research of lab equipment for over 65 years. They supply the same pumps that are made by KNF group that is selected for this mission.

The expected lead time for the sample pump from KNF group is 5-7 days.

The expected lead time for the sample pump from Cole-Parmer is 5 days.

Titanium for Inside Material

Supplier: TMS Titanium

Backup Supplier: Titanium Industries, Inc (TI)

Narrative: TMS Titanium was chosen as the main, first supplier for the titanium because of the type of titanium it offers, which aligned with the team's wanted specifications. The titanium that Titanium industries offer is ideal for aerospace applications. Titanium is reliable to block heat and other types of issues the Venusian atmosphere will give the aerobot, therefore having an aerospace proven type of titanium will be even better. The titanium is sold in sheets and can be offered within specific sizes and dimensions which works for the team's goal. Also, TMS Titanium gave direct costs and delivery dates which was especially helpful as it gave a reliable goal estimated completion date. Titanium Industries was chosen because it also offered aerospace application titanium and offered almost everything TMS Titanium did. This is a great backup option for the team's choice of metal and can meet all the wanted requirements.

The expected lead time for a sheet of .304 mm titanium from TMS Titanium is 2-3 business days from the receipt of order.

The expected lead time for a sheet of .304 mm titanium from TI wasn't specifically stated but shouldn't take more than 5 business days.

Electromagnetic Latch

Supplier:Seco-Larm (COTS)

Backup Supplier:US Lock Supply (COTS)

Narrative: Seco-Larm was chosen as the primary supplier since they are the original manufacturers of the Electromagnetic Latch. This latch was chosen by them due to having no wire connection between the armature plate and the electromagnet. Additionally, it provides 80 lbs of force while having minimal power draw, weight, and size. Seco-Larm has been manufacturing locks for 55 years, and they are a global distributor of them and provide pre-sale and post-sale support. US Lock Supply was the backup supplier since they also hold the 80lb electromagnetic latch by Seco-Larm. US Lock Supply has provided hardware for over 60 years. They have many notable partners in their industry and have a large supply of products ready to ship same day nationally.

The expected lead time for the 80lb Electromagnetic Latch is 5 days for both Seco-Larm and US Lock Supply. This value was taken from the order receipt.

Titanium for frame

Supplier:TMS Titanium

Backups Supplier:Titanium Industries, Inc (TI)

Narrative: The titanium used for the outside of the aerobot is the same titanium used for the frame of the solar panel. Thermal Subsystem Section 2.1.4.4 gives more information on why these suppliers and material are picked for this material. The expected lead times are also acquired from Thermal Subsystem Section 2.1.4.4.

The expected lead time from TMS titanium is 2-3 days

The expected lead time from Titanium industries is less than 5 days.

Torsion Spring

Supplier: MW Components

Backup Supplier: Lee Spring

Narrative:The spring will be manufactured since finding a COTS component that meets the necessary requirements will be very difficult. It is hard to determine the exact force applied, and the spring design needs to stay within the 80lb force limit of the latch and have enough force to hold the solar panel frame up. MW Components was chosen since they deal with hastelloy springs and have 20+ US-based manufacturing facilities. They provide manufacturing for custom springs and wire forms while also having

experience in making these components for aerospace, energy, military, and medical fields. Furthermore, they are ISO9001, AS9100D, FAA, DoD, NASA, and ITAR compliant. The backup supplier, Lee Spring, also manufactures and distributes mechanical springs, wireforms, stamping, and fourslide parts worldwide. They also manufacture custom springs depending on the specifications, ranging from short prototypes to long-run production. When deciding the specifications for the spring, tests will need to be conducted on the solar panel frame and latch physically or using analytical software. To collect the data physically, the solar panel frame titanium will need to be shipped and machined along with the electromagnetic latch and adhesive. After conducting tests on the forces caused by the frame and latch, a suitable design for the spring can be calculated. When comparing the time to manufacture springs with other companies online, such as Stalder Spring Works, the expected lead time is 4 weeks.

Germanium Window

Supplier: Edmund Optics (COTS)

Backup Supplier: OptoSigma (COTS)

Narrative: Edmund Optics was chosen due to the variety of options they have for the Germanium windows. Germanium windows are specifically good for their durability and effectiveness for Longwave Infrared Cameras. Edmund Optics is a leading global optical solutions provider, and its equipment has reached a variety of markets. Similarly, OptoSigma also provides similar Germanium windows to those of Edmund Optics. They are also a worldwide Photonics Components manufacturer, so they are experienced with developing lenses and windows for optics.

The expected Lead time for Edmund Optics is 5 days, which is taken from the order receipt.

There is no exact lead time mentioned for OptoSigma, but since it is a COTS component that is similar to Edmund Optics, it is assumed the lead time is also 5 days.

FM 680-1

Supplier: Jaco Aerospace (COTS)

Backup Supplier: Pacific Coast Composites (COTS)

Narrative: Jaco Aerospace has lots of equipment and experience involving aircraft, chemical, and many other fields. They deal with industrial tapes, adhesives, sealants, coatings, chemicals, etc. Furthermore, NASA has previously acquired products from them before one of these including the FM 680-1 adhesive. Similarly, Pacific Coast Companies supplies FM 680-1 and is an expert in handling advanced composite materials. They have many other products on top of adhesives, such as metals, filler, fabrics, and more for many different fields. The exact lead times were not stated on the websites, but since both are COTS products and will be shipped, the expected lead time at most will be around 8 days.

2.1.1.5 Mechanical Subsystem Verification Plans

The mechanical subsystem needs to make sure all instrumentation gets the necessary deployment or access it needs. To ensure that all instrumentation is able to function properly by having the necessary access points and deployment, the instrumentation will be run as a demonstration. This will verify that the sample pump is pumping into the Spectrometers, that the solar panels are deployed, and that the Infrared Longwave Camera is able to collect data. Mock deployment allows for testing the positioning and function of the instrumentation and verifying if the mechanical subsystem was able to ensure the instrumentation collected quality measurements. A test deployment will verify that the system is sturdy enough to stay attached to the balloon during the mission. The system needs to house all the necessary instrumentation, The instrumentation can't be exposed to the outside environment directly, and taking measurements will ensure all components are located in the correct position for optimal functionality. A vibration isolation system will be mounted on the spectrometer, this can be verified by inspecting the connection on the vibration isolation system to the spectrometer and ensuring that they are firmly attached. To further ensure that the VIS system functions properly and is able to withstand forces, an analytical test will be done using simulation softwares. Using the models and material data of the VIS, forces can be applied to the VIS to verify if it will be able to withstand the forces. The simulation must use 3 VISs carrying a 16.5kg load that is also under the forces. This will represent the spectrometer and VIS system being implemented on the Aerobot, and it will verify that VIS is strong enough to survive. To verify that the aerobot has the necessary connection points to the main structure, the connection points themselves will be inspected. This can be done by taking measurements and ensuring that the measurements align on both ends. To ensure that all access points are safely sealed and secure, a test will be conducted by simulating the Venusian Environment. Sensors will be placed inside the aerobot to measure and see if there are any irregular readings such as an any unexpected gasses or increased temperatures that leak inside the aerobot. The aerobot will need to be powered on, and the mechanical subsystem components will need to be activated in the simulated environment to verify that the access panels are fully sealed.

The verification done proves that the sub assemblies of the mechanical subsystem provide the necessary access, deployment, safety, and functionality that are required from the subsystems.

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
ME-01	System shall give necessary access to all subsystems	Demonstration	Verifies that all subsystems have the necessary access points to function.	Run all subsystem components
ME-02	Systems access panels shall position itself to ensure	Test	Access for instrumentation must be made clear for quality measurements to be	Test instrument alignment and repeatability with measurement sensors in a

	quality measurements		taken	mock deployment
ME-03	System shall remain firmly attached to the balloon during descent	Demonstration	Demonstrating the assembly and deployment of the aerobot verifies its ability	Conduct full system deployment
ME-04	System shall house all instruments	Inspection	Space can be determined upon system assembly within CAD drawings	Ensure spatial compliance visually, virtually, and physically
ME-05	The spectrometer shall be securely mounted with a vibration isolation system to ensure stable measurements	Inspection	Stability can be verified through a structure and fixture review	Inspect mounting and vibration damping sub assemblies
ME-06	The mounted VIS system shall withstand different forces	Test	The VIS shall support a total payload mass of 16.5 kg under launch loads. Analyze a structural simulation and test to confirm real-world performance in static and dynamic loads.	Analysis on CAD model to simulate launch and static load test using a simulated mass on a vibration table
ME-07	The attachment points shall be compatible with the Aerobot's main structure	Inspection	Compatibility can be verified through a structure and fixture review	Inspect attachment points
ME-08	The access panel shall maintain a sealed environment when closed to prevent atmospheric exposure	Test	Testing the assembly against a Venusian environment will ensure its ability to shield internals and payloads	Test assembly in environmental chamber with sensors inside

Table 5

2.1.2 Power Subsystem Overview

The power system for the aerobot has 2 main functions, power generation and power distribution. The team designed a battery with a total power storage of 236.8 watt-hours. The total power draw from all systems is around a constant 117.36 watts if all are on at the same time. If the battery is deployed at full charge, the battery will be able to power all the equipment for around 2.02 hours without power generation. This is where the mission's power distribution schedule is implemented, as seen in the graph below. To conserve power, uncertain subsystems that are not necessary at that moment

will be powered off, which will allow the team's aerobot to consume less power and conserve battery charge. This will allow the incorporation of the NeXt Triple Junction Solar cells from Spectrolab to generate power and charge the battery. These solar panels will be able to generate 75 watts per hour, which will be enough to replenish the consumed power for a single cycle. For the wiring setup, the solar panels will be wired to the battery, while the battery will be wired up to each subassembly component, CDH, Spectrometers, ect...

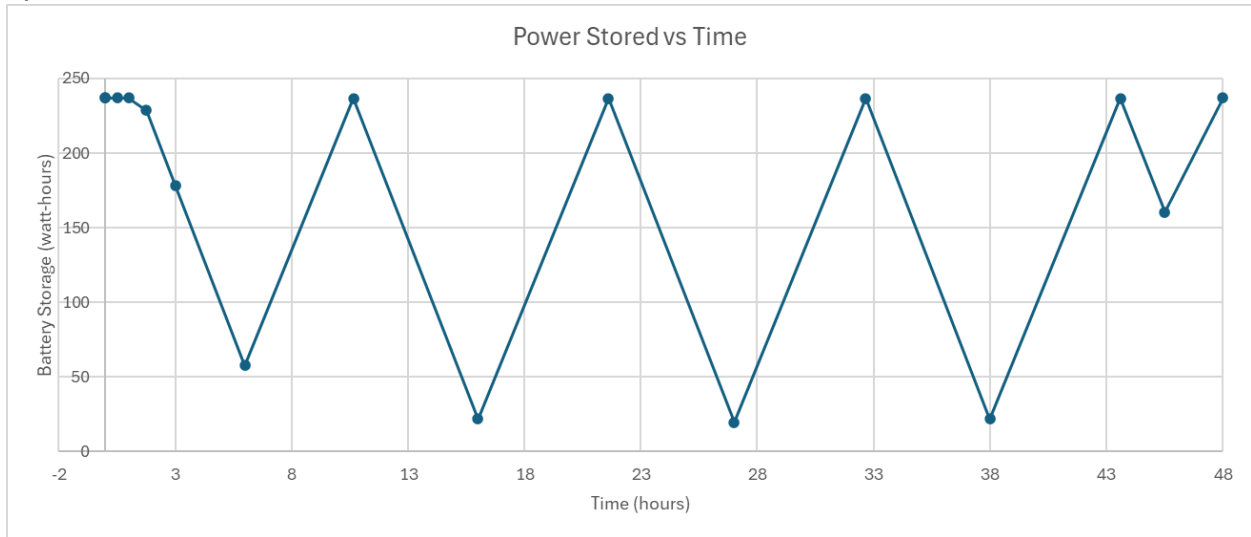


Fig. 6

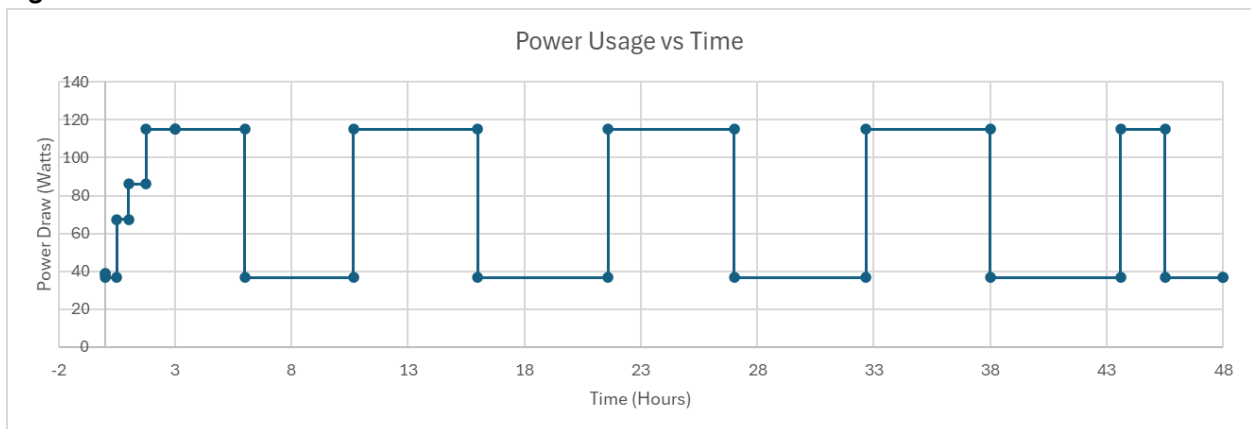


Fig. 7

The Power Stored vs Time plot shows the power stored in the battery throughout the cycles and mission. The plot assumes a constant 75 watts of power generation from the solar panels. The first 1 hour does drop in power since the power draw is less than 75 watts. However, after one hour power stored starts dropping since power usage goes to 86.05 watts, which is more than the 75 watts generated. After 3 hours, the final instrument, the infrasound detector, starts calibrating, meaning all instruments are now running. Once the battery gets down to 50 watts, all instruments shut down except for those in the thermal subsystem and CHD subsystem. Thermal and CHD are still needed to keep temperatures and communication. The beginning stages of the mission involved calibration for all the instrumentation, which is why there is a staggered step plot in the

first couple of hours of the Power Usage vs Time plot. The TOF spectrometer, UV spectrometer, Infrared Camera, and infrasound detectors all need calibration, and this occurs one at a time. The first recharge takes around 4.6 hours, and after that, every recharge takes 5.6 hours, and all instruments are also able to run for around 5.6 hours after each recharge. Near the end of this cycle, the instruments only run for around 2 hours before the battery starts to recharge. This is done so that by the end of the 48 hours, the battery will be fully charged. Having the battery at full charge is necessary in case Aerobot survives the fall to the surface of Venus. Solar panels will not be able to generate enough solar power due to the small solar irradiance on the surface, and additionally, either the free fall or high temperatures will make the solar panels unable to function. This means it is crucial to have a fully charged battery to power the necessary instruments in case data collection is possible.

2.1.2.1 Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
PWR-01	The system shall power the aerobot's crucial components for the duration of 48 hours	The system must provide power for the instrumentation to collect meaningful data and recharge	SYS-04	PWR-05, PWR-06, PWR-07	Demonstration
PWR-02	Power shall withstand high temperatures on Venus	Power must survive for the whole duration of the mission	SYS-01		Test
PWR-03	The Power System shall be securely mounted	The system must be stable to reduce failure and survive for the duration of the mission	SYS-01		Test
PWR-04	Power systems must be corrosion-resistant	The power system must survive for the whole duration of the mission	SYS-01		Test
PWR-05	Power generation shall be able to supply a minimum of 50 watts	The system must provide time for the instrumentation to collect meaningful data	PWR-01		Test
PWR-06	Power Storage shall exceed the total watt hours of the total power draw in watt hours of all components	The system must provide enough time for the instrumentation to collect meaningful data	PWR-01		Demonstration
PWR-07	The power system shall support varying loads for different instruments simultaneously	The power system must provide power to all instrumentation, which will have varying voltage loads and power requirements	PWR-01		Demonstration
PWR-08	The power system shall not exceed 10kg	To stay within the given weight requirement of 45kg	SR-01		Inspection
PWR-9	Power storage shall not exceed .1m ³ in volume	To stay within the 1 m ³ size requirement	SR-02		Inspection
PWR-10	Power Generation	To stay within the 1 m ³ size	SR-02		Inspection

	when undeployed shall not exceed a 1 m x 1 m x 1 m area	requirement			
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Table 5

The power subsystem needs to make sure that instruments are powered for a long enough period to ensure that effective data is collected. The power subsystem is in charge of making sure all important instruments that contribute to the survival of the aerobot are powered at all times.

To have enough time to collect meaningful data, there will need to be a minimum requirement for power generation. If power generation is too low, then most of the mission time will be wasted on recharging the battery.

Furthermore, having a large enough battery allows a longer period of time before the first recharge is necessary, which means more time for instruments to calibrate and turn on.

2.1.2.2 Power Sub-Assembly Overview

Power Storage

A Li-ion rechargeable battery will be used for power generation. Li-Ion batteries were used since they are rechargeable and it is a battery type that is frequently used in space applications meaning it is a reliable and cost effective battery cell material. The battery is a COTS component and the model is ABSL CM230 - 8s4p P20 28V 8Ah Li-Ion rechargeable battery from EnerSys. This battery was picked in particular due to it meeting the necessary power storage and wattage output requirements. Furthermore, this battery is space proven and fits within the space and weight requirements. The battery does not require cell balancing electronics making it easy to integrate. Additionally, the battery is space proven and has over 5.5 billion cell hours in orbit. Due to this the TLR of the battery is 9.

Operating temperature of the battery is between -20°C to 40°C and the battery contains a voltage range of 33.6 - 24 volts while having a nameplate capacity of 8Ah which results in a power storage of 236.8 watt-hours. The total power draw from all systems is around a constant 117.36 watts at most. If the battery is deployed at full charge, the battery will be able to power all the equipment for around 2.02 hours without power generation. To make sure there is enough power for the total duration of the mission, there will be power generation to recharge the battery. Depending on the situation, instrumentations will be paused or put on a cycle to allow the battery to recharge.

To hold the battery in place, welding could be an option since the exterior of the battery seems to be made out of a metal frame, however, the manufacturer does not list the material used for the exterior of the battery. Since the Aerobot interior will be composed of titanium, welding with mixed materials can cause the material to be brittle or not be secure. Due to this welding is avoided. Instead space grade adhesive will be used to attach the battery. A space grade adhesive that could be used is FM 680-1 which has a very high temperature rating and is able to withstand a shear force of 800 lbs at 600°F applied on a .5 in² surface (Collins 2005). The battery itself is 2.05 pounds

and will have, at most, temperatures of 75 °C and the bottom side being glued has a higher surface area than 0.5 in². This means the adhesive alone will be more than enough to withstand forces applied on the aerobot from the venus atmosphere. To further secure the battery in place, small titanium brackets can be welded to the bottom panel of the aerobot, using these brackets, nylon velcro can be run over and around the battery to further secure it in place.

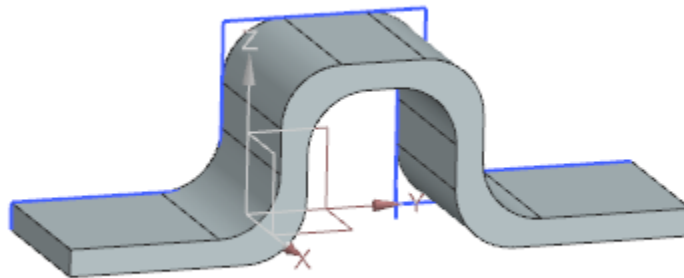


Fig. 2.1.2.2-1

Fig.2.1.2.2-1 shows a possible design for a bracket for the nylon velcro to go through. Placing 4 of these around the battery and welding them down and running the velcro around the battery to secure it. These brackets should be very small and big enough for the nylon to pass through

Power Generation

For power generation, solar panels were chosen. Solar panels were chosen due to their simplicity when deploying and its resistance to heat and sulfuric acid on Venus with the right modifications. Other methods for power generation such as heat generators either did not provide enough power, took up too much space, or weighed too much to be viable for the mission. In comparison, solar panels are very light weight and can be deployed using very simple mechanisms. The solar cells used for this mission are the NeXt Triple Junction Solar cells from Spectrolab which is a COTS component. A COTS component is chosen due to it already having a high efficiency rating of 29.5% and being tested in many space missions. This makes the TRL of the solar cells 9 which significantly reduces costs and scheduling time. The solar cells will be attached to a titanium frame which will act as the backplate and the team will create the attachment using EVA film. EVA film is used for solar cells and has a temperature rating of up to 150 °C which will be more than enough for this mission.

The solar cells from Spectrolab have an area of 59.65cm² and the designed titanium frame can fit 132 panels on it. Additionally, there will be another 81 panels on the top surface of the Aerobot. There will be a total of three titanium frames to hold and deploy the solar panels. With the 3 frames and the top surface of the Aerobot a total of 477 solar cells which will result in 2.84 m² of solar cells coverage. Around 60 km the solar irradiance is around 90±12 w/m² on venus (Moroz 1982). With the 29.5 % efficiency and 447 solar cells of 59.65cm² area, the solar panels will be able to generate around 75 watts. The weight of the solar panels is 84mg for every cm², this means the

total weight from the solar cells is 3.38×10^{-4} kg, which is very light. The total power usage of the whole aerobot is greater than 75 watts, additionally the power generation will fluctuate throughout the mission meaning it will not be possible to run all instrumentations for the full 48 hour duration of the mission. With a battery on full charge, and a constant 75 watts of power generation, the power will completely run out in around 15.79 hours. After that time, certain systems will need to be turned off to lower the power usage so the battery can start to charge back up.

The frame itself is slightly larger than the actual area taken up by all the solar cells. This is done to account for tolerances and potential wiring needed. The solar cells themselves will have their electrical terminals welded and a single electrical terminal will be used from the solar cells to connect the wires to. The solar cells can be welded in configurations of series and parallel to account for the teams required voltage after testing. The terminals for the solar cell shall be accessible from the top back of the solar panel frame so the wires can be soldered or welded to the terminals and routed to the battery. There shall be a small hole roughly the diameter of the wire near the spring joint for each solar panel frame so the wires can enter the interior of the chassis. For the solar cells on the top panel, holes can be cut out directly underneath the solar cells since they are positioned right above the aerobot. Anying wiring on the exterior should also be coated in Parylene to protect it from environmental damages.

The order of how the solar cells will be put together is with a layer of EVA adhesive on the milled out section of the frame, then the solar panels get placed on that section, followed by another layer of EVA adhesive and coverglass on the top. EVA adhesive helps offers positive thermal properties to the solar panel while also increasing the structural integrity of it. A test conducted at JPL by NASA concluded that a solar cell with coverglass and a coating of parylene immersed in sulfuric acid was able to withstand 96 hours with no corrosion and performance loss(Dawson 2022). Due to Parlyene's effectiveness it will be used to coat the surface of the coverglass. The coverglass is provided by both suppliers and Spectrolab offers coverglass thickness of up to 30 mills which will be the thickness used for these solar cells. The highest thickness of coverglass offered was chosen to further protect of the solar cells.

2.1.1.1.

2.1.2.3 Power Subsystem Recovery and Redundancy Plans

The power storage and power generation will not have any recovery or redundancy due to both being a large and heavy component. The battery for power storage has a low risk of failure since it is contained within the aerobot and is safe from the majority of the environmental hazards on the Venusian atmosphere. The notable risks for the battery will be overheating or getting damaged during the forces caused by the aerobot moving. However, these risks will be mitigated due to the battery being placed very closely to the thermal management implemented into the aerobot. The battery can operate at 40 °C which is lower than the maximum temperature reached on venus during our mission. However, this will not be an issue due the placement of the battery being on top of one radiot and placed next to the other radiator. There will also be an electric cooler between the battery and radiator making sure the battery stays cool.

The solar cells are too large and take up too much of an area to have redundancy plans for. The main concern will be damage taken from the environment. However, due to the coverglass and parylene coating sulfuric acid damage will be very unlikely. Furthermore the operating temperature of the solar cells go up to 80 °C which is higher than the highest temperature we will face during the mission. Due to these mitigation plans and impracticality of another set of solar cells, redundancy plans will not be added.

2.1.2.4 Power Subsystem Manufacturing and Procurement Plans

Power Storage

Battery

Supplier: EnergySYS (COTS)

Backup Supplier: GS Yuas (COTS)

Narrative: EnergySYS has experience working on technology relating to energy systems. They have lots of experience working on space-related missions, and their batteries are tailored for space missions. The subsidiary of EnergySYS, ABSL, developed the battery selected for this mission, and their rechargeable lithium-ion batteries have been the first to orbit Earth, Mars, and Venus. Additionally, they have worked with NASA before for the Parker Solar Probe. The battery chosen is the Li-ion Rechargeable Battery ABSL CM230 - 8s4p P20 28V 8Ah, which is a COTS component. This battery was chosen since it is already flight-proven and meets the aerobot's necessary power demand. Furthermore, the battery is not overly heavy and fits within the Aerobot. The battery is qualified by ASTRIUM for the CNES MICROSAT, and the battery is currently operating in both LEO and GEO orbits. Since the battery is flight-proven, it gives it a High TRL, which cuts costs and time for development of batteries. Another backup supplier supplying the same battery could not be found. To compensate for this GS Yuas is chosen to supply LSE12x Lithium-ion Cells. These cells will require more integration since they are individual cells and will need to be configured in parallel and series and at least 6 cells will be required. Having 6 cells when configured right will give similar power output, voltage, and amps, to the EnergySYS battery. Additionally, for integration, a way to house the cells will be necessary and control interfaces for the battery will also need to be implemented. GS Yuas was chosen since they have been manufacturing Li-Ion batteries for space missions for over 20 years and have manufactured the main battery on the ISS. Also, the LSE12x Cell has already passed qualifications and testing for space applications. GS Yuas explains that the LSE12x Cell is suitable for LEO, MEO, and GEO applications.

Since both items are COTS, the *shipping time was estimated* using DigiKey.

GA31462001, a battery from Zeus Battery Products, has similar weight and dimensions

of EnergySYS battery and 9 LSE12x Li-ion cells. This resulted in a lead time of 3-5 days.

Power Generation

Solar Cells

Supplier: Spectrolab(COTS)

Backup Supplier: Pumpkin Space Systems (COTS)

Narrative: Both Spectrolab and Pumpkin Space System provide coverglass for the solar cells. Spectrolab is very experienced with supplying solar cells for many space related missions. Spectrolab solar cells have been to mars and jupiter, along with countless used for satellites orbiting earth and for power generation of the ISS. Due to how reliable and mission tested the solar cell is it is decided to choose this COTS solar cell for the backup supplier for power generation. A backup supplier for an exact solar cell supplied by Spectrolab could not be found. However Pumpkin Space Systems has solar cells that are very similar in size and efficiency to those offered by Spectrolab. Pumpkin Space Systems is ITAR- registered and has significant experience designing and manufacturing components for small satellites. They have dozens of space missions that provide nanosatellite components. Their COTS solar cell was chosen since it is space proven and has a very high efficiency.

The lead time for both Spectrolab and Pumpkin Space System is 5-7 days. There was no direct shipping time for either component. Since both components are COTS and can be shipped the lead time is expected to only be the shipping time which in the US can be expected to be 5-7 days

Parylene

Supplier: Electronic Coating Technologies

Backup Supplier: Specialty Coating Systems

Narrative: Parylene was chosen since it is clear and non-reflective allowing it to be effecting on solar panels. Parylene is very strong against sulfuric acid and when combined with a coverglass the solar cells will be able to withstand the sulfuric acid in the atmosphere throughout the mission. The main supplier, Electronic Coating Technologies, are distributors of conformal coatings for many fields such as aerospace, automotive, medical, ect. Furthermore they deal with coatings that offer protection against corrosion and high temperatures. Electronic coating Technologies are also ITAR certified. The backup supplier, Specialty Coating Systems, is a worldwide distributor of coating and this includes custom parylene coatings. Their coatings are ultra-thin and pinhole free and provide protection from corrosive liquids, fluids, gases and chemicals. The coatings will need to be done by them meaning the solar cells and other instruments that require parylene coatings will be sent over to them to get coated. The expected lead time for Electronic Coating Technologies is 3-8 days according to their

website. A lead time for specialty coating systems was not able to be found but since they are similar to Electronic Coating Technology it can be assumed the lead time is also 3-8 days.

EVA Film

Supplier: Interlayer Solutions (COTS)

Backup Supplier: Emco Industrial Plastics Inc (COTS)

Narrative: EVA film is the most common adhesive used for making solar panels and when laying the solar with the backplate and coverglass. This is due to the toughness it adds to the final design and additional thermal protection that comes with it. For the solar panels, a layer of EVA film will be placed on the backplate, then the solar cells on top, then another layer of EVA film and finally the coverglass gets placed on top.

Interlayer Solutions also provides EVA films and is experienced in the field of lamination. Furthermore they have a product called Evalayer which is a EVA-based adhesive film which offers great strength and integrity due to its molecular cross-linking capabilities. Emco Industrial Plastics is a distributor of EVA in many different forms, sheet, tube, and film forms. They specialize in machining of all thermoplastics and is ITAR certified. They have many fabrication services for plastic as well such as precision cutting, line bending, oven bending, assembly, and many more.

Neither supplier indicates their lead time. However both claim they have quickly delivery and since both supplier items are COTS, the expected lead time will be considered as 8 days to ship.

2.1.1.2.

2.1.2.5 Power Subsystem Verification Plans

For the first requirement of the team's subsystem, the power system shall be able to run continuously for 48 hours while the power generation system is charging it consecutively. For the Duration of the mission on Venus, the power system will need to generate power, store power, and distribute power to the instruments. The way to verify this plan would be to run a test, turning on all of the subsystems that consume power, and hook up a power supply that is the exact same wattage per hour as the solar panels would. The team shall also test the power system against the Venusian environment to ensure its ability to perform at high temperatures. To verify this requirement, the team will set up the battery with solar panels with the cooling system in a chamber similar to Venus's temperatures to prove that it can operate with no issues. The power system must withstand the forces caused in any direction by high winds, lightning, and storms in the Venusian Environment. To verify that the power system can withstand these forces, the team should place the power system on a vibration table with fixtures enabling 3 axes of testing. Venus also has a high concentration of sulphuric acid in its atmosphere, which will be in direct contact with the team's power generation system.

The team needs to verify that the power system can withstand the sulfuric acid atmosphere, and to verify that the team will immerse the power generation system in a high concentration of Sulphuric Acid while generating power to prove reliable operation under acidic conditions. The power generation system also needs to be able to supply a minimum of 50 watts. Since the solar irradiance differs at different altitudes in the Venusian atmosphere, the team needs to take into account the chance of not getting enough solar energy to charge the battery fully on an off cycle. To verify that the team can get at least 50 watts, the team shall emit an irradiation level similar to Venus at 50 km and measure power generation from the solar cells. The aerobots power storage shall exceed the total watt hours of the total power draw in watt-hours of each and every component. If the storage takes more than one hour to fully drain, then there are more watt-hours in storage than the power draw. In order to verify this, the team will fully charge the power storage system, and run all of the systems until the storage runs out. The last testable requirement is that the power system shall be able to support varying loads for different instruments simultaneously. If power is being generated and stored while the instruments are running then the power system will be able to support varying loads. To verify this, the team will turn on different systems, all systems, one system, ect., with power generation deployed and battery storage connected. The rest of the verifications are solely measurable, such as the weight of the power system not exceeding the total weight of 10 kg. To verify the weight of the power system, weigh the battery and solar cells. The power system shall not exceed the volume of 1m³. To verify the volume specifications for the battery, measure the length, width, and height of the battery. Since the team's power generation system is on the outer shell of the aerobot, it cannot exceed the dimensions of 1m x 1m x 1m while not deployed. To verify this, measure the length, width, and height of the whole aerobot when solar cells are undeployed.

Table 2.1.2.5-01-

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PWR-01	The system shall power the aerobot's crucial components for 48 hours	Demonstration	Power must be generated and stored while the instruments are running	Turn on all systems with power generation deployed and battery storage connected
PWR-02	Power shall withstand high temperatures on Venus	Test	Testing the power system against the Venusian environment to ensure its ability to perform at high temperatures	Test battery with radiator and solar panels in at chamber at 55°C
PWR-03	The Power System shall be securely mounted	Test	Must withstand forces caused in all directions by high winds in the Venusian Environment	Power system placed on vibration table with fixture enables 3-axis testing

PWR-04	Power systems must be corrosion-resistant	Test	Venusian Atmosphere contains high concentration sulphuric acid, and power generation is directly exposed to the atmosphere	Immerse Power generation with coating in a high concentration of Sulphuric Acid while generating power
PWR-05	Power generation shall be able to supply a minimum of 50 watts	Test	Solar Irradiance differs at different altitudes in the Venusian Atmosphere	Emmit irradiation level similar to Venus at 50km and measure power generation from solar cells
PWR-06	Power Storage shall exceed the total watt hours of the total power draw in watt-hours of all components	Demonstration	If the storage takes more than one hour to fully drain, then there are more watt-hours in storage than the power draw	Fully charge the power storage and run all systems until the storage runs out
PWR-07	The power system shall support varying loads for different instruments simultaneously	Demonstration	If power is being generated and stored while the instruments are running then the power system supports varying loads	Turn on all systems with power generation deployed and battery storage connected
PWR-08	The power system shall not exceed 10kg	Inspection	Weight can be verified through a structure and fixture review	Weight battery and solar cells
PWR-9	Power storage shall not exceed .1m ³ in volume	Inspection	Size can be verified through a structure and fixture review	Measure the Length, Width, and Height of the Battery
PWR-10	Power Generation when undeployed shall not exceed a 1 m x 1 m x 1 m area	Inspection	Size can be verified through a structure and fixture review	Measure the Length, Width, and Height of the whole aerobot when solar cells are undeployed

2.1.3 CDH Subsystem Overview

The CDH or the Command and Data Handling system is the control system of Aether Solaris. Its mission is to ensure all electronic components, sensors and communication arrays are all working seamlessly. Not only that it's also responsible for processing scientific data, executing commands and carrying out mission critical tasks.

The Command Data Handling system works by controlling various systems including the flight computers to the memory, power control and more. Each of the named subsystems play a huge role in keeping the craft functional. The CDH was made to work in a TMR fashion, triple modular redundancy. As the name suggests, it means that there are essentially three physical copies of the same system. If one system fails then there will be two more to replace it. This ensures the reliability during the mission timeframe and the ability to find out if there are any broken CDH components if there are any issues. The memory part of the CDH also comprise many different type of memory so that if there are any catastrophic failures, the data will be moved to non-volatile storage to ensure that it's not lost. Lastly, the CDH communicate and acts

as an orchestrator to control the science system to ensure that they do their experiment at the right time.

Throughout the mission, the CDH “orchestrates” every stage. During flight, it uses data from sensors and camera to determine the aerobot's position and trajectory without GPS. Upon reaching target scientific zones, the CDH initiates scientific activities by activating instruments to measure atmospheric composition, pressure, temperature, and more. If there are any issues that happen at the time, the CDH will either ensure that they can safely finish their assigned task or shut them down accordingly.

Raw data initially stored in RAM or volatile memory, undergoes processing during the analysis phase. Specialized software extracts vital information, discarding superfluous data to ensure only the most relevant information is preserved for transmission. When it's time to relay data back to Earth, the CDH compresses and encodes the information, transmitting it via a high-speed radio system capable of rates exceeding 1 Gbps. It might also save a copy into the non-volatile memory storage like flash memory to ensure that there's a backup. If the data was lost in transmission, the CDH could pull it from storage and resend at any stage.

Running on a real-time operating system, the CDH software manages multiple tasks simultaneously, prioritizing urgent actions like maintaining balance or responding to threats. The RTOS is unlike the traditional OS so named “real time” due to its fast operating speed. They were made to act upon real time events hence it's perfect for this mission. The flight computer has dedicated features for autonomously managing navigation, troubleshooting, and error correction, all while a watchdog system continuously monitors functionality. In the event of a failure, the CDH can shift operations to backup systems due to its triple redundancy architecture to maintain the mission parameter.

Given Venus's extreme conditions, the CDH must be made to be resilient enough to survive the environment for as long as the mission dictates. Its protective casing is both cooled and shielded, with electronics engineered for radiation resistance. The radio system must also be designed to penetrate Venus's dense clouds, and most importantly, prevent data loss.

Beyond hardware redundancy, the CDH incorporates software-based safety checks. Cross-checking among the three redundant computers ensures accuracy, with automatic takeover in case of a malfunction. Regular system checks assess memory, power, and sensors, while the CDH optimizes power usage by deactivating non-essential components and maintaining critical functions during emergencies.

In essence, the CDH isn't just a control unit—it's the lifeblood of the mission. By making rapid decisions, processing scientific findings, transmitting communications, and solving problems, the CDH acts as the aerobot's brain and leader. Its robust construction enables it to withstand Venus's challenges while driving the mission toward its significant scientific objectives.

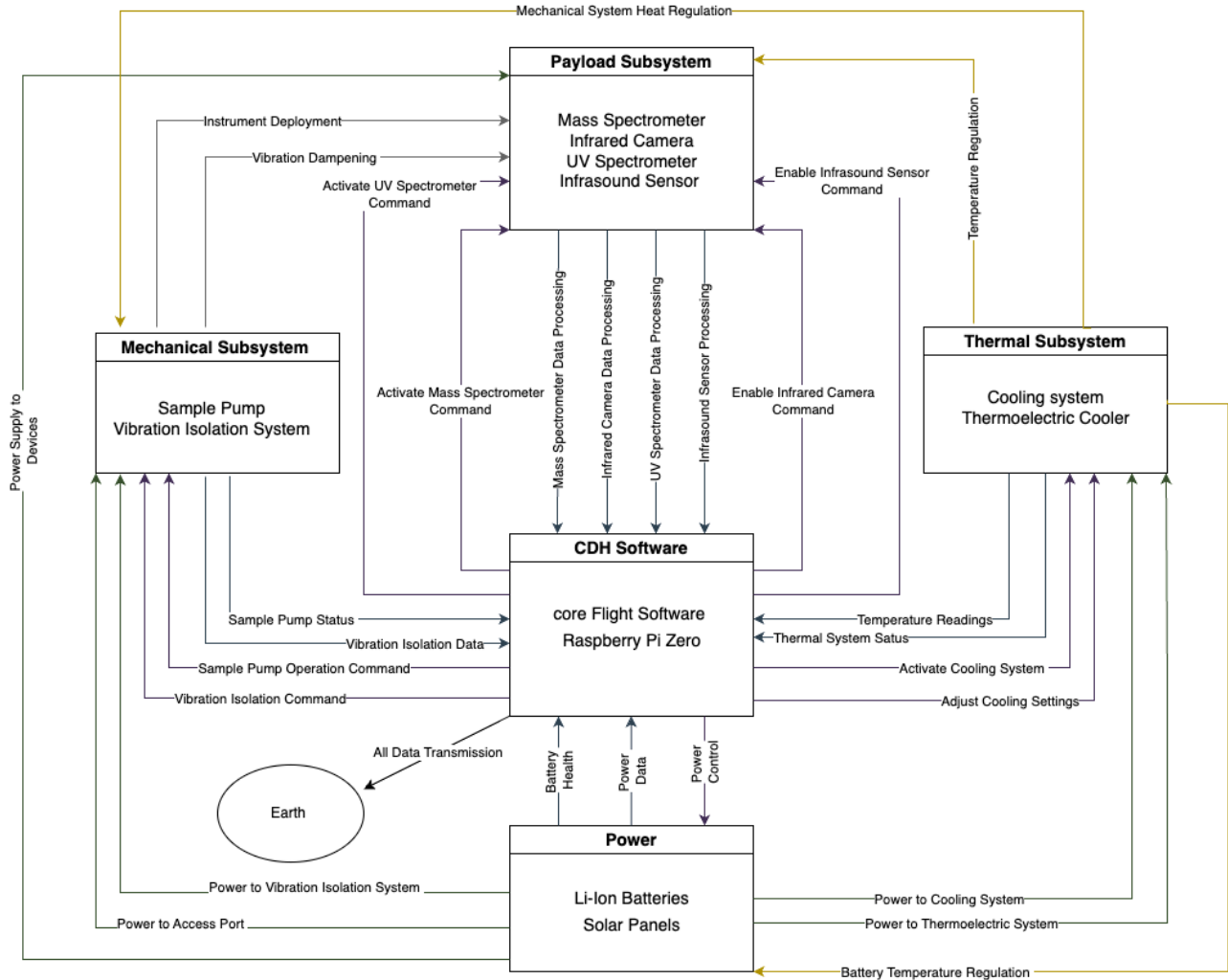


Fig.8

2.1.3.1 CDH Subsystem Requirements

To ensure a successful mission, the CDH must perform several fundamental functions. It should efficiently process and execute both autonomous decisions and commands from Earth with minimal latency while acquiring and processing real-time data from the payloads. The system must also support high speed telemetry transmission and communication while minimizing data loss and corruption. It must also be able to transmit its message and receive incoming messages through the thick atmosphere of Venus. Additionally, to fit with the mission parameter, the aerobot's CDH subsystem must also be able to navigate itself for both real-time hazard avoidance and to get to the correct landing site. In addition, due to the perilous atmosphere, the CDH must include a fault detection and recovery mechanism. And lastly, the power management must be robust and effective enough to ensure all crucial systems to the mission always get their power and to minimize power consumption.

Due to the nature of this scientific mission, the aerobot is expected to gather, process and transfer all of their acquired data back to Earth. This requires the system to maintain a robust and computation infrastructure onboard, incorporating a fast and powerful microprocessor to support real-time decision making. There should also be enough Random Access Memory (RAM) to encode or do digital processing on acquired data. As for the non-volatile storage, there should be enough to save mission critical software and to save telemetry data.

The Venusian atmospheric condition proves to be an interesting adversary for the communication aspect of this mission. Due to the thick cloud layers of the atmosphere, the aerobot is expected to have an RF transmission system strong enough to penetrate through the atmosphere at any expected elevation that it might find itself in. In addition, the data throughput of the system shall also be at least 1Gbps. This system must also have protection against extreme heat, radiation, and electromagnetic interference.

Lastly, ensuring redundancy and fault tolerance is most critical to the mission longevity. The CDH must feature at least triple redundant computers with automatic passover capabilities to maintain system integrity. Not only that, there must also be error correction and prevention due to the high amount of data that the system will acquire during its time in the Venusian atmosphere. Power redundancy is also crucial in having multiple power sources to ensure power integrity.

2.1.3.2 CDH Sub-Assembly Overview

The flight computers used in the Aether Solaris mission are Raspberry Pi Zero single-board computers. These computers are very small and light. Because of this, it is possible to use more than one without making the system too big or too heavy. Each computer weighs less than half a kilogram. This is important because the Command and Data Handling (CDH) system must be very reliable. It is responsible for saving mission data, running commands, and talking to the different parts of the spacecraft. If this system stops working, the mission could fail. The aerobot might lose important data that cannot be collected again.

The redundancy strategy will be extended beyond a single backup. By including three identical copies of the CDH system, the aerobot's fault tolerance can be significantly enhanced. This means that if both the primary and secondary units were to fail, a tertiary unit could take over without disrupting operations. To optimize this system, these computers will be wired in a circular configuration, ensuring that if one unit goes offline, the next available system takes over while the failed unit remains inactive for diagnostic evaluation. This prevents an immediate reactivation of a recently failed system, minimizing the risk of repeated failures and allowing the CDH system to maintain continuous operation.

The aerobot will be conducting research within Venus's upper atmosphere and transmitting data collected to an orbiter, which will then transmit it back to Earth. There will be times during which the orbiter is occluded by Venus, and there will be no transmission occurring. Due to this, the CDH must contain the means to store information during the communication blackouts and the means to transmit it quickly to the orbiting craft once the blackout has ended. The thickness and composition of Venus's atmosphere must also be considered, because it may cause issues with transmission. It is speculated that because the aerobot will not be gathering any data

when it enters the Venusian atmosphere, there will not be much to transmit back to the orbiter. The only data that the system will be transmitting back will be the telemetry data and the health diagnostics of the system. This data could be very small and simplistic, similar to those transmitted from CubeSats.

NASA's Core Flight System (cFS) will be used as the primary software framework for the CDH system. This program is known for its reliability and modularity. It also has flight heritage being in space which is a benefit since it is proven to work. It's a real-time operating system (RTOS) that has been designed for space missions. This is crucial for data collection and the health monitoring of the system. cFS will be implemented using the programming language C to provide high performance and real-time processing capabilities. The development and testing will be managed within Visual Studio Code. This environment was chosen due to its powerful debugging tools, seamless integration with embedded systems and code management.

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans

The Venusian atmosphere offers incredible challenges for an aerobot with the task of gathering data. The Command and Data Handling subsystem is an important feature, as it executes commands, ensures communication and gathers important information. Taking this into consideration the CDH system must be designed to be resilient and reliable in order to mitigate the harsh realities of the planet. One of the biggest concerns with missions to the planet Venus is the extreme surface temperatures that can reach to about 1,173K. Any electronic component faces risk of material degradation and overheating. In addition, the thick acidic clouds and atmospheric pressure will add incredible stress to the systems. Due to these conditions, it is imperative for the CHD subsystem to be equipped with the necessary safeguards in order to ensure meeting mission objectives.

In order to address these challenges the Command and Data Handling subsystem features a system that consists of three identical, compact flight computers. These computers are in circular configuration, and this arrangement assures a hefty fault tolerance. If one of the systems fails, due to external factors or intense exposure, the next available unit automatically takes over and becomes the primary computer in control. This ring model system is designed to minimize the risk of system failure in order to achieve mission success. This handoff allows for the continual processing of crucial data and health monitoring. Ensuring that the aerobot never loses the ability to function and collect crucial information. This redundancy is practical for ensuring resiliency in an unpredictable and dangerous environment. With limited space, weight and energy resources, several small computing options were taken into consideration for this mission. Raspberry Pi Zero was selected as the flight computer for the CDH subsystem. Its compact form was kept in mind during the selection process. It is also energy efficient, making it easy to implement a triple redundancy system without having to significantly increase the volume or mass of the aerobot.

If a computing unit is to fail, the system will not only move on to the following functional computer. It will also isolate the non-functioning component in order to avoid a domino effect of failures that could potentially compromise the entire mission. A proactive approach in order to mitigate compatibility issues if control changes were to occur, is that each of the Raspberry Pi Zero systems will include identical firmware and

be configured with the same interface. The responsibilities programmed into each computer include executing commands, managing telemetry data, as well as receiving and transmitting communications from mission control on Earth. In addition, each computer has a built-in hardware Watchdog Timer. This is a self recovery mechanism that monitors system health continuously (Emmet). Each unit is automatically rebooted if it becomes unresponsive. This feature in the Raspberry Pi Zero increases autonomous resiliency in Venus' harsh environment and atmospheric conditions.

Incorporating all these elements together form a sturdy Command and Data Handling subsystem. One that is able to maintain operational tasks in lieu of unpredictable planetary conditions. By incorporating three identical Raspberry Pi Zero computers with synchronized firmware and autonomous recovery features, the system has layered safeguards. This strategic redundancy and recovery plan creates a functional and responsive aerobot while upholding Aether Solaris' mission objectives.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans

The CDH, or Command and Data Handling system, is one of the most important parts of the Aether Solaris aerobot. It controls everything. It collects data, runs commands, talks to other parts, and keeps the whole mission working the right way. Because of this, it needs to be made strong, simple, and reliable. If the CDH fails, the mission could fail too. So the plan for making and getting the CDH parts must be careful and smart.

The main computer used for the CDH is the Raspberry Pi Zero. This is a very small and light single board computer. It doesn't take up much space, which is perfect for a small flying robot like Aether Solaris. Also, it doesn't weigh much—less than half a kilogram—so it helps keep the total weight low. This makes it easier to fly in Venus's thick and hot atmosphere.

One good thing about using Raspberry Pi Zero is that it's easy to buy. It's a common product and cheap. There is no need to make the computer from scratch. This saves time and money. One simply must order enough units from the company or an approved supplier. After the boards arrive, the software can be installed and the computers tested. Only the ones that pass all the tests will be used.

To make the CDH more reliable, the team is going to use not just one computer, but three. This is called "triple redundancy." If the first one breaks, the second one takes over. If the second one also fails, the third one is still ready. They are all the same, so if one works, the rest will work too. This makes switching between them easy and safe. All three will be connected in a circle, so if one shuts down, the next one turns on. This setup also lets the aerobot's ground team test or fix the broken one later.

The Raspberry Pi computers need other parts to help them work. For example, they need power converters, connectors, heat sinks, and enclosures. Some parts can be bought from electronics stores or online. Other parts, like the enclosures, may need to be manufactured via 3D printing. The 3D printed boxes will protect the computers from heat, dust, and vibration. Special heat-resistant materials for this will be used.

The power converters will make sure the computer always gets the right voltage. Too much or too little power can break it. Every converter will be tested before using it. When assembling the aerobot, connectors that are strong and can't come loose easily

will be used. The wires and connectors will be tested to make sure they don't fail when the aerobot is moving or shaking.

Building the CDH system will follow a few steps. First, all the parts will be acquired. Then testing will make sure there are no bad ones. Next, the computer units will be built. This means putting the Raspberry Pi, the power parts, and the enclosure together. After that, the mission software will be installed. This software will help the CDH talk to sensors and other systems. Last, the full system will be tested. If everything works, the unit is ready to fly.

The backup units are built the same way. This makes it easier to fix problems. If a unit fails, the aerobot just switches to the next one. There is no need to figure out what is different between them. All parts are the same. The team will also make sure each computer has the same software version and settings. This makes the switch fast and smooth.

To store data, CDH will use SD cards. These are cheap and light and work well with Raspberry Pi. Each CDH computer will have its own SD card. These cards will save mission data and health info from the system. When the orbiter is not in view, the CDH will keep the data safe. When the orbiter comes back, the CDH will send the data quickly. The data will be small, like sensor readings and system checks, so the CDH doesn't need a lot of space.

The plan is to buy most parts early. That way, the team can test everything and fix problems before the mission. The team will order extra parts too, in case some don't work or break. This helps us avoid delays. For 3D printed parts, the team will print them in-house. This gives more control and allows changes to the design if needed.

The team building the CDH is small but skilled. Each person has a job—hardware, software, testing, or building. They will all work together to make sure the system is done right. Good teamwork is key to making the CDH safe and strong.

In the end, this plan gives Aether Solaris a CDH system that is cheap, small, light, and reliable. By using simple, known parts like Raspberry Pi Zero, and building in extra backups, the mission is made much safer. And by testing everything, the team lowers the risk of failure. This is how Aether Solaris makes sure the CDH system helps the mission succeed, from start to finish.

2.1.3.5 CDH System Verification Plans

The main objective of the Command and Data Handling System Verification Plan is to make sure that the subsystem fully meets all the requirements and mission critical design functions. Included in these requirements are environmental resilience, fault tolerance, system compatibility, data processing and effective communication while in Venus's extreme atmospheric conditions. The triple-redundancy system that is implemented will be verified through deliberate fault injection. Failures will be simulated and introduced into each of the three Raspberry Pi Zero computers in order to test the automatic failover and how well the system continues operation without the need of human intervention. On NASA's Core Flight System software the real-time operating system will be put under stress testing in order to validate the autonomous decision making processes and multitasking capabilities. The memory components will also be tested in order to account for proper storage of data, and backup tools to be used during communication delays or system emergencies.

A simulated mission environment will be used in order to test the efficiency of the autonomous navigation and command execution that will take place. The system's ability to navigate, recover and initiate tasks without human intervention will be monitored and verified during this process. In order to confirm the system's durability, the unit will also go through environmental tests that closely mimic that of Venus's harsh conditions. Electromagnetic compatibility tests will verify that there is no interference from such conditions between the components. The CDH subsystem will be considered ready for flight once it has demonstrated fault tolerance, accurate real time processing, environmental resilience and high data processing while in a simulated mission. All these are critical factors for the system to meet mission objectives.

2.1.4 Thermal Control Subsystem Overview

The thermal loading occurring in the aerobot system can be broken down into two modes of heat transfer, radiation and convection. These modes define the parameters at which decisions on thermal control systems are implemented. The primary source of radiation applied onto the aerobot system is solar radiation. Solar radiation is the largest source of heat flowing into the system. Radiation requires no medium and occurs through photons coming in contact with a system. Solar flux describes the amount of sunlight energy hitting a given surface. The intensity of solar flux is dependent on the distance an object is from the sun. The aerobot is within the Venusian atmosphere at an altitude of 50 to 70 km from the surface [D. Williams]. Since the aerobot resides in the planet's atmosphere, it will be assumed that it is the same distance Venus is from the sun. Also, the aerobot system resides in the mesosphere which is mainly just above the cloud layer. This allows for the assumption that the intensity of light entering the system will be the same as if in space. Therefore, the solar flux is dependent on Venus' distance from the sun and is calculated with the equation below.

$$q_{solar} = 1367/d^2$$

Equation 2.1.4.1

The solar loading on the aerobot system is dependent on the area (A) the sun hits, the absorptivity (α) of the surface it strikes, and the solar flux. Decreasing the area of the aerobot's exposed surface or the absorptivity of that surface will limit the intensity of solar loading. Equation 2.1.4.2 describes the solar loading relationship.

$$Q_{solar} = q_{solar} \cdot A \cdot \alpha$$

Equation 2.1.4.2

Venus is known as the morning star and the evening star due to the planet's high brightness. This brightness is also referred to as albedo where light or radiation is

reflected by a surface. There are two different types of albedo. Bond albedo is the measure of the total radiation reflectivity of a celestial body relative to the total incident radiation from the sun. Geometric albedo is the amount of radiation relative to that of a flat Lambertian surface where it acts as an ideal reflector at all wavelengths. In the case of Venus, bond albedo is useful in understanding how warm the planet is as well as incorporating the entire wavelength spectrum when reflected in all directions. This value for Venus is 0.77 [D. Williams, Venus Facts]. Albedo is important in the heat transfer of the aerobot due to the high reflectivity of light from the cloud layer. Since the system is just above this layer, albedo increases the solar loading. The effective solar flux in the case of albedo is changed and uses Equation 2.1.4.2 to find the extra solar loading. The equation below describes albedo's relationship with solar loading.

$$q_{effective} = q_{solar}(1 - albedo)$$

Equation 2.1.4.3

Radiation produced by the Venusian atmosphere is also taken into consideration when understanding temperature swings defined as the cold and hot cases. This radiation is governed by a fourth order system between the temperature of the aerobot system as well as the surrounding atmosphere. Emissivity (ϵ) plays an important role in defining the radiative feature of Venus. In the case of the aerobot the assumption that there is a perfect view factor (F) to Venus' atmosphere is made as well as the aerobot's temperature being 300 K, around room temperature. The Stefan-Boltzmann constant (σ) as well as the surface area plays a role in producing radiation. The governing equation is shown below.

$$Q_{radVenus} = \epsilon \sigma F A (T^4 - T_{surr}^4)$$

Equation 2.1.4.4

Finally, a major part of heat production is caused due to convective heat transfer. Convection requires a fluid, liquid or gas, to transfer heat through a surface. In this particular case, Venus' high winds produce this convective heat transfer that isn't negligible and must be taken into account. This form of heat transfer is a linear function between the surface and surroundings of the aerobot. However, the convection heat transfer coefficient, h , is a new variable that influences the convective loading applied on the craft. Equation 2.1.4.5 symbolises this relationship of heat transfer through convection.

$$Q_{radVenus} = h A (T - T_{surr})$$

Equation 2.1.4.5

However, unlike thermal conductivity occurring in conduction, the convection heat coefficient isn't a value that can be found in a table. It depends on a few parameters

including environment conditions and the geometry where the heat transfer is occurring. These parameters are known as Reynolds number, Prandtl's number, and Nusselt's number. Reynolds number determines whether the flow of a fluid is laminar, smooth, or turbulent, chaotic. Reynolds number is the ratio of inertial forces and viscous forces occurring on the aerobot. In this case, Reynolds number is dependent on the wind speed (V), the geometric property (Lx), and Venusian atmospheres viscosity (ν) as seen in Equation 2.1.4.5.

$$Re = \frac{VLx}{\nu}$$

Equation 2.1.4.6

In the case of the altitude parameters mentioned previously, the upper and lower bound wind speeds are 90 to 60 m/s respectively. The viscosity of the Venusian atmosphere will be assumed to be based on carbon dioxide physical properties. This is due to the atmosphere being made up of 96.5% carbon dioxide making the other gases negligible. Prandtl's number describes the thickness of velocity relative to the boundary layer where heat transfer occurs. This property is dependent on Venus' dynamic viscosity (μ), specific heat (C_p), and thermal conductivity (k) as seen below.

$$Pr = \frac{\mu C_p}{k}$$

Equation 2.1.4.7

Nusselt's number is a dimensionless quantity that divides the heat transfer coefficient relative to convection heat transfer over conduction. Once the Reynolds number and Prandtl's number is calculated, they are plugged into a range of equations that provides the Nusselt number. The equation used depends on the geometry and the type of flow, laminar or turbulent. In the case of the aerobot, the Reynolds number was turbulent leading to the use of the equation below.

$$Nu_D = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re_D}{282,000}\right)^{5/8}\right]^{4/5}$$

Equation 2.1.4.8

Finally, once the Nusselt number is found, the heat transfer coefficient (h) can be found through the relationship below where "D" represents length. The heat load of convection can finally be calculated by using Equation 2.1.4.5 when the heat transfer coefficient is found.

$$Nu = \frac{hD}{k}$$

Equation 2.1.4.9

The heat transfer for the two main modes convection and radiation can be qualitatively analyzed through the equations previously mentioned. Through these modes of heat transfer, the aerobot will experience direct solar loading, solar loading due to albedo, radiative heat transfer from the venusian environment, and convective heat transfer due to Venus' wind speeds at the given altitudes. As mentioned previously, the aerobot will experience a hot and a cold case. These cases incorporate different physical properties including wind speed, temperature, atmospheric pressure, density, and etc. The heat map below describes the hot case where temperatures rise up to 348 K with no thermal controls. The net heat transfer into the system is 1915 W of heat.

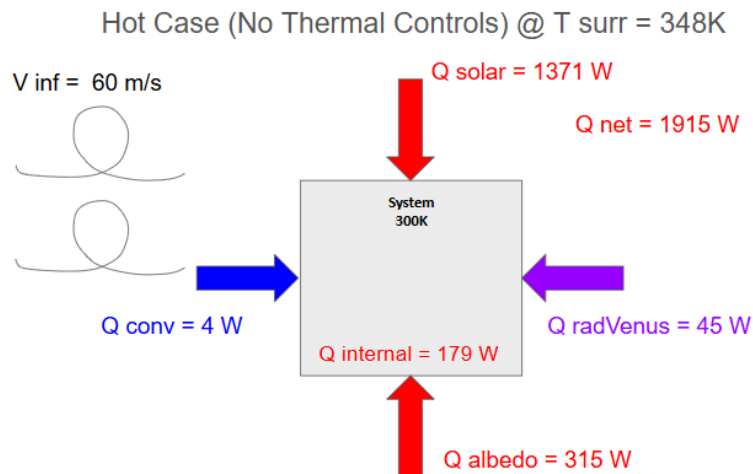


Figure 9

The heat map in the bottom figure represents the cold case analyzed with no thermal controls at temperatures of 230 K. The total heat into the system is 1829 W.

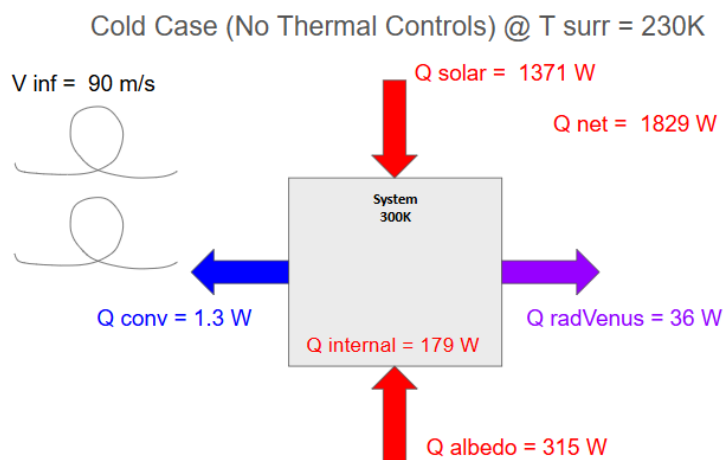


Figure 10

2.1.4.1 Thermal Control Subsystem Requirements

The thermal subsystems play an important role in mitigating the heat transfer of the aerobot system. The Aerobot shall maintain temperature ranges of all the system components. These temperature ranges shall be within operation standards where the components can operate accurately for their intended purpose. Thermal control of these components shall be implemented through the use of selective thermal coatings, body mounted radiators, and thermal electric coolers. Table 2.1.4.1 tabulates the requirement criteria of the thermal subsystem.

Table 2.1.4.1 Thermal Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
TH-01	System shall remain within 10 to 40 °C operating temperatures	System must keep operating temperature to survive full mission	SYS-01	-	Inspection	Blank
TH-02	System shall incorporate cooling techniques to maintain operating temperatures	System must remain at operating temperatures for instrumentation survival	SYS-02	TH-06, TR-07, TH-09	Inspection	Met
TH-03	System shall maintain structural integrity of the Aerobot while preventing unwanted thermal expansion	System must maintain structural integrity through operating temperatures	TH-01	-	Analysis	Met
TH-04	System shall have methods of insulation to protect from extreme heat	System must keep temperatures constant	TH-02	-	Analysis	Met
TH-05	System shall shield and have protective exterior	System must protect instruments inside	SYS-01	-	Test	Met
TH-06	System will have thermal coatings	System will have thermal coatings to block heat and radiation projected on aerobot	TH--02	-	Test	Met
TH-07	System will implement radiators	System radiators will work as temperature regulation and cooling technique	TH-02	TH-08	Test	Met
TH-08	Thermal coatings shall be applied onto radiator surfaces	Radiators must withstand heat loading	TH-06	-	Analysis	Met
TH-09	System will implement thermal electric coolers	The TECs shall transfer heat from internal components to the radiators via conduction	TH-02	-	Test	Met

2.1.4.2 Thermal Control Sub-Assembly Overview

Titanium for Outside of System

The thermal sub-assembly is made up of many components that come together to help regulate the temperature and radiation of the aerobot system. To start, the outer system consists of titanium to shield the aerobot of extreme heat and radiation that it'll face through the Venusian atmosphere. The grade 5 titanium of .012" thickness was chosen due to its proven ability to be used in aerospace applications as well as the fact that it will protect the aerobot greatly. This will surround the aerobot's six sides and be the material blocking our inner components from what it is surrounded by. Each side will add up to only 4.11 kg of weight which was a great weight efficient aspect that sold using this material for the mission even more. As stated in the mechanical subsection, titanium has proven to be the needed protection to heat and radiation that the outside of the aerobot will need for this mission.

This material, titanium, was also chosen for the mechanical subsection as the inner material for this system and was then considered for the outside after. Once compared to other possible choices, it was clear that titanium should be once again chosen. Titanium offers an amazing weight to strength ratio, and isn't too heavy but also gives the amount of strength that is needed. Corrosion and radiation was one of the biggest worries for this sub assembly due to it being the barrier that will block the system from those harmful conditions. However, titanium shows great resistance to both of those and any toxins that will be hitting the aerobot will not harm the system due to the titanium. Furthermore, as temperatures rise as we fall deeper into the Venusian atmosphere, the titanium will hold and withstand high temperatures because of its high melting point and ability to work in temperatures as high as 400 celsius.

Titanium will be the perfect material for this mission and will be very effective in protecting the aerobot from heat, radiation, corrosion and anything the system will be presented with. It will reflect and absorb heat and radiation, and will protect all of the inner components. Finally, because of the past aerospace applications it's been used in. It has a TRL of 8 and won't need further testing.

Thermal Coating

The thermal coating selected for the aerobot was the silver vaporized deposited thermal coating. The silver vaporized thermal coating is essentially a thin-film reflective layer that is made of deposited silver sprayed onto a surface that is fused with physical vapor deposits (PVD) that enhance thermal properties of the coating. The silver vaporized deposited coating provides optimal thermal properties where around 96% of the UV rays are reflected. In this case the coating has a very low absorptivity and emissivity. This allows the vehicle to mitigate against the intense solar loading and venus' sky radiation entering the vehicle. In situations where radiative heat transfer must be minimized, low-emittance metallic finishes are often used in spacecraft applications [Gilmore, pg. 143]. Due to the smaller size of the aerobot system it's

optimal to use these vaporized-deposited thermal coatings. Silver's vaporized-deposited coating has an absorptivity of 0.04 and an emissivity value of 0.02 which substantially decreases the heat transferring within the aerobot [Henniger, pg. 12]. The figure below shows the new values of heat added into the system with the applied silver vaporized coating for Venus' hot case.

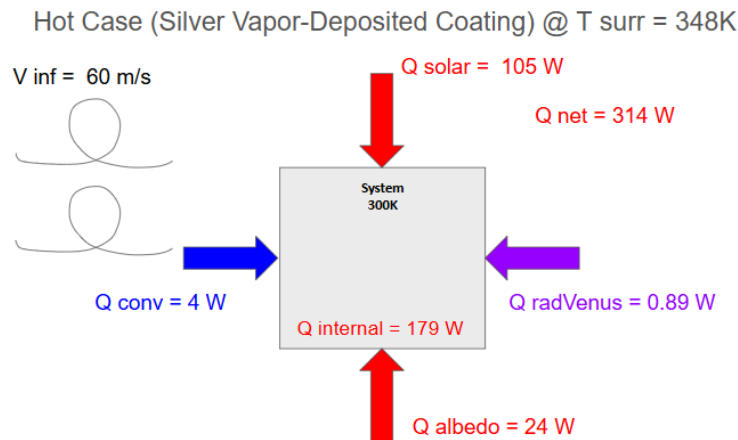


Figure 11

As seen there is a dramatic decrease in solar loading applied to the Aerobot as mentioned earlier. Figure 2.1.4.4 illustrates the cold case of the Venusian atmosphere while applying the silver vapor-deposited thermal coating.

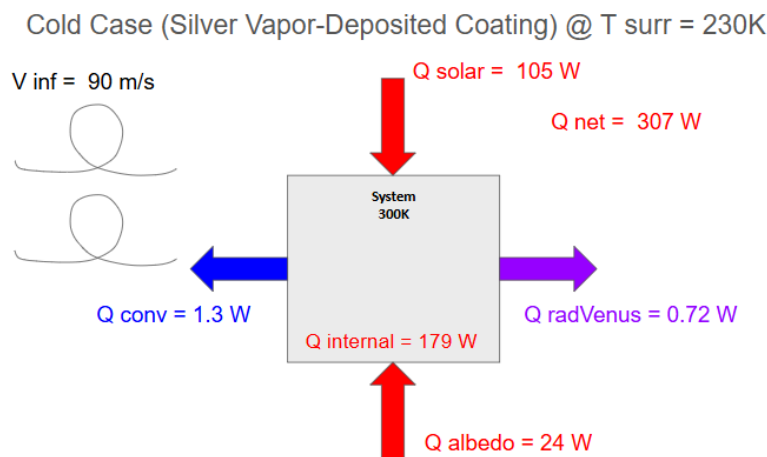


Figure 12

A few of the main threats of thermal coatings is degradation. This degradation can occur due to contaminants, UV radiation, atomic oxygen (AO), charged particles, and space debris to name a few. However, due to the duration of the mission being short at 48 hours the assumption that degradation is negligible is made since many of these issues occur over a longer period of time.

Radiators

A spacecraft's waste heat is rejected through radiator surfaces through infrared (IR) radiation. Radiators are designed in many ways including structural panels, flat-plate radiators mounted to the side of the spacecraft, and panels deployed after the spacecraft is in orbit. The design path chosen here is to implement deployable radiators that encompasses surfaces where the most critical components in the aerobot are located. The radiators will primarily focus on surfaces where instrumentation and power generation occurs since these are the most crucial components of the spacecraft. Most radiators are given surface finished with high IR emittance ($\epsilon > 0.8$) to maximize heat rejection and low solar absorptance ($\alpha < 0.2$) to limit heat loads from the sun [Gilmor, pg. 207]. White paint A276 will be sprayed over the radiator surface to limit heat loads on the surface as well as decreasing the radiator area sizing. The white coating has an emissivity value of $\epsilon = 0.92$ and an absorptivity value of $\alpha = 0.17$ which is typical for most radiator surface finishes [Henniger, pg. 8]. The area necessary to radiate out the remaining heat from the system is 0.95 m^2 . This value is calculated by using the worst case of heat loading on the vehicle, which in this case is the hot case at 314 W . Equations 2.1.4.10 and 2.1.4.11 analytically describe how the area of the radiators are calculated based on the thermal coatings added to the vehicle.

$$\Delta T_h = |T_{sys}^4 - T_h^4|$$

Equation 2.1.4.10

$$A_{radiator} = \frac{Q_h}{\sigma \epsilon \Delta T_h}$$

Equation 2.1.4.11

There consists of two radiators, one at each end below the top face of the vehicle. The radiators will collect heat through conduction where the instrumentations and the battery are placed near the walls. The thermal electric coolers will allow an ease of heat transfer to the radiators where the heat will then dissipate through radiation means. The isometric CAD design can be seen in the figure below.

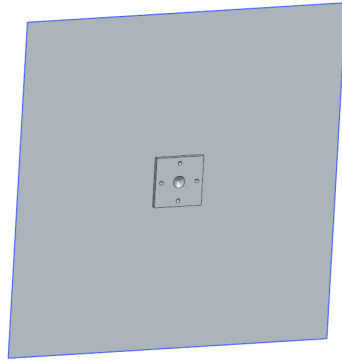


Figure 13

Each radiator is sized at 689 x 689 x 1.9 mm where in total it can dissipate a total area of 0.95 m^2 which is approximately the total radiator area needed to dissipate the rest of the heat after the thermal coating is added. The radiator is made up of Aluminum with a mass of 1.22 kg for each. This design is a custom fit from Sierra Space where they create custom sizings of radiators for consumer needs [Sierra space radiators]. The figure below is the supplier's version of the radiator.

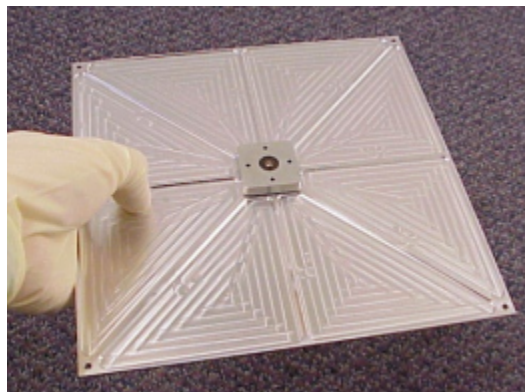


Figure 14

The design consists of a flat radiator panel integrally mounted on a heat switch. The radiator itself is mounted on the exterior of the vehicle as mentioned previously. The heat switch provides passive thermal control to the internal components of the aerobot. In the case of the design choice it'll be able to dissipate the rest of the thermal loading on the aerobot. As the temperature of the spacecraft increases above 300 kelvin, the switch conductance increases as well, allowing the excess heat to be transferred through the switch to the radiator and eventually to its surroundings. Also, the switch conductance decreases when the temperature of the aerobot decreases below the set point of 300 kelvin. This mechanism allows for the radiator to essentially act as an insulator by not taking heat out of the system.

Thermal Electric Coolers

The objective of thermal electric coolers (TECs) is to provide localized cooling to devices that require cold temperatures for adequate operations. These TECs are common in space applications and typically cool star trackers, infrared sensors (IR), and low noise amplifiers (LNAs) [Gilmore, pg 473]. TECs provide cooling via a phenomenon known as the Peltier effect, which is the cooling that results from the passage of an electric current through a junction that is created out of two dissimilar metals. Heat is then pumped from the cold junction to the hot junction. In this design, the implementation of TECs will be primarily used to mitigate instrumentation and power system temperature fluctuations. These TECs will transfer any heat conduction among close proximity components to the the structures surface that will then transfer to the radiators radiating the heat to the surroundings. Laird Thermal systems provides a robust catalogue of different off the shelf TECs that can be used for the majority of space applications. In the case of the design, the ceramic plate (CP) series provides TECs ranging from 1.8 through 118 W of cooling capacity which is well above what is needed for the mission. More specifically, MFG part number 63595-501 is the TEC used for the case of the aerobot system. It provides approximately 10.4 Watts of cooling capacity while weighing only 6 grams. Figure 2.1.4.5 illustrates the dimensions of the CP series TEC used in the mission.

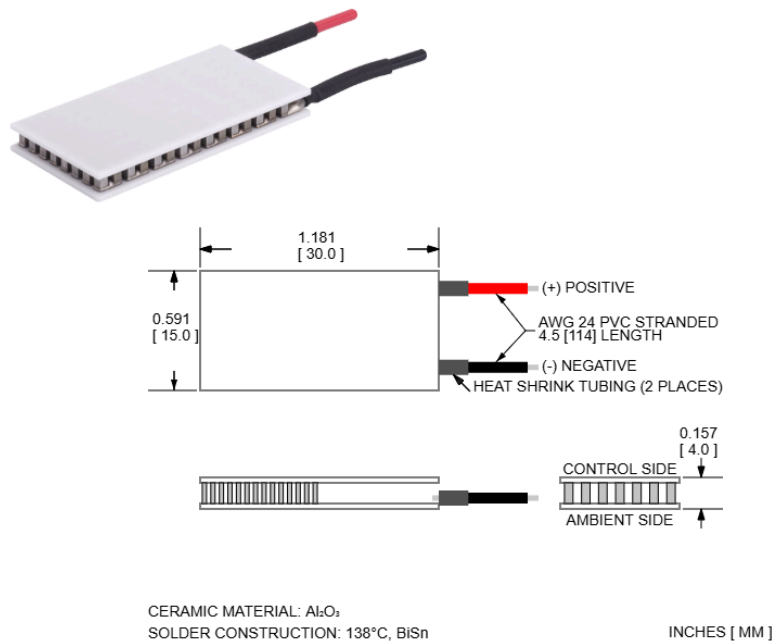


Figure 15

The specifications of the CP series TEC can be found in the figure below.

SPECIFICATIONS

Hot Side Temperature	27.0 °C	35.0 °C	50.0 °C
Qcmax ($\Delta T = 0$)	10.4 Watts	10.7 Watts	11.2 Watts
ΔT_{max} ($Q_c = 0$)	70.5°C	73.5°C	78.8°C
I _{max} (I @ ΔT_{max})	2.5 Amps	2.5 Amps	2.5 Amps
V _{max} (V @ ΔT_{max})	6.9 Volts	7.1 Volts	7.6 Volts
Module Resistance	2.54 Ohms	2.64 Ohms	2.84 Ohms
Max Operating Temperature	80 °C		
Weight	6.0 gram(s)		

Figure 16

Operational temperature

Components that are sensitive to temperatures, specifically the battery, will be located in positions that provide adequate thermal stability. The table below represents typical spacecraft element operating temperature requirements [SMAD, pg. 686].

2.1.4.2-01 Table 9: Typical Temperature Requirements

Equipment	Operational (°C)	Survival (°C)
Avionics Baseplates	-20 to 60	-40 to 75
Batteries	10 to 30	0 to 40
Hydrazine Fuel	15 to 40	5 to 50
Solar Arrays	-150 to 110	-200 to 130
Antennas	-100 to 100	-120 to 120
Reaction Wheels	-10 to 40	-20 to 50

Keeping these typical temperature requirements in mind, the aerobot will have components relating to avionics, batteries, solar arrays, and antennas. The operating temperatures of each component can be tabulated below.

2.1.4.2-02 Table 10: Operating Temperatures of Aerobot Components

Operating Temperatures of Aerobot Components	
Components	Operational Temperatures (°C)
Battery	-20 to 60
Sample Pump	Max 55
Raspberry Pi Zero	-40 to 85
Radiators	-130 to 100
Thermal Electric Coolers	Max 80
Aeroglaze White paint A276	-150 to 104
Infrasound Sensor	-40°C to +65
Time of mass spectrometer	-70 to 420
System Temperature Range	-10 to 40

SWAP Analysis

The thermal subsystem can be boiled down to five different components including the Titanium, Silver vapor-deposited coating, white paint, the radiators, and TECs. These component specifications can be analyzed in a SWAP analysis. The SWAP analysis of the thermal subsystem is detailed in the table below.

2.1.4.2-03 Table 11: SWAP Analysis of the Thermal Subsystem

SWAP Analysis of Thermal Subsystem			
Components	Size	Weight	Power
Titanium	Volume: 1 m ³ Thickness: 0.304 mm	4.11 kg	N/A
Silver Vapor-Deposited Coating	Volume 6m ³ Thickness: 300 nm	.01888 kg	N/A

SWAP Analysis of Thermal Subsystem			
White Paint A276	Radiator area: 0.95 m ²	1.12 kg	N/A
2x Radiators	689 x 689 x 1.9 mm	2x 1.22 kg	N/A
2x Thermal Electric Coolers	15x10x4 mm	2x 0.006 kg	34.4 W
Total:	N/A	7.87 kg	34.4 W

2.1.4.3 Thermal Control Subsystem Recovery and Redundancy Plans

Titanium for Outside of System

The titanium for the outside of the aerobot does not have a traditional redundancy plan as other components would. There isn't a backup system there in case of the material suddenly breaking or falling apart. The surrounding structure is completely surrounded by titanium, which is a safety factor in its own sense due to it being a structural overdesign. The design won't need a recovery plan because the material has shown in the past that it is reliable in these types of missions.

For recovery, in any case for damage that would happen to the material, there would be no need for worry. The titanium will be fully shielding the outside material on each side of the aerobot. The six panels should have the needed integrity to survive through the trip. It's not likely for there to be immense damage done to the outside of the system and therefore there isn't a recovery system needed. If there was a need for titanium on a panel or side to be replaced before launch, that would be okay as it is easily replaceable. The structure is reliable and will not need a recovery plan for the mission.

Silver Vapor Deposited Thermal Coating

Due to this being a coating that will be sprayed onto the aerobot, it doesn't have a recovery plan in a backup system type of way. However, in case of physical damage the aerobot will have two coatings of this thermal spray so the extra layer will help in case of damage to the first layer. This thermal coating is intended to protect from heat and radiation, but won't protect anything physically.

As for redundancy, as stated previously the aerobot will have two coatings worth of spray. This will be the way to absorb more heat and radiation, and having two layers will help with heat flow.

The thermal electric coolers act as a redundancy feature that can mitigate heat within the aerobot system. The radiators and thermal coatings allow for the system to be completely in thermal equilibrium not needing the thermal coolers to mitigate heat transfer among the components. As a redundancy plan, if budget allows, more thermal coolers can be applied to mitigate against a complete failure of the radiator system. As for the radiator itself, the heat switch acts as buffer or insulator if the radiator becomes overheated and faulty. This built in feature allows the differentiation between the two heated bodies, the aerobot and radiators.

2.1.4.4 Thermal Control Subsystem Manufacturing and Procurement Plans

Titanium for Outside Material

Supplier: TMS Titanium

Backup Supplier: Titanium Industries, Inc (TI)

Narrative: TMS Titanium was chosen as the main, first supplier for the titanium because of the type of titanium it offers, which aligned with the team's wanted specifications. The titanium that Titanium industries offer is ideal for aerospace applications. Titanium is reliable to block heat and other types of issues the Venusian atmosphere will give the aerobot, therefore having an aerospace proven type of titanium will be even better. The titanium is sold in sheets and can be offered within specific sizes and dimensions which works for the team's goal. Also, TMS Titanium gave direct costs and delivery dates which was especially helpful as it gave a reliable goal estimated completion date. Titanium Industries was chosen because it also offered aerospace application titanium and offered almost everything TMS Titanium did. This is a great backup option for the team's choice of metal and can meet all the wanted requirements.

The expected lead time for a sheet of .304 mm titanium from TMS Titanium is 2-3 business days from the receipt of order.

The expected lead time for a sheet of .304 mm titanium from TI wasn't specifically stated but shouldn't take more than 5 business days.

Silver Vapor Deposited Thermal Coatings

Supplier: Coulter, LLC

Backup Supplier: Huntington Ingalls Industries (formerly Alion and IITRI)

Narrative: Coulter was chosen because of their reliable and cost effective silver deposited thermal coating. They provide vacuum metallization and spray on coating services which include silver vapor deposited coatings. This mission will implement that coating because of its affordability and application on the aerobot. This type of coating is used for its low emissivity and low absorptivity. This means it won't absorb heat or radiation as much as other coatings and will also deflect it off the craft. The white silver

coatings usually don't have any type of significant degradation from any UV radiation and won't be a problem for a two day mission or less.

The expected lead time for the silver deposited thermal coating from Coulter is 5-7 business days from the receipt of order.

Thermal Electric Coolers

Supplier: Laird Technologies

Backup Supplier: Custom Thermoelectric

Narrative: Laird Technologies' broad family of thermal electric cooling systems offers design engineers with a wide range of cooling capacities, temperature differentials, form factors, finishing options and thermal cycling capabilities. Custom builds are also implemented for any design requirements needed for each space mission. This is quite an advantage since they make products for both large and small space missions. Laird thermal systems offers several product lines illustrated in a perceptual map in the figure below as a general guide as to where each product family fits with respect to their thermal attributes.

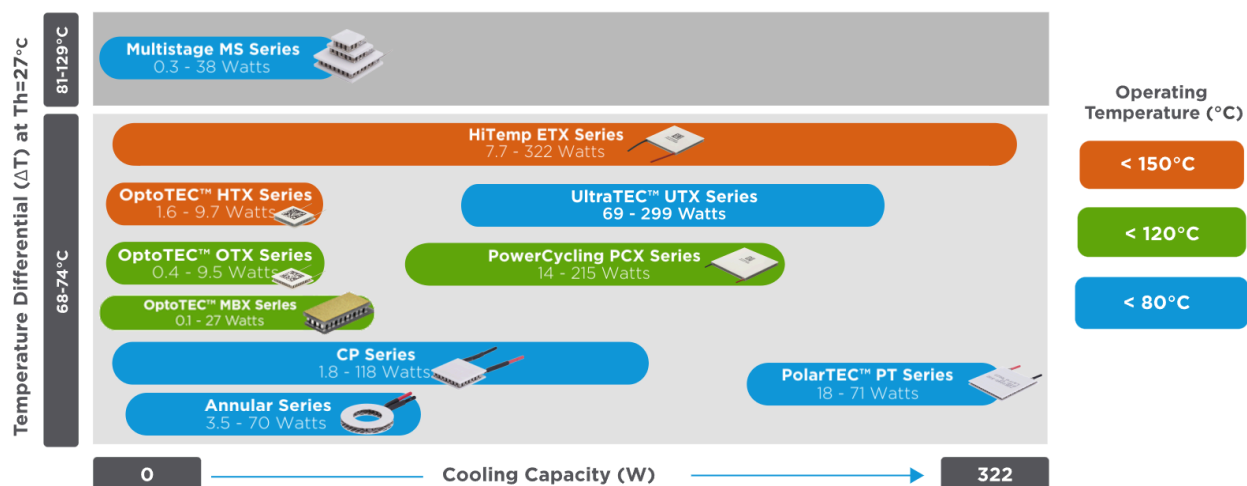


Fig 17

Product models including the UTX series, CP series, and PT series all provide adequate thermal control for the scientific components on the mission. Custom Thermoelectric provides a variety of thermal electric coolers primarily for smaller spacecraft. If costs become an issue Custom Thermoelectric provides good quality thermoelectric coolers at a reasonable cost.

White Paint A276

Supplier: Socomore

Backup Supplier: Huntington Ingalls Industries (formerly Alion and IITRI)

Narrative: Socomore provides reliable and cost effective sprayable thermal control coatings. This mission will implement Chemglaze A276 white paint based on its affordability as well as ease of application on the surface of the craft. This particular type of white paint is primarily used for short term missions which is perfect in this case. Socomore detailed technical report of the paint's properties as well as cost effectiveness and mission duration has led them to be the primary supplier. However, if the coating doesn't survive testing procedures for degradation, SG121FD white paint shall be the substitute. SG121FD white paint has a medium degradation rate in comparison to A276 being the highest for end of life procedures. This paint is typically used for missions lasting at a medium range of around 3 years. Further observation indicates that application of SG121FD white paint doesn't result in critical thermal conditions in either cold or hot orbital cases. Huntington Ingalls Industries (formerly Alion and IITRI) provides the SG121FD at a higher price point than that of the A276 but has the same difficulty of applying the coating on the spacecraft. Overall, using the planetary remote sensing instrument to estimate the SER it comes out to around 56.5 months for the thermal subsystem. There was very little information on the manufacturing website on this particularly.

Radiators

Supplier: Sierra Space

Backup Supplier: Innovative products and engineering

Narrative: Sierra space was chosen for implementation of the radiators due to their simple design. The radiator can be custom sized for any space mission application and is initially used for smaller sized satellites. The design consists of a flat radiator panel integrally mounted on a heat switch. This heat switch allows for mitigating against heat from the radiator to transfer back into the aerobot system keeping the two separate. Single panels can be used to control the temperature of specific components or multiple panels can be used to control the temperature of the entire spacecraft. The body mounted radiators are light weight and low cost with a conductance limit at Closed: 607 W/m² -C and Open: 7.8 W/m² -C. This conductance allows temperatures to remain between -10 °C to +50 °C which is perfect for the mission requirements.

2.1.4.4-01 Table 12: Thermal Control Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
TH-01	System shall remain within 10-40 Celsius operating	Inspection	Must perform within certain temperature range	Calculate total heat needed for every instrument to work, and

	temperatures			create ways to keep it down
TH-02	System shall incorporate cooling techniques to maintain operating temperatures	Inspection	Must cool down system as a whole	Test different methods of cooling to meet requirement
TH-03	System shall maintain structural integrity of the Aerobot while preventing unwanted thermal expansion	Analysis	Analyzing and comparing many types of materials will result in finding the best one for this mission	Must be composed of sturdy material that won't allow for heat build up . Compose a material search and comparison
TH-04	System shall have methods of insulation to protect from extreme heat	Analysis	Through observation and seeing how two different platings will affect heat flow, we will make this method work	Create outer shell and observe effects
TH-05	System shall shield and have protective exterior	Test	Shielding can be verified through a structure and fixture review	Inspect panels on sub assembly
TH-06	System will have thermal coatings	Test	The thermal coatings protect the system from heat and radiation. Testing which thermal coating has the lowest absorptivity and emissivity will confirm best one	Analysis on thermal coating applications and heat onto them to view results
TH-07	System will implement radiators	Test	Compatibility can be verified through a structure and fixture review	Inspect implementation points
TH-08	System will implement thermal electric coolers	Test	Testing the radiators with heated systems will ensure its ability to cool those systems down	Test assembly in the aerobot most heated systems w

On several occasions, significant uncertainty about the parasitic heat load on a thermal electric cooler can be verified through a recommended heat load testing. Such tests can be used with an oversized radiator and a possible heater with a dedicated power supply for independent hot-side temperature control. However, a temperature controlled heat sink can be used as well. Thermal runaway can also be a risk factor in TECs which may arise from constrained applications such as limited radiator area. This can be verified by reducing the thermal resistance between the TEC hot side and the heat sink. Thermal runaway as mentioned above is a condition in which temperature rises at the radiator necessitates an increase in drive power to the TEC. Therefore, causing a further increase in temperature at the radiator. In the case of this mission, TEC regulatory requirements will be tested through an environment similar to that of the Venusian atmosphere. Through this testing we can verify that the TEC will provide the

proper cooling capacity in mitigating heat transfer among the internal components of the aerobot and properly transmitting it to the radiators. Testing operating temperatures during this procedure will be crucial in verifying the TECs.

In the case of the radiators, the verification process of the heat switches are essential for the radiators to remain in operating temperatures. The switch conductance decreases when the temperature of the spacecraft drops below the set-point temperature. This insulates the spacecraft from the colder radiator panel and allows it to stay warm using a low-level of standby power. Therefore, the main aspect in verifying the heat switch would be to see if it's mitigating the radiator temperature spilling into the system. Another way to view this is to run an analysis and see how much heat leak can the aerobot manage. In other words a Switching Threshold Test must be performed. Also, a thermal cycling test will be performed. This test will allow for the engineer to verify that the heat switch is activating properly under different heating conditions as well as response to heat transfer through conductance.

2.1.5 Payload Subsystem Overview

Introduction

The atmosphere of Venus presents many hazards to the aerobot. Its carbon dioxide-rich atmosphere exerts 90 times the pressure of Earth's atmosphere and creates extreme surface temperatures reaching 737 K (Gillmann et al. 2022; Williams 2024). Volcanic activity appears to occur randomly rather than along organized plate boundaries, releasing sulfuric gases that contribute to Venus' thick, reflective cloud cover and furthering drive atmospheric heating (Smrekar et al. 2024). Extreme radiation exposure is a serious challenge for missions to Venus. Venus lacks a protective magnetic field, which makes it vulnerable to solar wind (Titov et al. 2007). This vulnerability exposes the planet to high levels of solar radiation. During solar flares, radiation spikes to 10–100x its average amount. Other atmospheric challenges include limited optical visibility, sulfuric acid rain, extreme wind speeds, and material decomposition.

Nonetheless, the aerobot aims to study many of the dangerous phenomena, primarily the volcanic activity and atmospheric composition. As such, the science instruments must simultaneously be capable of observing the planet, and isolated from it.

The science payload is supported by the CDH subsystem, which collects and transmits the data back to the orbiter and back to Earth. The CDH also controls when certain instruments power on, power off, take measurements, and calibrate themselves, in accordance with the sampling schedule and overall ConOps. The payload is also supported by the power subsystem, which works with CDH to ensure that each subsystem is fully powered when it needs to be operational and powered down when necessary. The payload is also supported by the thermal subsystem, which keeps the systems from becoming either too cold or too hot. Finally, the mechanical subsystem supports all other subsystems by providing the shell which isolates the aerobot's insides

from the harsh conditions of Venus. The mechanical subsystem also provides a vibration isolation mechanism to protect the subsystems during launch and during more turbulent portions of flight. Finally, the mechanical subsystem provides sample pumps which support the scientific instruments whose research is dependent upon interacting directly with atmospheric particles and provides a window for the Longwave Infrared Camera to see through.

Infrasound sensor

The purpose of the infrasound sensor lies in the second science objective of team Aether Solaris: Determine if modern volcanic or tectonic activity is influencing Venus's atmosphere. Infrasound waves are emitted by volcanic eruptions on Earth and fall below the range of human hearing, commonly propagating below 20Hz, and usually falling between 20 and 0.1Hz (McNutt et al, 2015). On Earth, volcanoes are not the only source of infrasound - it's commonly emitted by ocean waves, supersonic aircraft, nuclear explosions, mechanical/industrial sources, satellite re-entry or de-orbiting, avalanches, and rocket launches. (CTBTO, "Infrasound monitoring") However, on Venus, these phenomena do not happen as far as current science can discern, meaning it is a strong method of fulfilling this science objective, although data from all four science payload instruments will be vital to proving or disproving the existence of continued volcanic or tectonic activity on the surface of Venus.

The infrasound sensor chosen for this mission is the Chaparral Model 60-UHP2 Infrasound Sensor, developed by Chaparral Physics. The specific model selected by team Aether Solaris was designed for near field volcano monitoring and other large amplitude acoustic events (Chaparral Physics 2025). It weighs just 0.2 kg, takes up very little space (9.252 cm diameter, 4.29 cm tall), and has an operating temperature ranging from -40°C to +65°C. (Chaparral Physics 2025) Infrasonic sensors work by measuring ultra-low frequency vibrations and often operate by measuring pressure variations or particle displacement. (Exploring Infrasound 2024) Some infrasound sensors use piezoresistive pressure sensors, while others use capacitor sensors. (Liu et al, 2023)

The Chaparral sensor selected for this mission detects pressure changes from low-frequency sound waves (Chaparral Physics 2025) and has a sensitivity of 0.01 V/Pa at 1Hz, reaching a noise floor of 0.025 Pa at 1Hz.

TOF-MS

The Time-of-Flight Mass Spectrometer (TOF-MS) is one of the core instruments onboard the Aether Solaris mission. Its primary purpose is to analyze the chemical composition of complex gaseous environments with high sensitivity and speed. This instrument supports both scientific objectives of the mission: the atmospheric and geological analysis of Venus' environment. The TOF-MS will play a critical role in detecting and identifying atmospheric species, specifically trace gases, isotopes and potential biomarkers. This will be possible to achieve through the spectrometer's ability to measure the mass-to-charge ratio of ionized particles. The analytical resolution of the TOF-MS allows for differentiating between chemically similar species, such as sulfur dioxide (SO₂) versus hydrogen sulfide (H₂S), or between isotopes like ¹²CO₂ and ¹³CO₂. The further analysis of which will make it possible to further the knowledge on photochemical processes, gas cycling, and the anomalies origins in Venus' atmospheric

composition (Arevalo et al. 2019; Radke 2023), fulfilling the overarching science goal outlined in the Decadal Question 6.4: “How do planetary surfaces and interiors influence and interact with their host atmospheres?”. Given that the TOS-MS detection limits are in the parts-per-billion (ppb) to parts-per-trillion (ppt) range, makes it particularly well-suited to trace organic compounds and potential biosignature gases, including phosphine (PH_3), methane (CH_4), ammonia (NH_3), and certain nitrogen- or sulfur-bearing species (Radke 2023; SepSolve Analytical 2023). These gases have short atmospheric lifetime and could potentially be of a biological origin and thus are of high interest to astrobiology. Furthermore, the ability to identify isotopic ratios such as D/H or C/O contributes to broader planetary evolution studies and comparisons with Earth (Webster and Mahaffy 2012).

As described in 1.7 the TOF-MS operates in three primary stages: ionization, acceleration/separation, and detection. For this mission, the ionization stage will commence as the atmospheric samples are collected through an intake port and first ionized through electron ionization (EI) method. This implies that a beam of electrons will dislodge the electrons from neutral molecules and form positively charged ions. Throughout the second stage, the ions are then accelerated into a flight tube under the same electric potential. Since all ions receive equal energy, their velocity is inversely proportional to their mass, which means that lighter ions travel faster than heavier ones. During the third stage of operation, the ions will reach the end of the tube where the detector (electron multiplier) is located. Here their signal will be used to compute their time-of-flight and, subsequently, their mass-to-charge ratio, which will be recorded by the computer. This method was described by de Hoffman and Stroobant and was successfully utilized in the previous missions by allowing for full-spectrum mass data acquisition (2007). During this mission, it will allow for continuous, high-throughput sampling of Venus' environmental composition as the aerobot descends through various atmospheric layers.

The TOF-MS will operate over a mass range of 1–5000 amu (base requirement for this mission is 100-300 amu), allowing detection of both simple inorganic gases and large organic molecules. Its mass resolution ($m/\Delta m$) of 5000-46000 FWHM also exceeds the requirement and will allow for precise isotope ratio analysis. Its importance lies in interpreting volcanic outgassing (that is very elusive/short-lived), atmospheric cycling, and photochemical equilibrium (Radke 2023). For example, if the SO_2 spike will be identified in the lower cloud layers of Venus' atmosphere, it will indicate recent surface activity (Astronomy BS 2025). Additionally, the TOF-MS complements other payload instruments such as UV-spectrometer and Infrason detector, by providing molecular-level confirmation to photochemical or seismic events that will be picked up by other sensors.

Venus's atmosphere is harsh and presents this mission with a range of environmental challenges. Its high acidity (sulfuric acid aerosols), elevated surface temperatures ($\sim 460^\circ\text{C}$), and pressures reaching up to 92 bar (Williams 2024) have defined many of the mission's design constraints and operational requirements. TOF-MS instruments have demonstrated robustness in corrosive and low-pressure environments when installed within properly shielded enclosures (such as the aerobot payload) and supported by effective thermal control systems (Radke 2023). To mitigate the risk of environmental degradation over the course of the mission, the instrument will

be housed in a thermal-regulated enclosure with a nickel base coating to resist chemical corrosion. The outer thermal shell will incorporate a layer of Grade 5 titanium, known for its high strength-to-weight ratio and resistance to both acid corrosion and thermal stress. For temperature regulation, the aerobot exterior will feature two radiators. One will be mounted on the bottom and another on the side of the payload enclosure. This will allow it to dissipate excess heat absorbed from solar and atmospheric sources. Inside the payload enclosure, an electric cooler will be placed between the instrument array and the radiator walls, making sure that the thermal insulation and active regulation of internal temperatures are maintained. The TOF-MS will also require a high-voltage power subsystem for ion acceleration and detector operation, and data processing support to manage the high inflow of spectral data.

SPICAM

SPICAM (Spectroscopy for Investigation of Characteristics of the Atmosphere) was chosen for the Aether Solaris mission as the core UV spectrometer based on its heritage from Mars Express with modifications for Venusian conditions. Its dual-channel design combines a 180–320 nm ultraviolet spectrometer and near-IR spectrometer. It will enable solar/stellar occultation measurements and nadir observations. The sensor unit consists of an off-axis parabolic mirror and CCD (Charge-Coupled Device) detector which in result achieve 1.5 nm spectral resolution. (Bertaux et al, 2006) Such resolution is critical for detecting ozone, sulfur dioxide, and aerosol layers through differential absorption spectroscopy. With a 1 km vertical resolution and 0.5° field of view, the instrument's compact design (4.7 kg mass, 18W power) balances performance with mission constraints and could produce informative atmospheric profiles.

ASPERA-4 (Analyzer of Space Plasmas and Energetic Atoms) is an essential counterpart of the SPICAM that will investigate atmospheric erosion mechanisms using four sensors. The Neutral Particle Imager maps global ENA fluxes with 5° angular resolution, while the Ion Mass Analyzer resolves H⁺, He⁺, and O⁺ ions up to 20 keV/q. A rotating sensor assembly provides 4π steradian coverage, needed to characterize solar wind interaction with Venus' ionosphere. (Bertaux et al, 2006) The magnetometer (MAG) employs dual triaxial fluxgate sensors (one mounted on a 1-meter deployable boom to measure magnetic fields from 4 nT to 2 μT). Differential measurements between the boom-mounted and body-mounted sensors enable precise separation of spacecraft-generated fields from Venus' induced magnetotail. (Bertaux et al, 2006)

VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) combines a 0.25–1 μm imaging channel with a 1–5 μm high-resolution spectrometer. Cooled HgCdTe detectors achieve 0.5 K temperature accuracy for cloud-top dynamics analysis, while atmospheric transparency windows at 1.01 and 1.10 μm permit surface thermal emission mapping. (Bertaux et al, 2006) The Planetary Fourier Spectrometer (PFS) utilizes a double pendulum interferometer to profile atmospheric temperature structure between 55–100 km altitude, with 2 cm⁻¹ spectral resolution across 0.9–5.5 μm for tracking CO₂ absorption bands and trace gas distributions. (Bertaux et al, 2006)

The Venus Radio Science experiment (VeRa) employs X-band (8.4 GHz) and S-band (2.3 GHz) coherent signals for bistatic radar measurements and atmospheric occultation. Phase stability better than 0.1 mm/s enables derivation of neutral atmosphere density profiles with <100 m vertical resolution below 90 km altitude, while

differential Doppler measurements characterize ionospheric electron density gradients. Complementing these instruments, the Venus Monitoring Camera (VMC) provides context imaging through four spectral bands (365, 513, 965, 1010 nm), tracking cloud motions at 50 km altitude with 19° FOV and autonomous exposure control for dayside/nightside transitions. (Jean-Loup Bertaux, n.d.) This synergistic payload architecture addresses key mission objectives through coordinated observations – SPICAM and PFS constrain vertical atmospheric composition, while ASPERA-4/MAG quantify atmospheric escape processes. VIRTIS and VMC provide global dynamic context, with VeRa delivering precise atmospheric structure measurements. All instruments leverage flight-proven designs modified for Venus' extreme environment, ensuring reliability within mass/power constraints. (Jean-Loup Bertaux, n.d.)

LIR

The Longwave Infrared Camera (LIR) was chosen as a core payload instrument given its relative small mass and power requirements. It integrates efficiently with the power and data handling subsystems of the aerobot and its simple design and operational autonomy (requiring minimal real-time control) make it suitable for the Aether Solaris mission. The LIR is a thermal imaging instrument and its primary purpose is to measure cloud-top temperatures across Venus's atmosphere (in the 8–12 μm wavelength range). These measurements are important for detecting dynamic atmospheric phenomena such as thermal tides, stationary gravity waves, and large-scale circulation patterns (Lee 2007). The LIR directly supports the mission's objective of understanding how geological and atmospheric processes interact—addressing Decadal Survey Science Question 6.4: *“How do planetary surfaces and interiors influence and interact with their host atmospheres?”*

The LIR will be making continuous observations of Venus's thermal emission at the cloud-top level, allowing researchers to study the spatial and temporal distribution of temperatures across the planet's upper atmosphere. Even the small variations in cloud-top temperatures can be useful to understand features that are typical of Venus's atmosphere (Fukuhara et al. 2011; Lee 2007). For example, during the Akatsuki mission, the LIR was instrumental in identifying standing gravity waves above Aphrodite Terra, which may have been linked to surface topography influencing atmospheric flow (Taguchi et al. 2007). Ather Solaris mission aims to perform similar observations over the Mont Maat region and close by possibly active volcanic areas.

The LIR camera operates using an uncooled micro-bolometer array, an infrared detector technology. Micro-bolometers detect infrared radiation by measuring minute changes in the electrical resistance of their sensor elements as they absorb thermal energy (Fukuhara et al. 2011). Unlike cooled infrared detectors, micro-bolometers operate under less constricting parameters, reducing their complexity, power consumption, and mass. This was another important consideration for the aerobot-based mission like Aether Solaris. The LIR onboard this mission will build upon Akatsuki's design, with upgraded readout electronics and outlined earlier thermal

isolation. Like all instruments onboard the Aether Solaris platform, the LIR must withstand the extreme environmental conditions of Venus's upper atmosphere. Although the location in the atmosphere for LIR usage will differ (the aerobot will float in layers with moderate temperatures (~50–70°C), the surrounding corrosive atmosphere will still pose the threat to the aerobot. To address this, most of the LIR enclosure will be protected with nickel base coating, except it cannot be used on the front optical interface of the instrument due to its opacity in the infrared spectrum (especially within the 8–12 μm range). To maintain functionality, the germanium window opening is mounted to offer the consistent infrared transmission (inspired by Akatsuki mission design) (Taguchi et al. 2007).

The LIR's broad field of view and temperature variations measurements will allow it to complement other instruments on the payload, such as the TOF-MS. The LIR will add some contextual data on where thermal anomalies or transient features may be occurring. Together, they will create a better picture of potential volcanic or tectonic activity and what may characterize Venus' atmospheric stability.

2.1.5-01 Table 13 Science Instrumentation Requirements

Payload Instrument	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?	Internal environment	External Environment	Placement
TOF-MS	Mass range: 100-300 amu	Enables detection of heavy molecules in the Venus's atmosphere (sulfuric acid clusters and biosignatures)	The system shall measure the composition of trace gases and complex molecular structures in Venus' middle atmosphere during descent	shall operate within a range of 100–300 amu	Test	Met	~27°C, ~1 atm pressure	55-60 Km Altitude, ~90 atm pressure, 465°C	Internally mounted within the aerobot, on a titanium frame, stabilized with a wire rope Vibration Isolation System (VIS). It connects to the outside via a PTFE-lined sample intake tube that draws atmospheric gas inward via pressure differential.
	Mass Resolving Power: ≥ 500 –1000 (FWHM)	Required to distinguish between molecules of similar mass (isotopes or molecular fragments). Critical for chemical identification in complex atmospheric mixtures		shall have a mass resolving power ≥ 500 –1000 (FWHM)	Test	Met			
	Sensitivity: 10^{-3} to 10^{-4} molecules/cm ³	Allows to detect trace gases in Venus' atmosphere, where important species may exist in very low concentrations		shall have a sensitivity of 10^{-3} to 10^{-4} molecules/c m ³	Test	Met			

	Integration time: $\leq 1s$	High temporal resolution during the descent allows for reducing motion-related signal degradation and improves vertical profiling		shall integrate data at $\leq 1s$ intervals	Analysis	Met			
UV Spectrometer	Wavelength range: 180-400 nm	Covers UV absorption bands for species like SO_2 , O_3 , and potential unknown absorbers	The system shall detect UV-absorbing species and determine their vertical distribution across Venus' upper atmosphere	shall operate across 180–400 nm wavelength range	Test	Met	$\sim 27^\circ C$, ~ 1 atm pressure	55-60 Km Altitude, ~ 90 atm pressure, $465^\circ C$	Internally mounted with external optical access. It performs solar and stellar occultation, limb scanning, and nadir viewing — requiring a clear view through the aerobot's outer shell, likely via optical window or port.
	FOV/ Spatial resolution: $\sim 1^\circ / \leq 1.5 km$ per vertical layer	Allows for vertical profiling of atmospheric composition with sufficient resolution to observe structure in the upper cloud decks and photochemical layers		shall have a field of view (FOV) of $\sim 1^\circ$ and a vertical spatial resolution of $\leq 1.5 km$	Analysis	Met			
	Effective Area: $\sim 0.6 cm^2$ or better	Ensures enough light is collected in Venus' dense cloud layers to generate high Signal-to-Noise-Ratio spectra* within short integration times		shall have an effective optical collection area of $\geq 0.6 cm^2$	Inspection	Met			

	Spectral resolution: $\leq 1.5\text{nm}$	Needed to resolve narrow UV absorption features of trace gases and confidently determine concentration profiles		spectral resolution shall be $\leq 1.5\text{ nm}$	Test	Met			
Longwave infrared Camera	Wavelength range: $8\text{-}12\mu\text{m}$	Falls within thermal infrared emission window, allows for detection of the heat radiated from the mid- atmosphere level; measuring temperature variations and cloud opacity through relatively transparent regions of the atmosphere	The system shall measure thermal emissions in Venus' mid-atmosphere to derive cloud opacity and temperature structure	shall detect within the $8\text{--}12\text{ }\mu\text{m}$ wavelength range	Test	Met	$\sim 27^\circ\text{C}$, $\sim 1\text{ atm}$ pressure	55-60 Km Altitude, $\sim 90\text{ atm}$ pressure, 465°C	Internally mounted, thermally regulated. Has an outward-facing infrared-transparent window for passive thermal imaging of Venus's atmosphere. Calibrates using an internal blackbody target.
	Integration time: $\leq 1\text{s}$	Required to prevent motion blur and capture rapid temperature variations during aerobot drift		integration time shall be $\leq 1\text{ s}$	Analysis	Met			
	NETD: $\leq 0.3\text{K}$	Ensures the camera can detect fine-scale thermal differences in the Venusian cloud structure and		shall have a Noise Equivalent Temperature Difference (NETD) of	Test	Met			

		monitor dynamic weather features		≤0.3K					
	Spatial resolution: 50 km per pixel	Needed to match the expected imaging scale from altitude to allow for detection of mesoscale atmospheric features (partially met)		spatial resolution shall be ~50 km per pixel	Analysis	Not Met			
Infrasound sensor	Wavelength detection range of 0.002-20Hz	Covers the broad spectrum of atmospheric infrasound, including signals from natural phenomena (volcanic activity/atmospheric turbulence)	The system shall monitor low-frequency atmospheric pressure waves to identify seismic, volcanic, or dynamic weather activity	shall detect pressure waves in the 0.002–20 Hz frequency range	Test	Met	~27°C, ~1 atm pressure	upper cloud deck of Venus, approximately 65 km above the surface	Internally mounted within the aerobot's shell. It is acoustically coupled to the external atmosphere through ports or structure, but not directly exposed to wind. Measures low-frequency pressure oscillations from inside.
	Frequency range of 0.01-10 Hz	Covers low-frequency sound waves from events like volcanoes/turbulence in Venus' atmosphere		usable signal frequency range shall include 0.01–10 Hz	Test	Met			
	Sensitivity of 45.13+/- 0.23 microV/Pa	Covers low-frequency sound waves from events like volcanoes or		shall have a sensitivity of 45.13 ± 0.23 μV/Pa	Test	Met			

		turbulence in Venus' atmosphere.							
	Level of self-noise 0.025 Pa or less at 1 Hz	Ensures infrasound detection is not masked by internal instrument noise		self-noise shall be ≤ 0.025 Pa at 1 H	Test	Met			

2.1.1.3. Payload Subsystem Recovery and Redundancy Plans

Table 14

Science Measurement Requirements		Baseline Performance Requirements		Instrument			
Physical Parameters	Observables			MS-TOF	UV-Spec	Longwave Infrared Camera	Infrasound Detector
Identify composition of Isotopic Ratios: (D/H, $^{12}\text{C}/^{13}\text{C}$, $^{32}\text{S}/^{33}\text{S}/^{34}\text{S}$) Compounds: (CO_2 , SO_2 , OCS , PH_3 , and other trace gases) and any unidentified UV Blockers through Venus's cloud layers.	Use a mass spectrometer to measure variations of biosignature gasses at different altitudes. As well as absorbance spectra in specific UV ranges, around 180 to 400 nm wavelength range.	Mass range (amu)	100-300 amu	●	●	●	○
		Mass Resolving Power	$\geq 500-1000$ (FWHM)				
		Sensitivity	10^{-3} to 10^{-4} molecules/ cm^3				
		Integration Time	$\leq 1\text{s}$				

Identify aerosol particle composition particularly SO ₂ , H ₂ S, CO, and other volcanic emissions as well as thermal anomalies associated with active volcanism	Measure and collect different SO ₂ , H ₂ S, CO, at different altitudes using UV and a mass spectrometer in the 180 to 400 nm wavelength range as well.	Wavelength Range	180-400 nm / 8-12μm / 0.002-20Hz	●	●	●	●
		FOV/ Spatial Resolution	~1°/≤1.5km per vertical layer / 50 km per pixel				
		Effective Area	~0.6cm ² or better				
		Spectral Resolution	≤1.5nm				
		NETD	≤0.3K				
		Frequency Range	0.01-10 Hz				
		Sensitivity	45.13+/- 0.23 microV/Pa				
		Integration Time	≤1s				
		Self-Noise Level Below 20 Hz	0.025 Pa at 1 Hz				

2.1.5.3 Payload Subsystem Manufacturing and Procurement Plans

Time-Of-Flight Mass Spectrometer

Supplier: Bruker (COTS)

Backup Supplier: Spacetek (COTS)

Narrative:

In order to obtain a Time-Of-Flight (TOF) mass spectrometer with the required mass range, mass resolving power, and other qualifications outlined in the STM Instrument Performance Requirements, team Aether Solaris has selected Bruker as the supplier for the mission's Mass Spectrometer. Bruker is a worldwide company specializing in scientific molecular research, analytical instrumentation, and life sciences. Their focus on life sciences is advantageous for the Science Objective of investigating biological processes. When searching for evidence of life, seeking the services of a company known for working within this field may lead to a greater degree of precision and an end product better suited for the needs of the mission, and this is part of the rationale for Bruker's selection as the primary supplier for the TOF mass spectrometer.

In the event that Bruker becomes a nonviable option for this instrument, Spacetek provides a promising alternative. Spacetek is a newer company specializing in TOF mass spectrometry and residual gas analysis for rugged environments. They also specialize in miniaturizing TOF technology - a definite advantage when considering the space and mass constraints of the overall aerobot and science payload. The rationale for placing it as the backup, rather than the primary supplier, is that it is a newer company and thus may have less experience in manufacturing and design. Furthermore, Spacetek is far smaller than Bruker, and may have reduced manufacturing capability as a result, leading to its status as a backup supplier.

The TRL of the Bruker TOF-MS is 5, because although it has never been flight-tested, it has been used extensively in laboratory settings. Furthermore, Bruker is a large and well-established company (Bruker, "History."). In the event that the team must source the TOF-MS from the backup supplier, the TRL would likely drop to 4, because the backup supplier is a newer company, one thus with less experience in manufacturing mass spectrometers.

The exact manufacturing and shipping time for a mass spectrometer from Bruker is difficult to find without contacting suppliers directly. However, it can be estimated based on other information. The SER, estimated by the MCET, is 53.2 months using the estimates for Planetary, Remote Sensing Instruments (Fields and Particles). Information for this calculation (total mass and total max power) was taken directly from Bruker's website (Bruker, High-Value Life Science)

Infrasound Sensor

Supplier: Chaparral Physics (COTS)

Backup Supplier: Seismo Wave (COTS)

Narrative:

Team Aether Solaris's selected infrasonic sensor is a commercially available item, and as such, it is preferred that it is obtained from the manufacturer, Chaparral Physics. In the event that they are unable to manufacture this particular infrasound sensor for this mission, they do offer several other models of infrasonic sensor which may be useful for the detection of volcanic activity and may be carried aboard the aerobot. Chaparral Physics was chosen in part because of their extensive record - they have been manufacturing infrasound sensors since the 1950s, and their designs have been used in harsh Earth environments, such as Antarctic ice fields. While this is not directly compatible with flying in the Venusian atmosphere, a long record of manufacturing for applications outside a lab environment inspires confidence that Chaparral Physics will be capable of providing a sensor to meet both the scientific and environmental requirements presented by this mission's various goals and constraints.

In the event that Chaparral Physics is not able to manufacture *any* infrasound detector for use on this particular mission, Seismo Wave offers similarly compact and portable infrasound sensors, thus making them a supplier with the capabilities to manufacture an infrasonic sensor meeting the requirements of this mission. Seismo Wave was chosen due to their record of producing infrasonic sensors within the Hz range required for this mission and their product's history of use in volcanology. Their SIS-1 sensor was considered as an infrasonic sensor for the mission's trade studies, and fell short on resolution and volume, but should still suffice in the absence of other options. However, given that their sensors are not specifically made with harsh environments in mind the way Chaparral Physics' are, they are the secondary rather than primary supplier.

Chaparral Physics's infrasound sensor has been given a TRL of 5 for this mission, because it was designed specifically with harsh environments in mind, but has never been flight-tested. In the event that the team has to opt for the backup supplier, the TRL would remain a 5, as Seismo Wave also specializes in compact and rugged infrasonic sensors.

The exact manufacturing and shipping time for an infrasound sensor is difficult to find without contacting suppliers directly. However, for Chaparral Physics, the shipping time for all of their products is generally below 90 days. One can be reasonably sure that this applies to the 60-UHP2 Infrasound Sensor, because COTS infrasound sensors are the main focus of Chaparral Physics. Because for this mission, one of their standard off-the-shelf products will be purchased, the 90-day shipping estimate should serve the programmatic purposes of this mission. According to the MCCET, the SER is 24.4 months.

Estimated lead time for the backup supplier was not easily accessible on their website, so the MCCET was used to provide an estimate. An infrasonic sensor falls into the category of body-mounted in-situ instrument, and this was used to calculate the SER, which is estimated to be 26.3 months using the estimates for Planetary, in situ Instruments. The information used to calculate this (total mass and total max power) was sourced directly from Chaparral Physics (Chaparral, "Infrasound Sensor.").

SPICAM UV Spectrometer

Supplier: Airbus Defence and Space/Astrium (COTS)

Backup Supplier: Sarspec (COTS)

Narrative:

Given that the selected science instrument has already been flown in a mission (the Mars Express flight), it is the preference of Aether Solaris to obtain it from the same supplier which created it for the Mars Express flight. The original manufacturer of the SPICAM was Astrium. However, in 2013, it merged with Cassidian to form Airbus Defence and Space, which is thus listed as the primary supplier above.

In the event that Airbus Defence and Space is unable to manufacture the spectrometer by the needed deadline or to the needed specification, Sarspec should be capable of providing a product of equal quality, given that their focus of manufacturing is on UV Spectrometers. Their products are commonly used in biology, and they offer a range of spectrometers operating at a range of wavelengths. Some of their products are also quite small, a definite advantage for the size constraints of the aerobot system. However, given that their products are not created with environmental resilience in mind - and that they were not the original manufacturers of the SPICAM UV Spectrometer - they are a secondary, rather than a primary supplier.

The TRL for the SPICAM UV spectrometer is 7, in part because it has flown before. If it is possible to obtain the SPICAM from Airbus, who originally manufactured it, this TRL makes sense. However, in the event that it becomes necessary to source the spectrometer elsewhere, the TRL would likely drop to 5, because the spectrometer would no longer have been prepared by the company that originally made it when it traveled to Venus aboard Mars Express.

The SER for the SPICAM UV Spectrometer is 33.4 months, using the calculations for Planetary, Remote Sensing Instruments (Fields and Particles). The information required for these calculations (total mass and total power) was sourced directly from a Journal of Geophysical Research article written about the spectrometer's capabilities. (Bertaux et al., "SPICAM on Mars Express.")

Longwave Infrared Camera

Supplier: NEC Space Technology (COTS)

Backup Supplier: Teledyne Technologies (COTS)

Narrative:

Given that this device has already been flown in a mission to explore Venus, it is the preference of Aether Solaris to obtain it from the same manufacturer which built it for the Akatsuki mission. That supplier is NEC Space Technology. Their manufacturing repertoire includes additional JAXA missions (the Hayabusa probe and the Kibo Japanese Experiment Module), which well proves their reliability in manufacturing for space travel.

In the event that NEC Space Technology is unable to manufacture the camera on time or at all, Teledyne Technologies could provide a suitable alternative within the timeframe. They specialize in cameras with a similar wavelength range to what the Longwave Infrared Camera has and to what is needed for this mission. Teledyne

Technologies also works within aerospace and digital imaging: their products were used in the 2009 upgrade of the Hubble Space Telescope, and they have partnered with both NASA and JAXA over the years. This history and focus on imaging and aerospace technology makes them a viable backup supplier.

The TRL for the LIR is 7, in part because it has flown before. If it is possible to obtain the LIR from NEC Space Technology, who originally manufactured it, this TRL makes sense. However, in the event that it becomes necessary to source the spectrometer elsewhere, the TRL would likely drop to 5, because the LIR would no longer have been prepared by the company that originally made it when it traveled to Venus aboard Akatsuki.

The SER for the Longwave Infrared Camera, according to the MCCET, is 31.7 months, based on the estimates for Planetary, Remote Sensing Instruments (Optical and Microwave) and assuming that the specifications of it remain unchanged from the Akatsuki mission. The data for the SER calculation was sourced from an Earth, Planets, and Space article discussing the specifications and performance of the LIR. (Fukuhara et al., "Longwave Infrared Camera.")

2.1.5.4 Payload Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAY-01	System shall carry instrumentation that will collect data	Inspection	Verify all instruments are present and properly mounted	Via inspection of the CAD drawings, it will be verified whether the science payload components are present and attached within the superstructure.
PAY-02	System shall be securely mounted within the aerobot's superstructure	Test	Secure mount must withstand operational stresses	Vibration and shock testing shall be employed to ensure the system is securely mounted within the aerobot's superstructure and will remain so throughout the mission.
PAY-03	System shall measure infrasound throughout the flight.	Test	Can be verified through modeling and analytical assessment of sensitivity in the expected conditions	The ability of infrasound sensor to measure acoustic waves at the frequency expected for this mission will be analyzed through Static Performance Tests, Tonal Dynamic Performance Tests, and Broadband Dynamic Performance Tests which have previously been used to test the Chaparral Model 60-UHP2 Infrasound Sensor
PAY-04	System shall record images of the Venusian atmosphere and surface throughout the flight	Analysis	Validated through optical simulation and performance modeling	The ability of the system to record thermal images shall be confirmed through ground-based simulations of the LIR
PAY-05	System shall record measurements of the atmospheric composition throughout the flight and search for gasses which would indicate volcanic/tectonic activity	Analysis	Modeling/ simulation-based analysis using expected flight data inputs	The ability of the aerobot to measure atmospheric composition will be validated via simulations based on expected mission events and schedule

Table 15

2.2 Interface Control

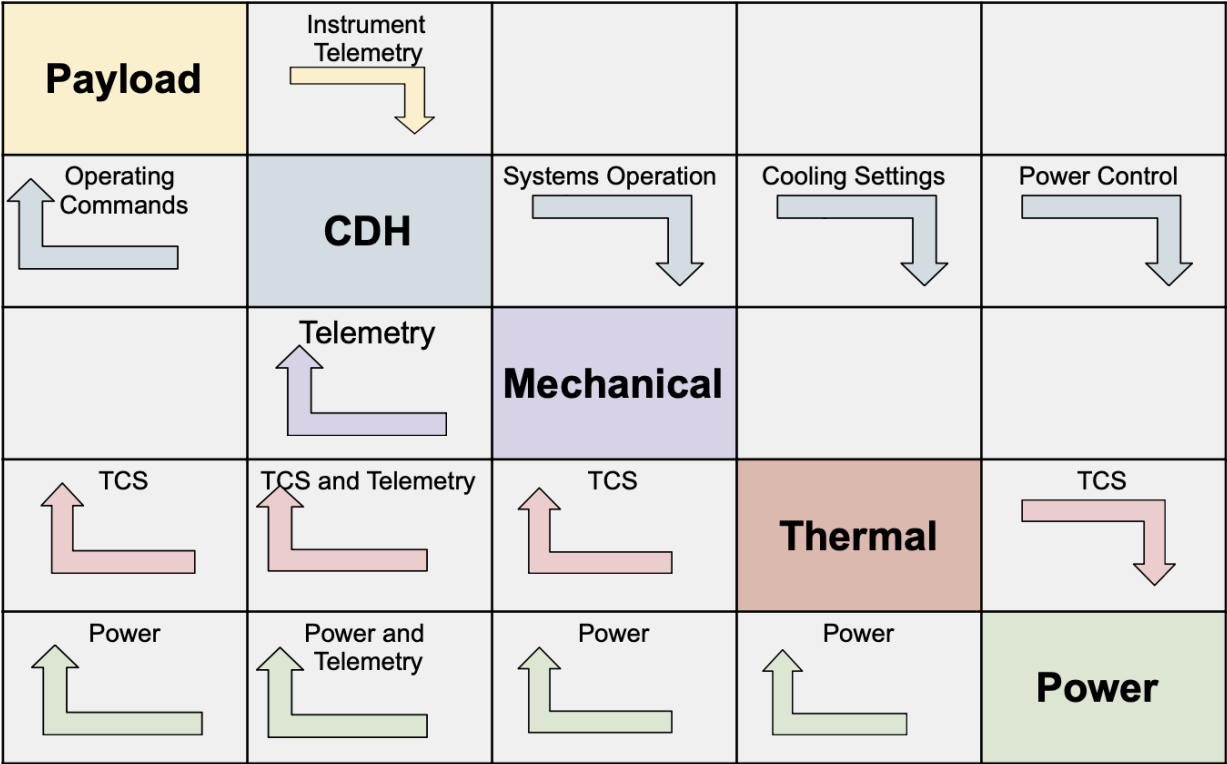
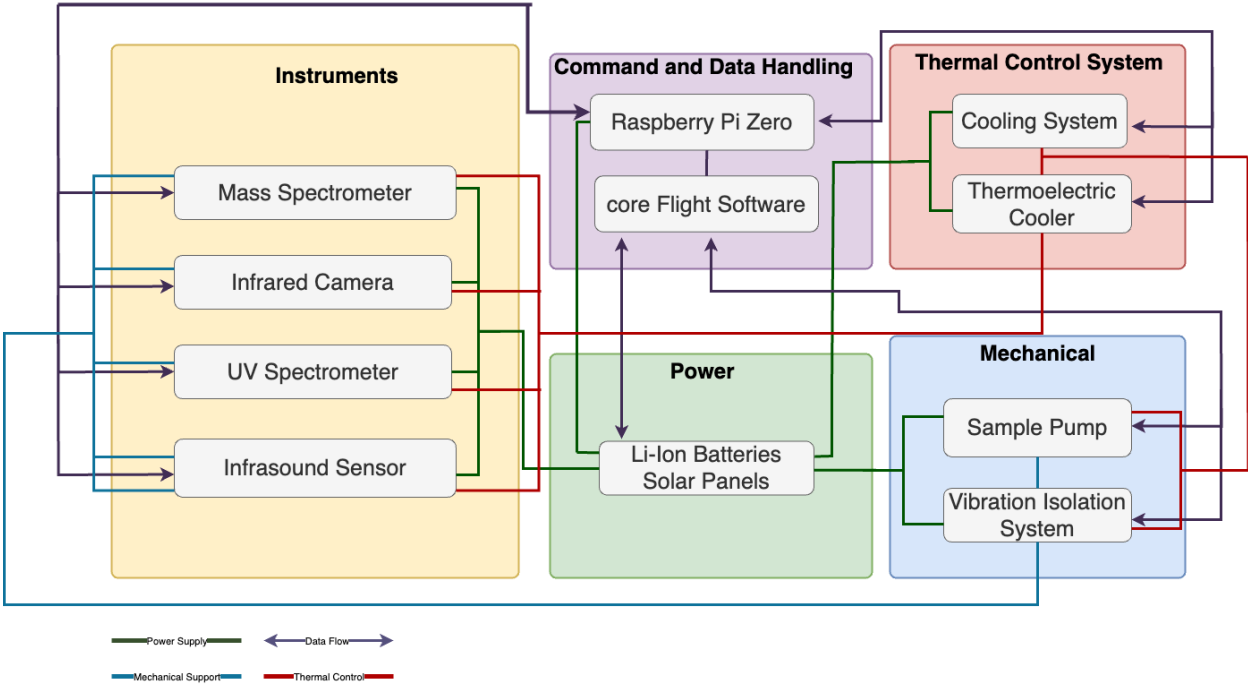


Fig.18

The diagram illustrates the connections between the multiple subsystems that work together to achieve the mission's objectives. These subsystems include Payload,

Power, Thermal Control, Mechanical and Command and Data Handling. Each subsystem has distinct responsibilities, and they exchange data and processes in order to ensure seamless operation. The heart of the subsystems is CDH, as it is the central processing unit that coordinates the system's operations. This subsystem consists of a lightweight computer, Raspberry Pi Zero, that runs the control software. The software being used is the core Flight Software and it manages data collection, commands and overall system functions. The Command and Data Handling subsystem communicates directly with the Payload instruments, storing and collecting its data for analysis purposes. It receives power from the Power subsystem in order to maintain software processes. It sends control signals to the Thermal control subsystem to regulate cooling as needed. In addition, connecting with the Mechanical subsystem consists of accessing structural status and receiving vibration dampening. The Payload consists of the scientific instruments that are responsible for data collection. The instruments and their functions are as follows: The Mass Spectrometer analyzes chemical composition, Infrared camera provides temperature mapping and detects thermal signatures, UV Spectrometer captures ultraviolet light to analyze its composition and the Infrared sensor captures thermal radiation in order to study temperature variations. These instruments rely on the Power subsystem to supply power. They send the data collected to be stored by the Command and Data Handling subsystem and it has its instrument temperature regulated by the thermal control subsystem. The Power subsystem consists of Li-Ion batteries and Solar Panels that provide energy to all the subsystems. The thermal control subsystem is made up of two components, the cooling system and the thermoelectric cooler. This subsystem regulates the heat dissipation and maintains operational temperatures for the sensitive parts. It prevents the instruments from overheating. The Mechanical subsystem provides two important aspects to the system, the sample pump and the vibration isolation system. This subsystem ensures the physical protection of the payload instruments, works with thermal control to dissipate heat and maintains stability for the command and data handling subsystem to prevent failure from mechanical disturbances.

3. 3 Science Mission Plan

3.1 Science Objectives

The proposed Venus aerobot mission sets out to accomplish two primary science objectives: (1) to identify potential biosignatures and key chemical processes within Venus's atmosphere, and (2) to determine whether modern volcanic or tectonic activity is currently shaping the planet's climate and surface environment. These goals were chosen based on the scientific need to understand why Venus experienced a runaway greenhouse effect while Earth remained habitable. Studying the chemical composition of Venus's atmosphere - particularly isotopic ratios (such as D/H, $^{12}\text{C}/^{13}\text{C}$, and sulfur isotopes) and trace gases like CO_2 , SO_2 , OCS , and PH_3 - can provide evidence of atmospheric disequilibrium or chemical anomalies that may be linked to biological or volcanic activity (Greaves et al., 2020; Arevalo et al., 2019).

The payload includes a Time-of-Flight Mass Spectrometer (TOF-MS) that will enable vertically profile trace gases and isotopes. It is capable of detecting atmospheric species down to parts-per-trillion levels (Radke 2023). A UV spectrometer

(SPICAM) will complement TOF-MS by identifying gas distributions, including SO₂ and Venus's unknown UV absorber (Bertaux et al. 2006). The Longwave Infrared Camera (LIR) will help detect thermal anomalies and create cloud-top temperature profiles to map circulation patterns and pinpoint transient heating that could be potentially linked to surface activity (Fukuhara et al. 2011). Finally, an infrasound detector will capture low-frequency acoustic signals from tectonic shifts or eruptions near Maat Mons to complement the other payload instrument results. Together, these instruments offer a layered and synergistic approach to understanding Venus's interior-atmosphere interactions, directly addressing Decadal Science Question 6.4: *How do planetary surfaces and interiors influence and interact with their host atmospheres?*

3.2 Experimental Logic, Approach, and Method of Investigation

Four primary scientific instruments, included in the payload for this mission, are bound to fulfill the mission's science objectives of detecting biosignatures and chemical processes in Venus's atmosphere and identifying ongoing tectonic and volcanic activity on the ground. The approach is grounded in vertical atmospheric profiling, spectral analysis, acoustic monitoring, and thermal imaging. There is a strong emphasis on integrating multi-instrument data collected across various altitudes within the Venus's cloud layer until the aerobot lands or disintegrates.

To fulfill the science objectives, data from each instrument will be used in conjunction with its peers to draw conclusions, and the presence and operation of several instruments within the science payload will function as a backup in the event that one should fail. For example, data collected by the UV-Vis spectrometer and the TOF-MS will give information about molecular composition of the atmosphere, and data from both will be used to draw conclusions on Venusian biosignatures and chemical processes. Evidence for volcanic and tectonic activity can come in the form of thermal anomalies (made visible by the LIR), infrasound (made visible by the infrasound sensor), and certain aerosols and gasses commonly associated with eruptions, particularly SO₂, H₂S, and CO. Data on aerosols and atmospheric makeup will be collected by both the TOF mass spectrometer and UV spectrometer. To increase the chance of a valid conclusion being drawn, several instruments will collect data relevant to each science goal, providing a cross-sectional view of the atmosphere and planet's surface.

In addition to this, each instrument shall be configured, calibrated, and operated such that it does not interfere with the data collection by the other instruments. For example, the thermal calibration of the LIR will validate its readings against known data from the VERITAS mission, and in the event of a >2K deviation from predicted values, the focal plane array will undergo recalibration. The Chaparral Model 60-UHP2 infrasound sensor will undergo baseline calibration which will allow it to establish a background noise level based on data collected at 70 km AGL, where wind speed and atmospheric turbulence are lower. Furthermore, every 12 hours, all instruments will undergo a coordinated observation campaign with the aim of detecting and eliminating discrepancies between the measurements taken by instruments. For example, were the concentration of methane as measured by both TOF-MS and UV spectrometer to differ widely between the two instruments, concern over calibration would be well justified. In the event that two values have a deviation of >15%, safe mode diagnostics will be initiated. In short, the planned instrument calibration and testing regime will ensure that the instruments, despite being constrained within a compact space, will work together rather than interfering with each other.

The mission's Concept of Operations (ConOps) implements a phased instrument calibration and data collection strategy optimized for Venus' 50-70 km operational altitude and power constraints. Following deployment from the orbiter (Stage 1), Stage 2 initiates a 6-hour sequential calibration sequence where instruments are activated individually to prevent electromagnetic interference or sensor cross-talk:

1. Time-of-Flight Mass Spectrometer (TOF-MS) - 1.5 hours (baseline sensitivity verification at 10^{-4} molecules/cm³)
2. SPICAM UV Spectrometer - 1.25 hours (wavelength calibration across 180-320 nm range)
3. Longwave Infrared Camera (LIR) - 1.75 hours (thermal calibration to 0.3K NETD specification)
4. Chaparral 60-UHP2 Infrasound Sensor - 1.5 hours (frequency response validation at 0.1-40 Hz)

This staggered approach ensures <1% measurement error margin while limiting peak power draw to 85W - within the battery's 236.8 Wh capacity. Post-calibration, the aerobot enters a 4.3-hour recharge phase using Spectrolab NeXt solar arrays generating 75W/hr under Venus' 90W/m² irradiance, restoring full battery capacity for sustained operations. During Stage 3 (50-70 km altitude), the aerobot executes 6x 2.5-hour science cycles (15 hours total) with all instruments active. Each cycle consumes 212.5Wh, leaving 24.3Wh margin for contingency operations. Power-intensive instruments like the TOF-MS (28W) and LIR (22W) operate continuously, while the UV Spectrometer (18W) and Infrasound Sensor (7W) use intermittent sampling to maintain thermal stability. At 60 km altitude threshold, the system initiates power conservation protocols:

1. Deactivates TOF-MS and LIR (combined 50W savings)

2. Prioritizes UV Spectrometer for atmospheric composition analysis (SO_2 , PH_3 tracking)
3. Maintains Infrasonic Sensor for volcanic event detection (0.01V/Pa sensitivity)

This configuration reduces power consumption to 25W, enabling indefinite operation on solar generation alone (75W/hr surplus) until surface impact. Should the aerobot survive impact on Maat Mons, it executes a 2.25-hour recalibration (UV Spectrometer: 45 minutes, Infrasonic Sensor: 1 hour, joint operation verification: 30 minutes) before final surface phase operations. The UV/Infrasonic combination was selected for their combined 25W draw and complementary science value - UV tracks post-impact gas emissions while infrasonic monitors residual tectonic activity.

Primarily, this mission will take place in the atmosphere of the planet, and thus the amount of visual context that can be provided by JMARS is perhaps more limited than it would be for a ground-based mission. However, the aerobot has the scientific goal of measuring volcanic and tectonic activity, which takes place on the planet and not in the atmosphere. Included below is a JMARS image highlighting the volcanos that the mission will observe from above. Additionally, there is a second JMARS image showing Maat and Ozza Mons using emissivity data collected by the Magellan mission. Emissivity of a surface is defined as the result of dividing thermal power emitted by that surface by the power emitted by a black body of the same size and at the same physical temperature. (Astropedia - Venus Magellan Global Microwave Emissivity 4641m, 2025)

This definition, and the image pictured below, leads one to the conclusion that the thermal power emitted by both mountains (but particularly Ozza Mons) is greater than the surrounding area as captured by Magellan, which may indicate volcanic or tectonic activity and effectively illustrates why this region is of interest for the aerobot's mission. It also provides a visual for what the aerobot may expect to see.

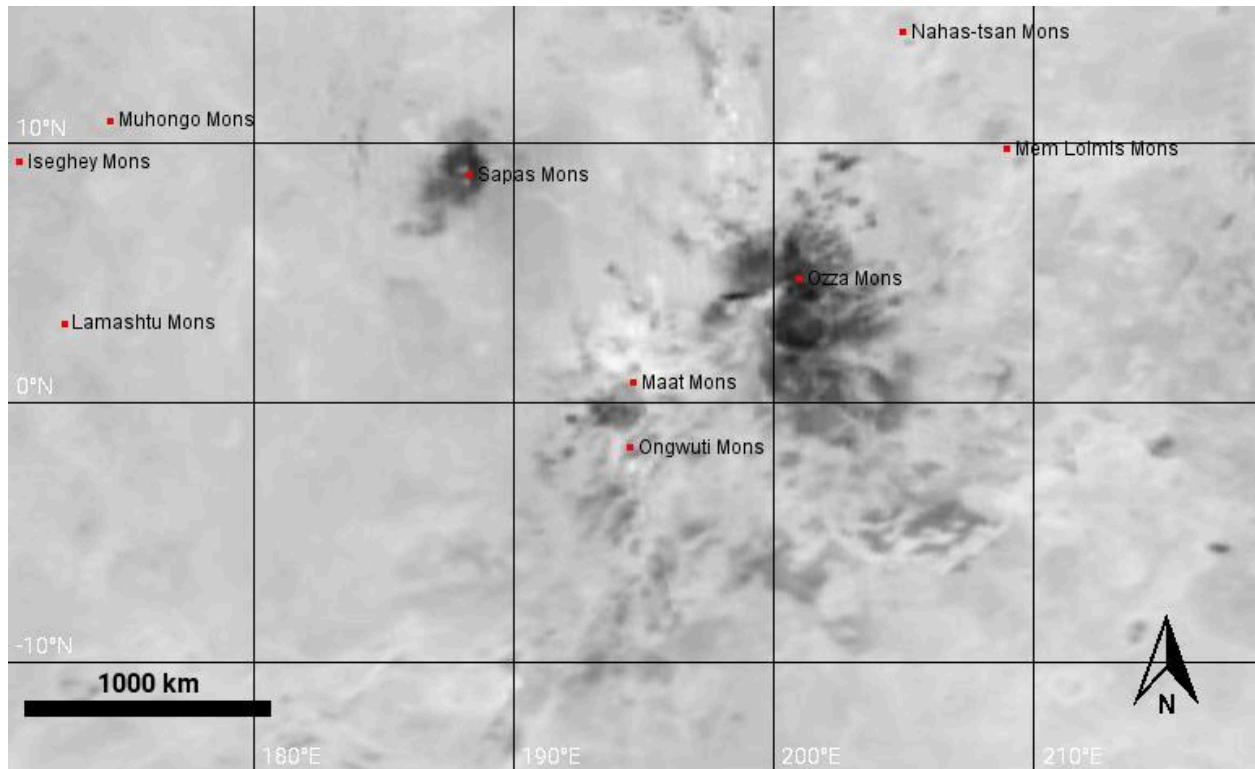


Fig 19: Image taken from JMARS software showing the labeled location of Maat and Ozza mons area at center. Shape layer: Venus Magellan Emissivity. The map was generated using JMARS software, which provides detailed topographic and geological data to assist in mission planning.

3.3 Payload Success Criteria

The Longwave Infrared Camera will investigate volcanic or tectonic activity through thermal imaging. Its associated failure modes are miscalibration (leading to potential false positives and flawed data), detection of thermal emissions from non-planetary sources (such as the other instruments contained within the science payload and the aerobot at large), and power failures. The LIR lacks moving parts, eliminating the potential of a mechanical failure. In order to be successful, the LIR shall calibrate properly, send timely data to the CDH subsystem, not interfere with other science payload or aerobot subsystems or operations, and operate for the duration of the mission, although it will power off on occasion to conserve power or to recalibrate.

The Time Of Flight Mass Spectrometer shall investigate the atmospheric composition of Venus. As such, it must be able to discern between various molecules with a high degree of precision. The failure modes associated with its operation include miscalibration (leading to potential false positives and general bad data), failure of the sample pump associated with the TOF-MS (which would render it unable to collect data at all), and power failures. In order to be considered successful, the TOF-MS shall calibrate properly, send timely data to the CDH subsystem, and operate for the duration of the mission, although it will power off on occasion to conserve power or to recalibrate. A optional goal for this instrument is survival and continued operation after

the conclusion of the 48-hour mission period, as the balloon degrades and fails. Although it is beyond the mission's scope, were the aerobot to survive post-balloon failure, any additional data that could be collected would be invaluable, hence why this goal may be considered, so long as it does not interfere with any other goals or exceed costs.

The Chaparral Model 60-UHP2 Infrasound Sensor will detect evidence of volcanic or tectonic activity by detecting acoustic waves below 20 Hz. The failure modes associated with it include miscalibration (leading to false positives and bad data), self-noise, noise from other instruments, or wind noise (all of which would lead to false positives and data from which conclusions may not be able to be drawn), and power failures. Success criteria include calibrating properly, collecting data and sending it to the CDH subsystem in a timely manner, and operating for the duration of the mission, although it will power off on occasion to conserve power or to recalibrate. A stretch goal for this instrument is to survive and continue operating beyond the nominal 48-hour mission duration. While this might exceed the baseline of a mission scope, any additional data collected during this extended period would offer valuable scientific knowledge.

The UV spectrometer shall serve a similar purpose to the TOF-MS, characterizing the composition of the atmosphere. As such, it must be able to discern between various molecules with a high degree of precision. The failure modes associated with its operation include miscalibration (leading to potential false positives and general bad data), failure of the sample pump associated with the UV spectrometer (which would render it unable to collect data at all), and power failures. An additional failure mode is the contamination of the blank sample, which would skew the data as the spectrometer would no longer be measuring against a valid control sample. In order to be considered successful, the spectrometer shall calibrate properly, send timely data to the CDH subsystem, and operate for the duration of the mission, although it will power off on occasion to conserve power or to recalibrate. A stretch goal for this instrument is to survive and continue operating beyond the nominal 48-hour mission duration. While this might exceed the baseline of a mission scope, any additional data collected during this extended period would offer valuable scientific knowledge.

Team Aether Solaris's first science deliverable, "Determine potential biosignatures and chemical processes in Venus's atmosphere, including identifying the nature of the "unknown UV blockers," to provide evidence of the Greenhouse Effect", is significant for a variety of reasons, as is set forth in *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*. Primary among these reasons is the sheer significance of finding evidence for extraterrestrial life. Furthermore, Venus's atmospheric chemical processes are poorly understood, and an increased amount of data on them would give scientists a framework to better understand the atmospheric characteristics of other worlds. (National Academies of Sciences, *Origins, Worlds, and Life*.) The means by which UV light is absorbed in Venus's atmosphere, and its impact on the planet's atmospheric dynamics, is also unclear and has thus been identified as a science goal of the aerobot mission.

Team Aether Solaris's second science deliverable, "Determine if modern volcanic or tectonic activity is influencing Venus's atmosphere" is likewise significant. Volcanic activity shapes the formation of geologic features across the solar system, yet its

presence and impact on planets besides Earth remains poorly understood (National Academies of Sciences, *Origins, Worlds, and Life*). It is hypothesized, for example, that plumes on the moon Triton influence atmospheric composition and Triton's characteristic layer of haze - however, this remains largely theoretical. Likewise on Venus, volcanism/interior outgassing has played a role in the formation of the atmosphere (National Academies of Sciences, *Origins, Worlds, and Life*) but whether volcanic and tectonic activity continues to influence the planet's atmosphere is still unknown. By gathering data on volcanic signatures and atmospheric composition, an answer to this question may be devised. The significance of this, in addition to the increased knowledge of Earth's neighboring world, would be data which may be used to provide frameworks for future missions and atmospheric science on worlds similar to Venus.

Category	Minimum Success	Optimum Success	Stretch Goal
Longwave Infrared Camera	Collect visual data over 48 hours at a spatial resolution of 70km per pixel	Collect visual data over 48 hours at a spatial resolution of 70km per pixel with 98% accuracy	Collect visual data over 48 hours at a spatial resolution of 70km per pixel with 98% or higher accuracy, continuing to collect data as the balloon degrades and the aerobot enters uncontrolled descent
Chaparral Model 60-UHP2 Infrasonic Sensor	Collect infrasonic data over 24 hours at a sensitivity of 0.01V/Pa at 1 Hz	Collect infrasonic data over 24 hours at a sensitivity of 0.01V/Pa at 1 Hz with 98% accuracy	Collect infrasonic data over 24 hours at a sensitivity of 0.01V/Pa at 1 Hz with 98% accuracy or higher, continuing to collect data as the balloon degrades and the aerobot enters uncontrolled descent
Time of Flight mass spectrometer	Collect data on the composition of the atmosphere over 48 hours at a sensitivity of 10^{-4} to 10^{-5} molecules/cm ³	Collect data on the composition of the atmosphere over 48 hours at a sensitivity of 10^{-4} to 10^{-5} molecules/cm ³ with 98% accuracy	Collect data on the composition of the atmosphere over 48 hours at a sensitivity of 10^{-4} to 10^{-5} molecules/cm ³ with 98% accuracy or

			higher, continuing to collect data as the balloon degrades and the aerobot enters uncontrolled descent
UV spectrometer	Collect data on the composition of the atmosphere over 48 hours at a spectral resolution of 1.5nm	Collect data on the composition of the atmosphere over 48 hours at a spectral resolution of 1.5nm with 98% accuracy	Collect data on the composition of the atmosphere over 48 hours at a spectral resolution of 1.5nm with 98% accuracy or higher, continuing to collect data as the balloon degrades and the aerobot enters uncontrolled descent

Table 16 Science payload success table

Note: the infrasonic sensor has a shorter operating timespan because it will spend 24 hours establishing baseline wind noise in order to later filter it out from the measurements taken.

3.4 Testing and Calibration Measurements

The Chaparral Model 60-UHP2 infrasound sensor will undergo baseline calibration using Venus's ambient acoustic environment during the aerobot's initial deployment at 70 km altitude, where atmospheric turbulence is minimal. A 24-hour "quiet period" will establish background noise levels (0.01–10 Hz range), with subsequent data compared against known pressure oscillations caused by Venus's super-rotating wind. To validate tectonic/volcanic signal detection, the sensor will monitor the Maat Mons region during predicted magma intrusion events based on orbital thermal anomaly forecasts from the VERITAS mission. Cross-calibration will occur by correlating infrasound waveforms with simultaneous Longwave Infrared Camera (LIR) observations of volcanic plume formation and UV Spectrometer (SPICAM) SO₂ spikes. Pressure sensitivity (45.13 μ V/Pa) will be verified using the aerobot's barometric sensors, with a 0.025 Pa resolution threshold set to distinguish noise from genuine seismic events.

UV Spectrometer (SPICAM) Calibration and Validation

The SPICAM UV spectrometer will perform stellar occultation calibrations using Alpha Lyrae (Vega) as a reference standard during nighttime operations. By measuring Vega's unattenuated spectrum (200–320 nm range) and comparing it to Mars Express mission baselines, the instrument will establish absolute radiometric accuracy. Daytime atmospheric scans will validate SO₂ absorption bands at 280 nm and 310 nm against

the Venus International Reference Atmosphere (VIRA) model, with discrepancies >5% triggering autonomous gain adjustments. To mitigate sulfuric acid aerosol interference, the team will implement real-time aerosol correction algorithms using the 350–400 nm continuum, leveraging the known scattering properties of H₂SO₄ droplets from Pioneer Venus data. Cross-instrument validation will occur via correlation with TOF-Mass Spectrometer sulfur species measurements at matching altitudes.

Longwave Infrared Camera (LIR) Thermal Calibration

The Akatsuki-derived LIR camera will execute a two-stage calibration protocol:

1. **Blackbody Reference:** A built-in boron nitride blackbody target (emissivity $\epsilon=0.98\pm0.01$) maintained at 300K by thermoelectric coolers will provide in-situ radiometric calibration every 6 hours.
2. **Surface Feature Cross-Check:** The camera will image the Maat Mons caldera floor during nadir passes, comparing observed brightness temperatures (8–12 μm band) with VERITAS synthetic aperture radar (SAR) topographic maps and known basalt emissivity spectra¹. A >2K deviation from predicted values will trigger focal plane array recalibration.

Diurnal thermal inertia measurements of surface features will validate temporal response characteristics, with 16.7 ms integration times verified against the rotation rate of Venus's super-rotating atmosphere.

TOF-Mass Spectrometer Performance Verification

The Time-of-Flight (TOF) mass spectrometer will conduct in-situ sensitivity tests using Venus's well-characterized atmospheric composition at 65 km altitude (96% CO₂, 3.5% N₂). A reference gas cell containing 500 ppm SO₂ in CO₂ will be analyzed hourly to maintain mass accuracy (1–5000 amu range) and sensitivity (10⁻⁵ molecules/cm³). Isotopic ratio validation will occur through continuous measurement of ¹²C/¹³C in CO₂, comparing results to ground-truth values from the Pioneer Venus Large Probe Neutral Mass Spectrometer. To confirm volcanic gas detection capability, the instrument will perform targeted analyses during LIR-observed thermal anomalies, with positive PH₃ identifications requiring simultaneous UV Spectrometer absorption at 234–238 nm. Pumping efficiency (1 L/min) will be monitored via pressure differentials across the Teflon PTFE sampling line, with >10% deviation triggering redundant pump activation.

Cross-Instrument Validation Protocol

All instruments will participate in coordinated observation campaigns every 12 hours:

1. Simultaneous measurement of SO₂ concentrations at fixed altitudes (UV Spectrometer absorption vs. TOF-MS ionization counts)
2. Correlation of infrasound event timing with LIR thermal pulse detection (≤ 5 sec latency)
3. Altitude-dependent methane profile validation (TOF-MS vs. UV Spectrometer 3.3 μm band secondary channel)

Data concordance thresholds require <15% deviation between instrument pairs for key species (SO₂, OCS, PH₃), with larger discrepancies initiating safe-mode diagnostics.

Example Testing Schedule:

Time Since Start (hr:min)	Activity	Instrument(s)	Success Criteria
00:00–00:30	Aerobot stabilization post-deployment	N/A	CDH confirms nominal altitude/pressure
00:30–01:00	TOF internal gas calibration	Mass Spectrometer	CO ₂ peak resolution ≤0.01 amu drift
01:00–01:45	UV Solar Occultation test	UV Spectrometer	SO ₂ band depth matches model within 5%
01:45–03:00	LIR blackbody/VERITAS cross-calibration	Infrared camera	ΔT ≤0.5 K relative to orbiter
03:00–04:30	Infrasound actuator test	Infrasound sensor	Frequency response ~2% of pre-launch data
04:30–06:00	Full-System Nominal Operation	All Instruments	Data packets received with <1% packet loss

Table 17

3.5 Precision and Accuracy of Instrumentation

Time-of-Flight (TOF) Mass Spectrometer

The TOF mass spectrometer provides a mass resolving power of 5,000–46,000 (FWHM), enabling precise differentiation of isotopic ratios with an accuracy of ±0.01 amu. This resolution ensures detection of trace gases (e.g., PH₃, SO₂) at sensitivities down to 10⁻⁵–10⁻⁶ molecules/cm³, critical for identifying biosignatures. However, pump flow rate variations (1–6 L/min) under Venus's 92-bar atmospheric pressure introduce ±5% uncertainty in gas density measurements, necessitating cross-calibration with UV spectrometer data to validate absolute concentrations.

SPICAM UV Spectrometer

The UV spectrometer operates with a spectral resolution of 1.5 nm across the 180–320 nm range, allowing detection of SO₂ absorption bands at 280 nm with ±5% accuracy relative to Venus Express datasets. Solar occultation calibration during terminator passages reduces systematic errors to <2% for vertical SO₂ profiles¹. However, sulfuric acid aerosol scattering introduces ±10% uncertainty in backscatter intensity at 320 nm, requiring iterative correction using Pioneer Venus radiative transfer models.

Longwave Infrared Camera (LIR)

The LIR achieves a noise-equivalent temperature difference (NETD) of 0.3 K, enabling surface thermal anomaly detection ≥3 K above background. Blackbody calibration against a 300 K reference plate ensures absolute temperature accuracy of ±0.5 K. Spatial resolution limitations (70 km/pixel) introduce ±15% uncertainty in pinpointing volcanic hotspots smaller than 20 km², necessitating corroboration with infrasound event timing.

Chaparral Infrasound Sensor

The sensor exhibits a self-noise floor of 0.025 Pa RMS at 1 Hz, allowing detection of pressure fluctuations ≥0.05 Pa with ±10% amplitude accuracy. Frequency response linearity (0.1–40 Hz) is maintained within ±2% of pre-launch data via piezoelectric actuator validation. Cross-talk from aerobot turbulence introduces ±0.01 Pa uncertainty, mitigated by barometric pressure correlation and orbital seismic event timing.

Impact on Data Validity

Accuracies are sufficient to meet mission requirements (e.g., PH₃ detection at 10–410⁻⁴ molecules/cm³, volcanic thermal anomalies ≥3 K). Redundant measurements (e.g., SO₂ via UV and mass spectrometry) will resolve instrument-specific uncertainties, while automated recalibration protocols ensure data integrity during the 48-hour operational window.

3.6 Expected Data & Analysis

While the environment and atmosphere of Venus is undeniably harsh, spacecraft have ventured there several times over the past decades, and from the information they have provided, a picture of what team Aether Solaris expects to find there may be assembled. In order to fulfill the scientific objectives set forth in the STM, the payload must identify aerosol composition, in particular SO₂, CO, and H₂S, which are associated with volcanic activity. It must also identify thermal and sonic anomalies associated with volcanic or tectonic activity. Finally, it must identify the composition of isotopic ratios, (D/H, ¹²C/¹³C, ³²S/³³S/³⁴S), compounds, (CO₂, SO₂, OCS, PH₃, and other trace gases) and any unidentified UV blockers through Venus's cloud layers. The mission will carry an off-the-shelf mass spectrometer and infrasound sensor, as well as an infrared camera and UV spectrometer previously developed for space travel in prior missions.

Venus's atmosphere consists of 96% CO₂, 3.5% N₂, 0.006% Ar, 0.003% O₂, and

0.001% Ne (*Massive Atmosphere of Venus.*). The science instruments measuring atmospheric chemicals (TOF-MS and UV-VIS spectrophotometer) will thus likely detect many of these chemicals, in roughly the percentages mentioned above. Specifically within the upper atmosphere and the cloud layer, between 50 and 70 km AGL (that is to say, where this mission will take place), one encounters clouds of H_2SO_4 (*Massive Atmosphere of Venus.*), and it is to be expected that the TOF-MS and UV-VIS spectrophotometer will thus detect this chemical.

A sample dataset from a TOF-MS is shown below in Figure 20. The mass of the ions measured by the TOF-MS is derived from their kinetic energy and the time it takes them to travel a known distance. The x-axis depicts mass per charge - for singly charged ions, this is simply the mass of the ion. The y-axis depicts the abundance of the detected ions, and represents intensity, measured in volts. When using a TOF-MS to search for ions whose presence indicates volcanic activity or biological processes, the peaks on the graph will indicate the relative abundance of molecules with a particular mass per charge. This metric can then be used to find the mass and chemical formula of said molecules. The graphs representing the data received from the aerobot will likely have a different distribution of peaks than the graph pictured below, as it is looking for entirely different molecules. Nonetheless, the graph pictured below provides a sample of what data collected through mass spectrometry can look like.

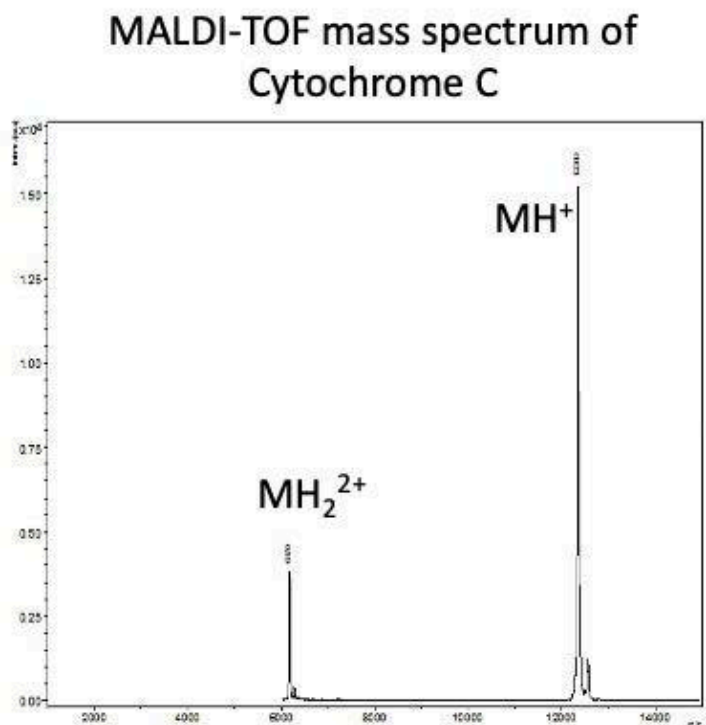


Fig.20

Image source: Bruker AutoFlex Speed MALDI-TOF/TOF Mass Spectrometer, Rensselaer Biotech, accessed April 19, 2025, <https://biotech.rpi.edu/equipment/bruker-autoflex-speed-maldi-toftof-mass-spectrometer>.

The data collected on charge per mass during this mission will be used to

calculate which molecules were present at which altitudes, and the relative concentrations of each compared to prior data and known hallmarks of biological processes or volcanic activity will be used in conjunction with other data to determine the source of said molecules. For example, if the TOF-MS detects SO_2 , CO , or H_2S (or some combination of all three) in higher concentrations than would be expected given accepted scientific data on Venus's upper atmosphere, this would be a potential indication of volcanic activity on the surface. Corroborating evidence for this theory may come in the form of infrasonic and infrared measurements indicating volcanic activity.

The data obtained by TOF-MS can be interpreted by analyzing peaks in the mass spectrum. For that, the x-axis (m/z) will indicate mass-to-charge ratio and the y-axis will show the relative ion abundance. The peaks then will be characterized. For example, m/z of $\text{SO}_2 \approx 64$, $\text{H}_2\text{S} \approx 34$, $\text{CO} \approx 28$. That will determine which gasses and in which concentrations they are present. Taking the data from the previous missions like Pioneer Venus or Venera will become a baseline for comparison. Any anomalies from that baseline will be recorded and analyzed, providing an understanding of the ongoing processes (for example, elevated SO_2 would point toward active volcanism).

The UV spectrometer included within this mission's science payload will work to fulfill many of the same science objectives as the TOF-MS. It measures the amount of UV or visible light (of a known wavelength) absorbed by a sample when compared to a blank sample, and based upon the known absorbance of various substances, the composition of the sample may be discerned. A sample graph from a UV spectrometer is pictured below. The absorbance of different wavelengths of light by a sample is used in conjunction with calibration curves in order to determine the composition of the sample. The data collected by the aerobot will form different peaks and valleys than those shown on this graph, because it will be measuring different chemicals. Information collected by a UV-VIS spectrometer will allow those analyzing the data to determine the presence and relative concentration of molecules in the sample based on known absorbance properties of compounds known to be in Venus's atmosphere and compounds that this mission hopes to find within the atmosphere. This, in conjunction with data collected by the other science payload instruments, would allow team Aether Solaris to draw conclusions on the science objectives.

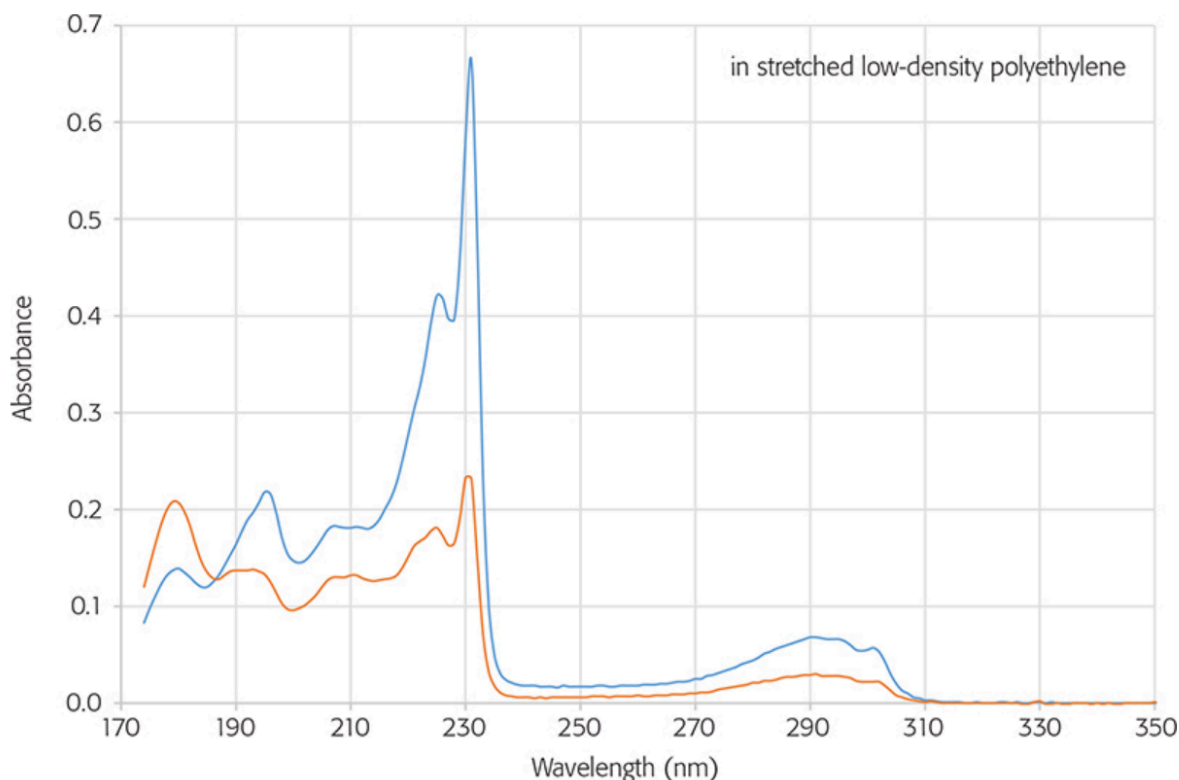


Image source: Andreas Noelle and Gerd K. Hartmann, "The UV/Vis+ photochemistry database," Spectroscopy Europe, 2020, <https://www.spectroscopyeurope.com/article/uvvis-photochemistry-database>.

Fig. 21

The data obtained by UV-VIS data will be processed by comparing recorded absorbance spectra against known reference spectra of gases such as SO_2 , OCS , and PH_3 . For that, the Beer-Lambert law can be used (Evdokimova et al. 2021). Absorbance values at specific wavelengths (for example, $\sim 200\text{--}230\text{nm}$ for SO_2) can be translated into concentration estimates. Then it can be plotted temporally and plotted accounting for altitude to identify atmospheric layers with chemical irregularities. To help identify the unknown UV absorber in Venus's atmosphere, previous research was looking into persistent absorbance feature in the $330\text{--}370\text{ nm}$ range (where unexplained absorption has been consistently observed). Recent modeling suggests that OSSO (disulfur dioxide) may be a significant contributor to this anomaly (Egan et al. 2025). This mission will have an opportunity to confirm that if there are some unknown compounds present, they are potentially tied to new atmospheric chemistry or an under researched biological material.

The science payload will also include an infrasound sensor, which will be detecting acoustic waves from $0.1\text{ Hz} - 40\text{ Hz}$. The reason for this instrument's inclusion is to detect evidence of volcanic or tectonic activity, which is often indicated by acoustic waves of below 20 Hz - thus, data indicating infrasound waves within that range will be of particular importance for this mission. An example dataset collected by an infrasound sensor is included below. This particular image comes from data gathered on the 2008

eruption of Kasatochi Volcano, making it particularly relevant for this mission's science objectives. The data collected during this mission will be looking for similar patterns and similar frequencies and pressure measurements, but obviously the eventual data may look different from this graph.

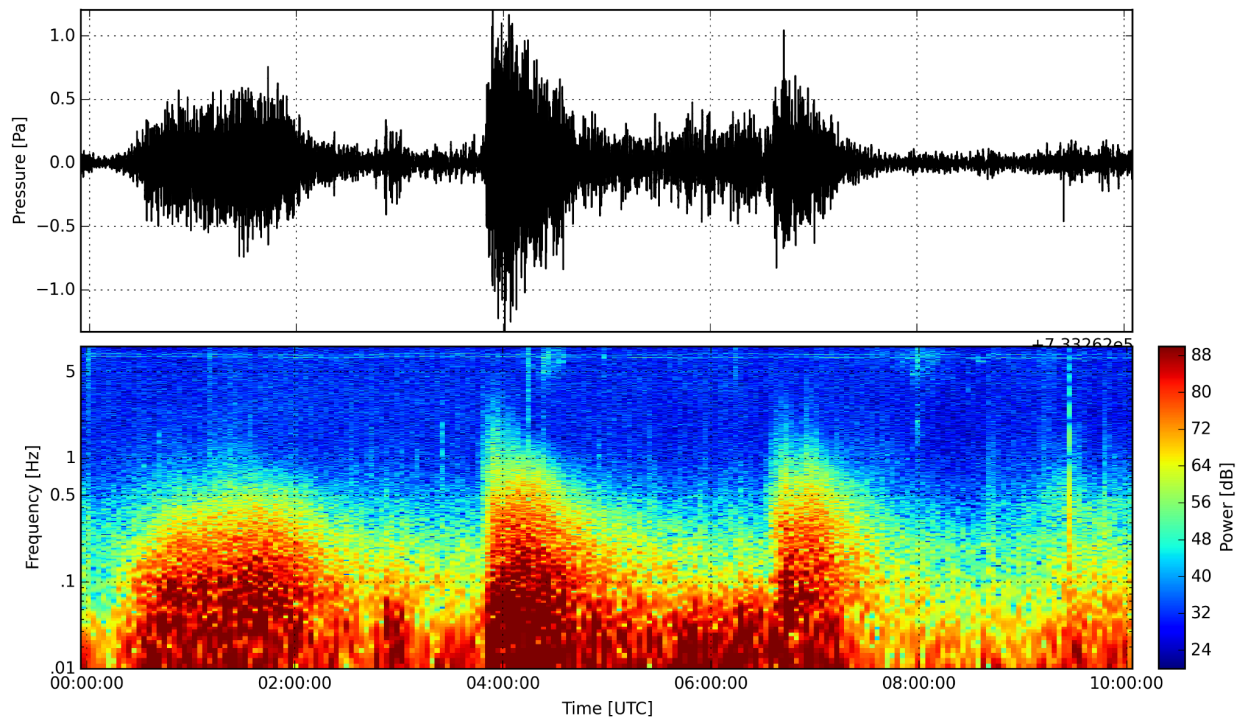


Fig. 22

Image source: Alaska Volcano Observatory/University of Alaska Fairbanks, "Image 87631."

Image source: <https://avo.alaska.edu/image/view/87631> - Credit: Image courtesy of the AVO/UAF-GI.

Analysis of the infrasound data can be done by examining the frequency and pressure detected by the sensor over a period of time and examining whether these results are statistically significant. If they are statistically significant, the presence (or lack) of corroborating evidence from other science instruments will allow conclusions to be drawn.

Potential sources of error include self-noise generated by the sensor or by other science payload instruments, which may be mitigated by flight-configuration ground testing and calibration of all components. Another source of error may be linked to the way in which infrasonic detection is utilized in Earth-based experiments and how this differs from the aerobot's configuration. A greater number of infrasonic sensors in an interconnected array reduces the signal-to-noise ratio (that is, the extent to which the signal can be isolated from the surrounding noise ("Infrasound Monitoring," CTBTO.) leading to better data overall. The aerobot is unable to carry an array of sensors the way an earth-based monitoring system would, potentially leading to a higher signal to noise ratio and more uncertainty. An additional source of error is the location environment of the sensor. Ideally, earth-based sensors are deployed within dense

rainforest ("Infrasound Monitoring," CTBTO.) to protect the sensors from prevailing winds. While the infrasonic sensor will be contained within the aerobot's outer shell and thus not be directly exposed to the winds of Venus, the wind introduces a potential source of error. In order to mitigate the risk posed by this, ground testing should include testing the infrasonic sensor in flight configuration with high windspeeds to see what impact they have on the data collected and, if this is the case, how one may discern the data from the wind noise.

Finally, the science payload will include an infrared camera, the same model as was flown on board the JAXA Akatsuki mission. Expected data from this instrument would take the form of image data, and while one can expect the resolution and image quality from Akatsuki to carry over to this mission, Akatsuki observed the planet from afar, while the aerobot will be entering the atmosphere itself. Pictured below is an image of Venus, captured post-orbital insertion at 10 μm .

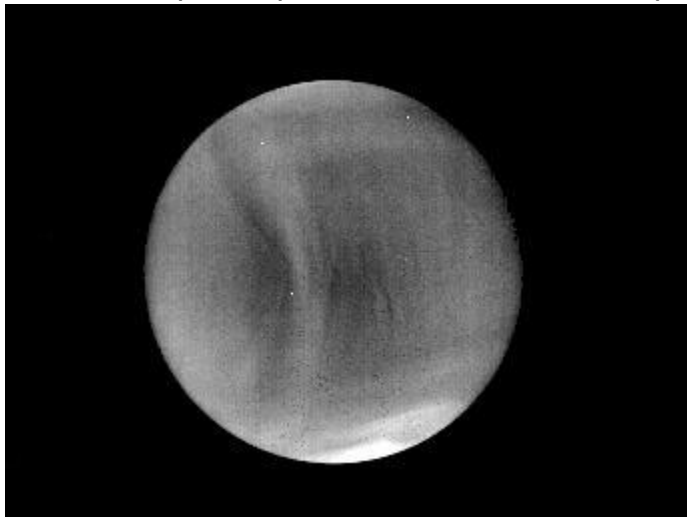


Fig 23

Image source: (Venus' Image Acquired by LIR after Venus Orbit Insertion | Gallery | Venus Climate Orbiter AKATSUKI, 2015)

Image source: <https://akatsuki.isas.jaxa.jp/en/gallery/data/001043.html>
Akatsuki, "Image 001043."

The primary difference between Akatsuki and the aerobot mission with regards to the data collected by the LIR is that the aerobot will be collecting data in situ while Akatsuki orbited the planet. The instrument will thus have to be differently calibrated from Akatsuki to reflect the different conditions it is placed within. A potential source of error is miscalibration specifically with regards to the temperature. During testing of Akatsuki, the LIR was kept at 300K, a nominal temperature for orbit. Within the altitude range that the aerobot would be operating within (50-70 km AGL) the temperature commonly falls between 100 and 200 K (*Massive Atmosphere of Venus*). A fix for this would be to calibrate the LIR within the expected operating temperature, and test it in the flight configuration specifically to see its ability to adequately process data within the temperature range expected. An additional fix would be extensive testing of the thermal regulation system, which should be a priority of the team regardless.

An additional potential source of error is heat emitted from the camera or from other payload components themselves, as the LIR's uncooled micro-bolometer array

(UMBA) detects thermal radiation from the lens and optical mount in addition to the Venusian atmosphere. (Fukuhara et al., "Longwave Infrared Camera.") For the Akatsuki mission, the required stability of the lens temperature was calculated to be ± 2.3 K, and testing was conducted by taking images of a uniform blackbody under various thermal conditions. From this, the conclusion was drawn that if the optical mount temperature is within 293.5-304.6 K, LIR can take an image of an object whose temperature is as low as 203 K. This, too, presents a potential source of error, as the temperature range the aerobot is expected to interact with (given its altitude and closeness to the cloud layer) may reach below 203K. The lack of available in-situ data for the specific altitude range that is to be studied further complicates matters - however, a mitigation strategy for this potential source of error is to test the abilities of the LIR to capture accurate images below 203K, and, if that is not possible, to determine what impact the lower temperature has on the images gathered.

4. Mission Risk Management

4.1 Safety and Hazard Overview

Mission safety is a priority for the Aether Solaris team, a hybrid method is utilized in order to be proactive on risk mitigation. The team uses a combination of NASA's Risk Informed Decision Making (RIDM) with Continuous Risk Management (CRM), this method helps to identify hazards early and ensure that they are being continuously monitored throughout the mission's progression. Although this mission is considered lower-cost, meaning that it allows for greater tolerance of risk, the team still maintains a high level of advisory for risks associated in any subsystem. Each risk that is identified is categorized by severity, likelihood and consequence, using a high, moderate or low scale. The risks are documented on a risk log and depicted on a risk matrix. The classification of each risk helps the team to analyze which items should be prioritized. Each subteam that has a risk associated with them, has a team member assigned in order to maintain accountability and have a person that the mission assurance specialist can check in with for updates. With every risk the team has an option to accept it, monitor or watch it, research it further, mitigate it or close it. The option chosen depends on the risk that has been identified and how the team feels it would impact the success of meeting mission objectives. Items of concern that are identified are re-classified once tests have been conducted and concern is deemed less critical than when it was previously found. When this happens the risk is updated on the risk log and risk matrix and the prioritization of other risks is elevated. This helps the team to continue progressing in lowering risks identified. Incorporating these methods allows the Aether Solaris team to meet NASA's standards for being responsible space explorers.

Planetary protection protocols are taken into consideration with two main goals in mind. To prevent forward contamination of planets and to protect Earth from extraterrestrial material that can be brought back by a spacecraft. Under planetary protection Venus is classified as a category 2. This indicated that there is a low risk for

contamination due to its extreme surface temperatures, lack of water availability and acidic atmosphere (Zorzano). According to COSPAR's Planetary Protection Policy a category 2 classification requires documentation rather than extensive sterilization procedures. However, due to the fact that the aerobot will be moving through Venus' atmosphere, there is still a slight risk of contamination. In order to stay in compliance with Article IX of the United Nations Outer Space Treaty, the team will ensure that the aerobot will have limited surface interactions and will follow protocols regarding sterilization. The Aether Solaris team has outlined a simple decommissioning and end-of-life plan for the aerobot that minimizes residual risks and aligns with planetary protection guidelines. Once the aerobot has completed its mission objectives it will fully descend into Venus's surface, where the extreme temperatures and pressure will powerfully disintegrate until it is nothing. This end-of-life strategy prevents any space debris that the aerobot could produce and reduces the interference of any future missions to Venus. Before the final goodbye all systems that are active, including instrumentation and communication will be deactivated in order to ensure full closure of the mission.

4.1.1 Risk Analysis

A risk log has been maintained and continuously updated as tests and changes are conducted on structures, materials and software. The risks for this mission are categorized based on severity using three levels, high, moderate and low. During this process weak points within the system that are tested are identified, flagged and tracked. This allows the different subteams to conduct further research and hardening techniques in order to mitigate the found issues. As the systems are strengthened, the risks are reduced, resulting in the reclassification of that unit's risk status.

The mechanical subteam is responsible for managing the risks associated with the mechanical system and materials. There was a risk that was previously identified involving the strength of the structural material. This was a risk because if the sheltering home for the instruments proves itself to be weak, it will lead to a damaged aerobot. This impacts the safety of the science instruments, which can end up leading to potential instrumentation failure. In order to mitigate this risk, the team has chosen aerospace grade titanium sheets (Grade 5, 0.012" thick). These sheets are proven to be corrosion resistant and have a thermal resilience of up to 673K. The titanium also has a TRL of 8 and has been widely used in many aerospace structures. The choice of this type of titanium sheet has led the team to classify that this risk will be accepted moving forward. A minimal chance of structural risk is anticipated at the moment, decreasing it to a low risk at the time. The risk involving the vibration isolation system that was previously identified in the MDR remains. There is still concern that the isolation system may not be effective in minimizing vibrations. The excessive vibrations can lead to performance

interference for the payload instruments. This can impact the accuracy of data collection for the mass spectrometer and the sensors. The mitigation approach involves implementing quality mounts and materials. The team has selected a Wire Rope Vibration Isolation System using three IDC SM3-070-A isolators that will be arranged in a triangular configuration. This VIS allows for six degrees of freedom for dampening, operating at 5-7 Hz. These materials have been rated for high temperature environments and vacuum conditions, with a TRL of 6. Keeping this in mind the team will continue to undergo additional testing before launch. Although risk has slightly decreased with testing, the team continues to identify this risk as moderate, due to the unpredictability of the complex Venusian atmosphere. A new risk was identified for the mechanical subsection. This risk has to do with the addition of the NMP 09 Sample Pump. There is concern for how well the pump will perform in a high-temperature, acidic environment. If the pump fails to maintain the required flow rate, the sample flow to the Mass Spectrometer can be compromised. This would result in a lack of data accuracy and decrease in payload instrument functionality. This risk will be watched by the team and given a classification of low for now. This classification is given because the pump has a TRL of 6. In addition, it connects using Teflon PTFE tubing and a titanium ring welded to the hull in order to be corrosion resistant. Proper verification before launch will take place in order to double check its reliability.

The power subsystem is responsible for the aerobot's energy distribution. Making sure that power is consistent and reliable is crucial to ensure mission objectives are met. The risk previously identified regarding the solid-state batteries has been mitigated by the team and is now closed. There was a possibility that the solid-state batteries could stop working, degrade or malfunction, leading to the loss of power for the system. This would result in operational failure, leaving a non-operational spacecraft in space. Since this risk was classified as high the team decided to replace it with a Li-Ion battery. This new battery choice was selected because of its proven performance in both Low Earth Orbit and Geostationary Orbit. It has also been reliable in previous missions and meets all the space and power constraints. The power distribution failure through ineffective connections still remains a risk. However, it has been reclassified by the team from high to moderate due to a recent update in the power subsystem. The team has decided to include solar panels as an additional and independent source of power. If complications were to arise due to faulty electrical connections or wiring, power can still be supplied to the aerobot. This backup power supply ensures that the mission continues to meet its objectives. Rigorous testing before launch and verification of quality wiring will still remain considering the classification is still set to moderate.

The thermal subsystem is responsible for regulating the aerobot's temperature and maintaining it within the operational limits. A cooling system failure has been previously identified as a risk, as it is important for maintaining functional temperatures in the extreme heat conditions of Venus. Overheating could create problems like

damage to the aerobot's instruments and system. In order to mitigate this problem the team will be conducting thermal testing in an environment of similar heat conditionals as Venus. The team also selected TMS Titanium for the outside material, this type of titanium is ideal for aerospace application. This risk is still classified as high risk and will be watched. The second risk that was identified involves the failure of the thermoelectric cooler. The function of this system is to regulate the temperature of the aerobot, without it extreme temperature exposure can occur. This failure can cause instruments to overheat and malfunction. The team's mitigation strategy involves designing an optimal heat dissipation system and testing in extreme temperatures. This risk is still labeled as a moderate risk, however design improvements have helped lower concerns.

The command and data handling subteam is responsible for handling the execution of operations, and the processing of commands and data transmission. Communication failure was previously identified as a high risk for this subsystem. A failure in this could prevent the aerobot from receiving or sending critical commands to and from earth. This would lead to a loss of communication and loss of crucial information for mission success. The team has mitigated this risk by implementing a triple redundancy system using the Raspberry Pi Zero flight computers. It is configured as a circular failover system, where control is passed seamlessly from a failed unit to an operating one. This plan ensures that if one computer is non operational during the mission it will be isolated while the next available one continues to process crucial data. While mitigated, the team still considers this as a high risk, due to communication and data transmission being an imperative part of mission objective achievement. The second risk that was identified in this subsystem involves the Core Flight Software and the possibility of a malfunction. Software malfunctions or glitches could prevent the aerobot from executing commands resulting in operational issues, system errors and erroneous data. The triple-redundancy system implemented by the CDH engineers will provide aid for this risk as well. It supports software resiliency, each unit contains identical firmware in order to promote compatibility among the systems. The Visual Code Studio provides robust debugging and embedded integration. The Raspberry Pi Zero Computers used are also equipped with Watchdog Timers that provide immediate rebooting properties and system health diagnostics during unresponsive events. In addition, regular software and patch updates will be incorporated in order to keep systems up to date. This risk will be watched and continues to be a moderate risk due to the possibility of unforeseen software issues presented in the actual Venusian environment.

The instrumentation subteam focuses on the scientific instruments on the aerobot and how they operate and collect data in space. Potential failure of the mass spectrometer through dust and debris is a risk that has been previously identified for this subsystem. This instrument is crucial for analyzing atmospheric particles in order to understand chemical compositions. A contamination of this equipment would negatively

impact the quality of the data that is being collected. The team has implemented Improved shielding of the science instruments as the mitigation approach. In addition, pre-launch inspections and verification is also being incorporated. This risk is now being watched and continues to be classified as moderate. The second risk that was identified relates to the sensors, such as the UV Spectrometer and Infrared Camera. There is a possibility that they can malfunction due to the radiation and temperature exposure. Malfunctioning sensors results in unreliable data results. The mitigation approach involving this risk incorporates radiation shielding and temperature resistant coating to be inserted in order to protect the sensors. Stress testing will also be part of the mitigation process. This is considered a low risk by the team because of the protective shielding and the overall structure of the aerobot is designed to prevent dust and debris from entering it. The suppliers selected also have prior flight heritage, the UV spectrometer was used in Mars Express and the Infrared sensor camera was used in the Akatsuki Venus mission.

Beyond engineering challenges, the team has also taken programmatic risks into consideration for this mission. There were three key risks that have been previously identified during the risk identification process of the MDR. The first risk involves personnel absence or turnover, as this can impact meeting deadlines and create delays, It also increases the difficulty of maintaining system progression. At this time it is still considered a low risk for this mission. The team will continue to accept this concern due to the proactive approach that is implemented. In this mission multiple members are assigned to different subsystem teams, through a cross training approach. Every member is assigned a primary role along with two secondary roles in different subsystems. Each subsystem in this mission consists of at least two individuals, allowing the team to adapt and step in during unexpected absences or turnover. While no turnovers have occurred thus far, there have been instances where team members have stepped in to help in different subsystems. Reinforcing why this risk remains low. Financial limitations in the team's budget is the second risk that was previously identified. Budget constraints can negatively impact mission success by limiting testing phases or essential material usage. It may force the team to cut corners and make compromises in areas that can then create higher risks in certain subsystems. It remains a moderate risk at this time and is being watched through careful financial planning and continuous budget review.. Funding opportunities presented by the outreach specialists also allows a steady stream of revenue throughout the mission progression. This offers more flexibility and a financial safety net if unforeseen expenses occur. Timeline delays in the last risk that was identified regarding programmatics. Timeline delays can result in missed milestones and increased costs for additional resources. It continues to be a risk and is being watched. The team will continue to embrace a strong intercommunication work environment, this helps to ensure that tasks are being worked on and completed. The team also uses a project

management tool, Teamhood, and weekly meetings in order to manage tasks. This visual interface helps the team plan, assign and track tasks in real time and fosters accountability among members of the team.

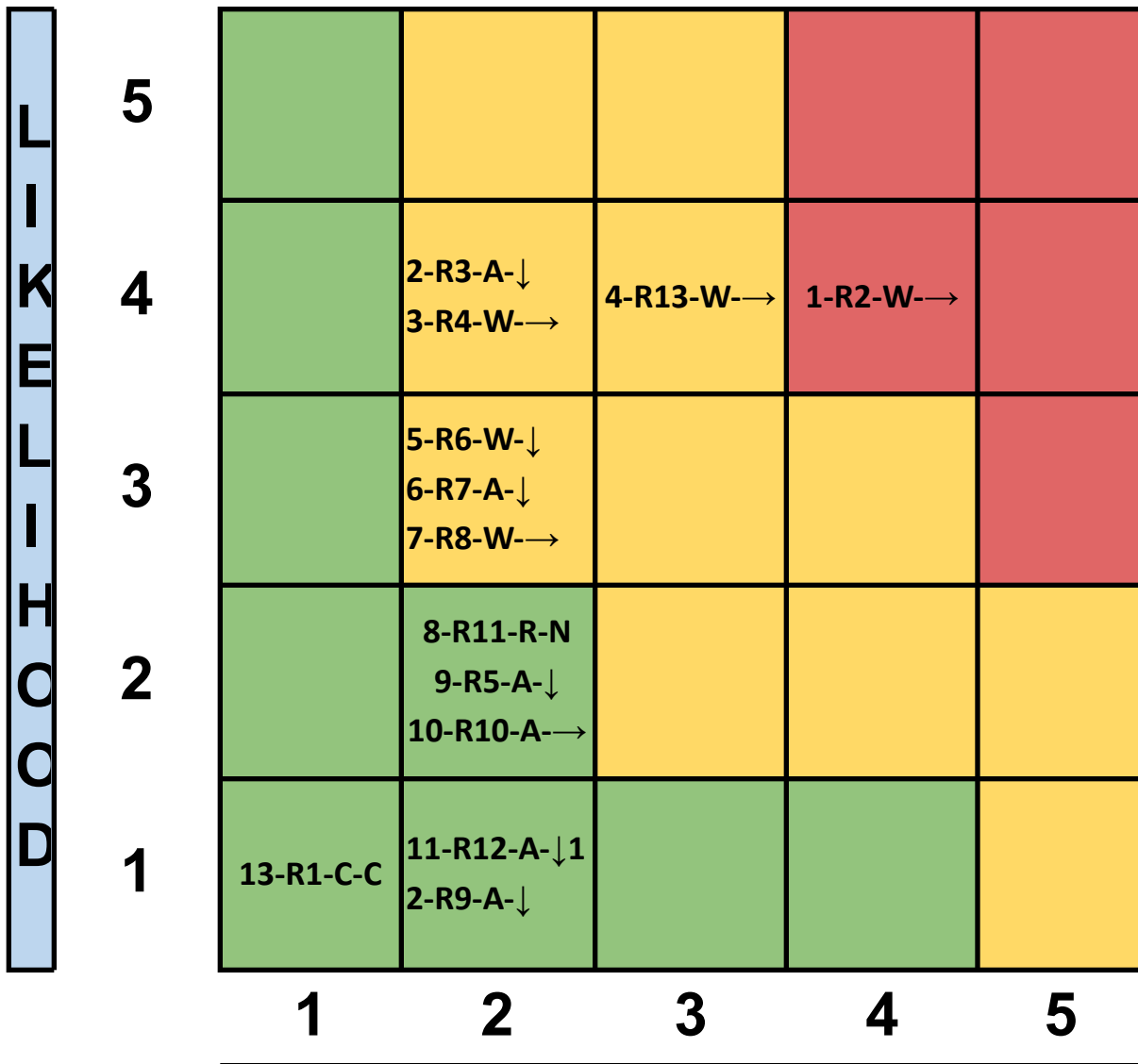


Fig.24

Rank	Risk ID #	WBS Element	Risk Owner	Category	Timeframe	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
Prioritize from color or data to address ed	Unique ID assigned to each risk. Any have a prioritized code to designate what level the risk is tracked at.	What WBS element the risk affects the most	Which team member is assigned responsibility over seeing the risks closure	What effects will this risk cause? An increase in cost, a loss of schedule margin or launch date, or loss of technical data to be collected?	What is the timeframe until the risk will be addressed?	A short descriptive title of the risk	A more thorough description of the risk following the appropriate format of "Given that [CONDITION], there is a possibility of [DEPARTURE] adversely impacting [ASSET], which can result in [CONSEQUENCE]"	Likelihood of the risk to occur, see the Resource sheet for more information	Consequence of the risk, see the Resource sheet for more information	High level indicator of the criticality of the risk	How the risk will be handled or not	Trend of any changes to the risk's L/C over its life cycle	Specific actions that will be implemented to mitigate the risk by either lowering the L and/or the C. Add or remove as many mitigation actions as needed and assign a new line and number (1.2.3...) to them. Carry this number across the first few rows where mitigation plans are mentioned and completed	Updates on the mitigation plans throughout their life cycle	The date that a mitigation plan should have an update by	A specific event that will be associated with the trigger date	The expected date the risk will be closed out	A specific event that will be associated with the closure date	The date followed by a short description of any changes or status updates to this risk. Example: (10/22/2024). The risk's L was changed from a 2 to a 1 after completing mitigation plan #1.
1	R2	Payload Subsystem	Nicholas Rosallo	Scope	Long Term	Cooling System Failure	Given that the cooling system fails, there is a possibility of there being a malfunction in the active cooling components, adversely impacting the thermal subsystem and payload instruments, which can result in overheating of instruments leading to damage.	4	4	High	Watch (W)	→ Neutral	Team will conduct thermal testing in an environment of similar heat conditions as the planet Venus	Thermal testing scheduled. TMS Titanium selected for outer shell	6/10/26- Right after the Titanium frame and structural subsystem fabrication milestones are done	Thermal testing using the TMS Titanium has been completed and reviewed by thermal team	8/30/28- After thermal testing finishes and confirms durability in Venus like condition	When the system passes a full thermal testing without complications	03/20/25- TMS Titanium selected
2	R3	Payload Subsystem	Sunny Nguyen	Scope	Long Term	Communication Failure	Given that there is communication failure, there us a possibility of there being a signal transmission disrupted, adversely impacting the CHD subsystem, which can result in the inability to send/receive commands, causing operational failure.	2	4	Moderate	Accept (A)	↓ Decrease	The team will implement a triple-redundancy system using the Raspberry Pi Zero light computers.	Triple-redundancy system implemented, research on Raspberry Pi Zero computers done	03/15/27- After the completion of communication relay testing and initial CDH validation	When testing of the communication system confirms full system functionality.	06/20/28- After communication validation and testing during the Environmental Testing phase	When communication system vs fully verified to work under space-like conditions.	03/14/25- Triple redundancy system implemented
3	R4	Payload Subsystem	Thivru Plakkutige Don	Scope	Medium Term	Power Distribution Failure	Given that the power does not distribute effectively, there is a possibility that the electrical connections or wires are not properly placed, adversely impacting the whole function of subsystems, which can result in power loss and objectives not met and mission fails.	2	4	Moderate	Watch (W)	→ Neutral	The team has decided to implement a solar panel as an additional source of power.	Solar panel implemented, tests scheduled	12/15/27- When the power subsystem is validated in a successful simulation	Power efficiency testing confirms that all systems are receiving power correctly.	08/14/28- When testing to withstand rigorous temperatures is completed.	When testing confirms stable, uninterrupted power across all subsystem in a harsh environment similar to that of Venus.	04/02/25- Solar panel integrated in power subsystem, leading to reduced risk.
4	R13	Programatics Subsystem	Christian Santori	Cost	Long Term	Financial Limitations	Given that there is unexpected financial limitations, there is a possibility that the team will not be able to fund important tests, which can result in heightened risks and systems not being tested before launch.	3	4	Moderate	Watch (W)	→ Neutral	The team will be carefully planning finances and will be continually reviewing the budget. Outreach plan has also provided opportunities for revenue to be streaming in during mission progression.	Monthly budget reviews, revenue stream	05/21/27- Every month the budget will be reviewed and updated	Testing schedules and subsystem changes taken into account.	10/02/28- After the end of the mission testing phase D commences.	When all tests and subsystem changes are complete and team is getting ready for launch.	03/31/25- Systems and testing reviewed, outreach plan allocated for revenue streaming in during mission.
5	R6	Payload Subsystem	Thivru Plakkutige Don	Scope	Medium Term	Ineffective Vibration Isolation	Given that the vibration isolation system is ineffective, there is a possibility of excessive vibrations mess with instrument effectiveness, adversely impacting Mass spectrometer/sensors, which can result in the reduced accuracy of data collected and could cause system failure.	2	3	Moderate	Watch (W)	↓ Decrease	The team will be implementing quality mounts and materials. Have selected a Wire Rope Vibration Isolation System using three IDC SMS-570-A isolators, that will be arranged in a triangular configuration.	Wire Rope Vibration System selected	10/25/27- When testing of mechanical stress capabilities has begun.	The completion of mechanical and vibration testing.	11/25/27- Towards the end of the mechanical stress testing timeline.	Successful completion of mechanical stress testing.	04/15/25- Team selected a specific VIB system
6	R7	Payload Subsystem	Christian Santori	Scope	Medium Term	Sensor Malfunction	Given that there is a sensor malfunction, there is a possibility of exposure to radiation and temperature fluctuations, adversely impacting the UV Spectrometer and Infrared Sensor, which can result in reduced accuracy of readings and lack of scientific measurements for objectives.	2	3	Moderate	Accept (A)	↓ Decrease	Team has incorporated radiation shielding and temperature resistant coating to be inserted in order to protect the sensors.	Stress testing has been scheduled	10/30/27- Once testing to ensure survival begin	Thermal and stress testing complete and shown successful sensor usage.	08/14/28- Once validating under Venus condition finishes	Sensor reliability is confirmed after testing under Venus the conditions.	03/20/25- TMS Titanium selected
7	R8	Payload Subsystem	Juan Rosas	Scope	Medium Term	Ineffective Thermoelectric Cooler	Given that the thermoelectric cooler is ineffective, there is a possibility of little to no cooling aspect in extreme condition, adversely impacting the payload instruments and all the subsystems, which can result in the instruments lose functionality due to inability to regulate temperature.	2	3	Moderate	Watch (W)	→ Neutral	The team will design an optimal heat dissipation system and test in conditions with extreme temperatures.	Thermal testing scheduled	6/15/27- After prototype testing	When the thermoelectric cooler is subjected to Venus-like condition in thermal testing and has no complications.	8/30/28- After thermal testing finishes and confirms durability in Venus like condition	When the system passes a full thermal testing without complications	03/22/25- Design improvements by thermal subsystem team have decreased this concern.
8	R11	Payload Subsystem	Juan Rosas	Scope	Short Term	Sample Pump Reliability	Given that the Sample Pump fails to maintain the required flow rate, there is a possibility that the pump may not provide the required flow rate to maintain consistent performance, adversely impacting the sample flow to the Mass Spectrometer, which can result in lack of data accuracy and payload instrument functionality.	2	2	Low	Research (R)	New	The team has chosen a sample pump with a TRL of 6, that uses Teflon PTFE tubing and a titanium ring that is corrosion resistant.	Mechanical testing scheduled	10/30/27- Once testing to ensure survival begin	Completion of testing in simulated Venusian environment is completed.	08/14/28- Once validating under Venus condition finishes	Successful validation of sample pump is done during simulation testing	04/11/25- Sample pump with a TRL of 6 chosen
9	R5	Payload Subsystem	Angie Apolinar	Scope	Medium Term	Software Malfunction	Given that the software malfunctions, there is a possibility that the core Flight Software encounters errors or data corruption, adversely impacting the CDH subsystem, which can result in the loss of data leading to mission failure.	2	2	Low	Accept (A)	↓ Decrease	The team will implement a triple-redundancy system using the Raspberry Pi Zero light computers. Identical firmware is also installed in order to promote compatibility among the system.	CDH data handling set to be tested and validated	03/04/27- Once all CDH data handling is 100% validated	Software safeguards and features are validated by the CDH subsystem.	01/31/28- Once all the CDH components are tested in Venus-like condition and show reliability	When the system shows full reliability during testing with no complications.	03/14/25- Triple redundancy system implemented, identical firmware installed
10	R10	Payload Subsystem	Acony Lanford	Scope	Medium Term	Mass Spectrometer Contamination	Given that there is a Mass Spectrometer contamination, there is a possibility of dust or debris enters the instrument due to lack of shielding, adversely impacting the Mass Spectrometer, which can result in inaccurate data collection due to compromised chemical analysis.	2	2	Low	Accept (A)	→ Neutral	The team has implemented improved shielding of the science instruments through the use of TMS Titanium. Pre-launch inspections and verification is also	TSM Titanium chosen for outside housing of instruments, pre-launch inspection added.	10/30/27- Once testing to ensure survival begin	Completion of shielding testing against contamination.	08/14/28- Once validating under Venus condition finishes	Once the system is validated against contamination during testing	03/20/25- TMS Titanium selected
11	R12	Programatics Subsystem	Christian Santori	Scope	Medium Term	Personnel Absence or Turnover	Given that there is alot of personnel absence or turnover, there is a possibility that systems will not be worked on or progression, which can result in deadlines being met.	2	1	Low	Accept (A)	↓ Decrease	The team has assigned multiple members into different subsystem teams. Everyone is cross-trained in different subsystems.	Team is cross-trained in different subsystems	04/25/25- During weekly meetings check in with subsystems.	Subsystems have shown progression despite absences.	12/20/25- After several months have passed using this approach.	When the cross-training approach has been viable in maintaining systems progression.	03/26/25- Risk identified and cross-training has been in use
12	R9	Payload Subsystem	Christian Santori	Scope	Medium Term	Structural Material Strength	Given that the structural material may not be able to handle launch stresses, there is a possibility of damaged or fractured materials, adversely impacting housing and shielding of the science instruments, which can result in exposing science instruments and damaging them.	2	1	Low	Accept (A)	↓ Decrease	The team has chosen aerospace grade titanium with a TRL of 8.	Stress testing has been scheduled. Aerospace-grade Titanium has been selected	10/25/27- When testing of mechanical stress capabilities has begun.	When stress testing has demonstrated the strength of the titanium used.	11/25/27- Towards the end of the mechanical stress testing timeline.	When the system is validated by the mechanical subsystem team as reliable and strong.	04/04/25- TMS Titanium with a TRL of 8 implemented into the structural material, leading to decrease of risk.
13	R1	Payload Subsystem	Ethan Fernandez	Scope	Medium Term	Solid State Battery Malfunction	Given that the solid state batteries malfunction, there is a possibility that the batteries degrade or don't work, adversely impacting the whole function of the subsystems, which can result in lack of power to systems, objectives not met and mission fails	1	1	Low	Close (C)	Closed	The team has replaced this type of battery and has now replaced it with Li-Ion batteries	Battery type has been replaced and no longer in use	03/31/25- Update has been given, team has decided a different route	N/A	3/31/25- Team has replaced battery type	N/A	03/31/25- Team has replaced Solid-State Batteries with Li-Ion batteries

3.1.1. 4.1.2 Failure Mode and Effect Analysis (FMEA)

The Failure Mode and Effect Analysis (FMEA) identifies failure modes of critical subsystems and how they affect the trajectory of the mission while providing solutions. The three critical subsystems within this mission are the solid state battery, the thermal cooling systems, and the communication subsystem. These subsystems are the most risk prone and crucial subsystems that ensure mission success on Venus. The table Below represents the FMEA done for each critical subsystem risk.

Tbl 3.1.1-01

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Solid State Battery	Lithium dendrite formation	Short circuiting and degraded performance.	9	overcharging or lower temperature charging, improper electrolyte formulation	7	Use of magnetic imaging systems including NMR and MRI	5	315	Using different materials, optimizing charging cycles
	Void Creation	Short circuiting and degraded performance.	8	during charging and discharging, expansion and contraction of materials due to temp.	7	Use of magnetic imaging systems including NMR and MRI	5	280	Optimizing charging cycles, replacing liquid electrolyte to solid
	Mechanical Damage	Physical damage to battery	6	Harsh Wind gusts due to Venusian environment	8	Implement mechanically stable interfaces	4	192	Adding an extra Battery, proper placement in Aerobot system
	Overheating	Reduced battery performance. risk of fire	7	Thermal cooling system failure,	5	Allocating extra thermal regulators around the battery	4	140	Improve thermal systems, adding TEC or radiators
Thermal Cooling System	Radiators not deploying	Overheating, lack of heat dissipation	8	High wind speeds, blockage of other component	7	Slow controlled deployment	2	112	Add extra radiators, use stronger deployment mechanisms

				s					
	Thermal Coating degradation	More solar radiation entering the system	6	Intense solar rays	4	spraying multiple surfaces including radiators and all surfaces	3	72	Switch to SG121FD white paint
	Thermal electric coolers malfunctioning	system critical thermal failure	7	Thermal cycle fatigue	8	Using different materials, thermal buffer layers	5	280	Add redundant TECs
	Insulation Failure	Excessive heat gain	9	aging degradation	3	Adding extra MLI	3	81	Switching type of MLI
Communication Systems	Antenna mechanical malfunction	comms are down	9	High wind speeds, blockage of other components	7	Improving mounting mechanism	4	252	Adding an extra
	Signal interference	Lots of noise in signal	7	Thick cloud cover	6	Data compression tech	4	168	Multiple Antennas
	Antenna pointing Failure	Poor signal and comms	8	High wind speeds	7	Making sure aerobot is stable	4	224	Adding an extra
	Tracking systems	Can't track aerobot	9	dense cloud coverage	6	Advanced tracking algorithm	3	162	Using multiple relay satellites

Beginning with solid state batteries the main failure mode that needs to be addressed the most is the possibility of Lithium dendrite formation. This is primarily due to the charging cycles of the battery causing the growth of dendrites. Optimizing charging patterns and improving materials for the electrodes would be a great solution. The main threat to the thermal cooling system would be thermal electrical malfunction. This is caused by thermal cycle fatigue leading to cracks to occur and intensify. Using other materials to mitigate unwanted thermal expansion or adding a redundant thermal electric cooler would improve system functionality. Finally, the main failure mode plaguing the communication systems would be the Antenna's mechanical malfunction. This is caused by the Venusian environment of high winds. Improving mounting mechanisms or adding a redundant system would be a proper solution.

3.1.2. 4.1.3 Personnel Hazards and Mitigations

Safety of personnel is crucial when embarking in the manufacturing, integration, and testing of spacecraft components. This section shall address general safety considerations and requirements dealing with mechanical, electrical, and fire hazards. These hazards are taken into consideration when discussing plant protocols, research facilities (even in the office), and general lab safety. In general for lab and plant protocols having personal protective equipment (PPE) is standard across the board. A protective helmet (hard hat) is required for work in areas where there is a potential for injury to the head when working in a plant. Each employee shall use appropriate eye or face protection and a face shield. This is necessary, when exposed to eye or face hazards from flying particles, sparks, molten metal, liquid chemicals, acids or caustic liquids, chemical gases or vapors, radiant heat, electrical hazard, or potentially injurious light radiation. This is especially relevant when mixing toxic chemicals in a lab setting. An eye wash station shall be in place to prevent any further injury or possible blindness. Foot protection is important and must be closed foot (no sandals) when on the floor of a plant or a lab facility. Foot protection can prevent slippery or hot surfaces in general. Foot protection shall be considered for occupations such as metal work, shipping, receiving and warehouse operations, construction, and facility maintenance. PPE for hand protection shall be used whenever the potential exists for exposure to hazards, including skin absorption of harmful substances, severe cuts or lacerations; severe abrasions; punctures; chemical burns; thermal burns; and harmful temperature extremes. Ear protection is necessary when around above safe noise levels. These could include loud wind tunnels in research facilities, when testing aircraft engines, and much more. Apparel is also a consideration in safety. Loose clothing especially in a manufacturing facility can get caught in machinery, could cause chemical spills, and much more. These are the few general PPE standards that are followed across the board [Glenn Safety Manual, Ch. 15].

Mechanical hazards play a huge role in personnel hazards and safety. A few mechanical hazards are sharp edges and protrusions including surfaces, edges, crevices, points, burrs, wire ends, screw heads, corners, and etc. when, if contacted, can lead to injury or damage of equipment. These surface finishes must comply with ANSI/ASME/B46 safety standards. Any mechanical device that stores potential energy like a spring, levers, cranks, and etc, can cause injury when improperly installed. These are more prevalent throughout the manufacturing process.

Electrical hazards involve potential electrical shocks leading to injury. The design of any electrical components shall consider the effects of a worst case, credible, hazardous scenario involving the highest internal voltage applied to or generated within the equipment. These electrical hazards can include exposed loose wiring during integration, potential sparks from damaged electrical components, and non insulated sections of components. All electrical components must be grounded and wearing proper hand protection when handling these components as well as being mindful of

conductive surfaces. Also, keeping in mind any liquids around electrical components that could cause damage to the equipment or personnel.

Fire hazard control shall be implemented when the cabin atmosphere is oxygenated greater than 30% by volume and must be monitored accordingly. Manual implementation of fire extinguishers, fire alarms, and exit routes shall be utilized across the board. Uninsulated cables and wiring can pose a massive fire risk during testing procedures. Power cables in under floor spaces shall be either type Mineral Insulated Metal Sheathed cable, Metal Clad cable, or Armored Cable cables or installed in approved conduit or metallic tubing. When working with propellants and fuels, fire hazards increase substantially especially when testing rocket engines. The risk also increases when storing and handling these combustible materials. Other possible fire hazards may include dust of certain powdered materials, water damage on electrical circuits, extreme temperatures causing certain chemicals to become a fire risk, and etc.

5 Activity Plan

5.1 Project Management Approach

All of the following phase changes in personnel vary and are purely based on testing and launch.

Tbl 18

Quantity (Varying from Phases)	Team (Role)	Responsibility (Skills)	Budget/ Salary (U.S. Medians)
Total: 3-30	Engineering:	N/A - Contribute to design, construction, implementation	Total: \$168k-\$2.12M per/yr
1-3	Systems Engineer Team	Manages technical coordination across all subsystems, ensuring mission requirements, risk assessment, and system-level integration are met.	\$80,000 per/yr
1-3	Software/Computer Engineer Team	Develops and implements software and onboard computing.	\$80,000 per/yr
1-4	Mechanical Engineer Team	Designs, analyzes, and integrates structural components.	\$80,000 per/yr
0-3	Power Engineer Team	Develops power generation, storage, and distribution systems.	\$80,000 per/yr

0-3	Thermal/Hardware Engineer Team	Designs thermal insulation and heat management systems.	\$80,000 per/yr
0-6	Mission Integration & Testing Team	Leads assembly, integration, and testing of all components, ensuring system functionality, compatibility, and performance validation.	\$60,000 per/yr
0-5	Verification & Validation (V&V) Team	Confirms that mission systems meet design specifications through testing.	\$60,000 per/yr
0-3	Maintenance Engineers/Technician Team	Handles pre-launch diagnostics, assembly, troubleshooting, and final checks.	\$60,000 per/yr
Total: 2-11	Science:	N/A - Contribute to research, discovery, analysis	Total: \$160k-\$880k per/yr
2-3	Science & Instrumentation Team	Defines mission science objectives; designs and/or validates instruments; supports operations; analyzes and disseminates data to achieve mission's goals	\$80,000 per/yr
0-2	Geology/Surface Analysts	Integrates imaging, compositional and contextual data to reconstruct geological history, assesses surface processes, and interprets the physical evolution of planetary terrains	\$80,000 per/yr
0-2	Biochemist/Data Researcher Team	Analyzes mission data'; develops detection mechanisms; interprets findings	\$80,000 per/yr
0-2	Atmospheric Science Team	Analyzes atmospheric composition, dynamics and climate processes	\$80,000 per/yr
0-2	Remote Sensing & Imaging Team	Captures, processes, interprets visual and spectral data to map surface features; monitors environmental changes, and supports scientific analysis across mission objectives	\$80,000 per/yr
Total: 17-21	Programmatic:	N/A - Contribute to scheduling, planning, development	Total: \$1.02M-\$1.26M per/yr

3	Budget & Resource Manager/Analyst Team	Oversees financial planning; tracks expenditures; allocates mission resources	\$60,000 per/yr
3	Quality & Risk Assessment Expert	Identifies potential technical and operational risks; implements mitigation strategies; ensures compliance with safety, performance and reliability standards	\$60,000 per/yr
2-3	Outreach Team	Communicates mission goals, discoveries and impacts to the public, educators and stakeholders	\$60,000 per/yr
2	Business Handlers or Deal Makers	Negotiates partnerships, manages contracts, and secures funding opportunities to support mission objectives	\$60,000 per/yr
3	Logistics & Resource Management Team	Coordinates the procurement, transportation, and allocation of the equipment, materials, and personnel to ensure timely and efficient mission operations	\$60,000 per/yr
3	Safety & Reliability Team	Ensures that all mission systems and operations meet rigorous safety standards and reliability requirements; identifies potential failure points and implements measures to prevent mission-critical issues	\$60,000 per/yr
1-4	Mission Operations Team	Manages day-to-day control of the spacecraft and instruments; executes mission plans; monitors system health; responds to anomalies to ensure successful mission performance	\$60,000 per/yr
Total: 2	Leaders/Management:	N/A - Contribute to organization, leading, direction, administration, success	Total: \$240k per/yr
1	Program Manager	Oversees the success of mission and each discipline; coordinating between teams; managing schedules and budgets; ensuring the technical, scientific, and strategic objectives are met on time and within scope of NASA	\$120,000 per/yr

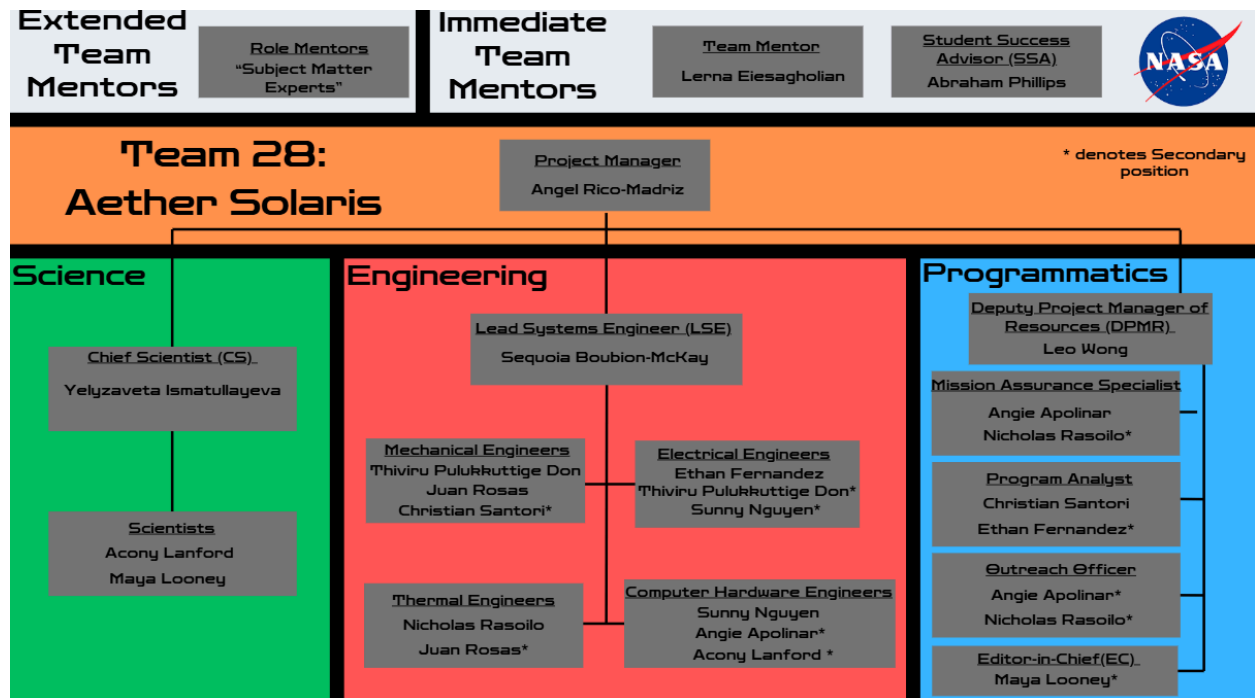
		requirements	
1	Insurance Fund Manager	Designated reserve that provides financial protection against mission risks, covering potential losses or delays	\$120,000 per/yr
Total: 24-64	All Personnel	N/A	Total: \$1.588M-\$4.5M per/yr

Tbl 19

Subteam	C	D	E	F
Systems Engineering	3	3	0	1
Software/Computer Engineering	3	3	2	1
Mechanical Engineering	4	4	2	1
Power Engineering	3	3	0	0
Thermal/Hardware Engineering	3	3	2	0
Mission Integration & Testing	6	6	3	0
Verification & Validation (V&V)	5	5	0	0
Maintenance Engineers/Technician Team	3	3	0	0
Total Technicians	3	3	0	0
Total Engineering	27	27	9	3
Science & Instrumentation	2	2	3	3
Geology/Surface Analysts	0	0	2	2
Biochemist/Data Researcher	0	0	2	2
Atmospheric Science	0	0	2	2
Remote Sensing & Imaging	0	0	2	2
Total Science	2	2	11	11
Budget & Resource Manager/Analyst Team	3	3	3	3
Quality & Risk Assessment Expert	3	3	3	3
Outreach Team	2	2	2	3
Business Handlers or Deal Makers	2	2	2	2
Logistics & Resource Management Team	3	3	3	3
Safety & Reliability Team	3	3	3	3
Mission Operations Team	3	3	4	1
Total Programmatic	19	19	20	18

Program Manager	1	1	1	1
Insurance Fund Manager	1	1	0	1
Total Leadership	2	2	1	2
Total Personnel	53	53	41	34

Fig 25



5.2 Mission Schedule

5.2.1 Schedule Basis of Estimate

Phase C	Date Start	Date Complete	Justification
Key Decision Point D (KDP-D)	September 2025	September 2025	Approve final design specifications
Mechanical Structural Subsystem Fabrication	October 2025	May 2026	Overall timeline for Structural Subsystem manufacturing
Titanium frame manufacturing	October 2025	December 2025	Total time allotted for the Titanium manufacturing
Balloon Delivery	March 2026	March 2026	Appropriate 6 month time gap for balloon to be delivered
Vibration isolation system design & testing	January 2026	May 2026	Validate the anti-vibration design and begin manufacturing
CDR (Critical Design Review)	May 2026	June 2026	Finalize all subsystem designs before assembly and fabrication
Subsystem Fabrication Starts	July 2026	December 2026	Start fabrication for each subsystem
Power Subsystem	July 2026	December 2026	Start designing the battery module to correct power specifications and implement
High-capacity battery pack assembly	July 2026	September 2026	Assemble the battery pack per specifications
Power regulation circuit design & testing	October 2026	December 2026	Design power system and test once completed

Command & Data Handling (CDH) Subsystem	August 2026	March 2027	Design of the CDH software
Raspberry Pi Zero integration & software validation	August 2026	November 2026	To ensure Raspberry Pi Zero software is ready for integration
Data storage & fault-tolerant system testing	December 2026	March 2027	CDH data handling is 100% validated
Initial System Assembly	March 2027	June 2027	Complete Integration of CDH hardware and software as a subsystem
Component Level Testing	October 2027	January 2028	Begin testing each subsystem to ensure survivability on the journey to venus
Mechanical stress & vibration tests	October 2027	November 2027	Testing of the mechanical subsystem stress capabilities
Power efficiency tests	November 2027	December 2027	To validate the power subsystems effort in a successful mission
CDH communication relay validation	December 2027	January 2028	To ensure the CDH is reliable and successful in communication
SIR (System Integration Review)	January 2028	March 2028	Ensures all components function together
Full System Integration Begins	May 2028	June 2028	Final assembly of individual subsystems
Instrument mounting and final checks	May 2028	June 2028	Final assembly of the payload and subsystem integration with the spacecraft
Environmental Testing	June 2028	August 2028	Validating system under Venus conditions
Thermal stress tests	June 2028	August 2028	Testing to withstand the rigorous temperatures on

			Venus
Electromagnetic interference testing	June 2028	August 2028	Testing for electronic failures or interference with communication
System Integration Complete	October 1st 2028	October 1st 2028	Ready for Phase D

Phase D		Date	Justification
KDP - D (Key Decision Point)	November 2028	November 2028	Key milestone for transitioning from integrating each system to final verification of a successful system
Thermal Vacuum and Environment Testing Completion	November 2028	December 2028	Testing the rocket to withstand different pressures, and the sulfuric acid atmosphere
ORR (Operational Readiness Review)	December 2028	December 2028	Ensures the spacecraft is 100% proven to be operational on its journey to Venus
FRR (Flight Readiness Review)	January 2029	January 2029	Ensures the spacecraft is 100% validated to be placed on the launch pad
LRR (Launch Readiness Review)	February 2029	February 2029	Ensures that the spacecraft and launch control are in successful communication and readiness

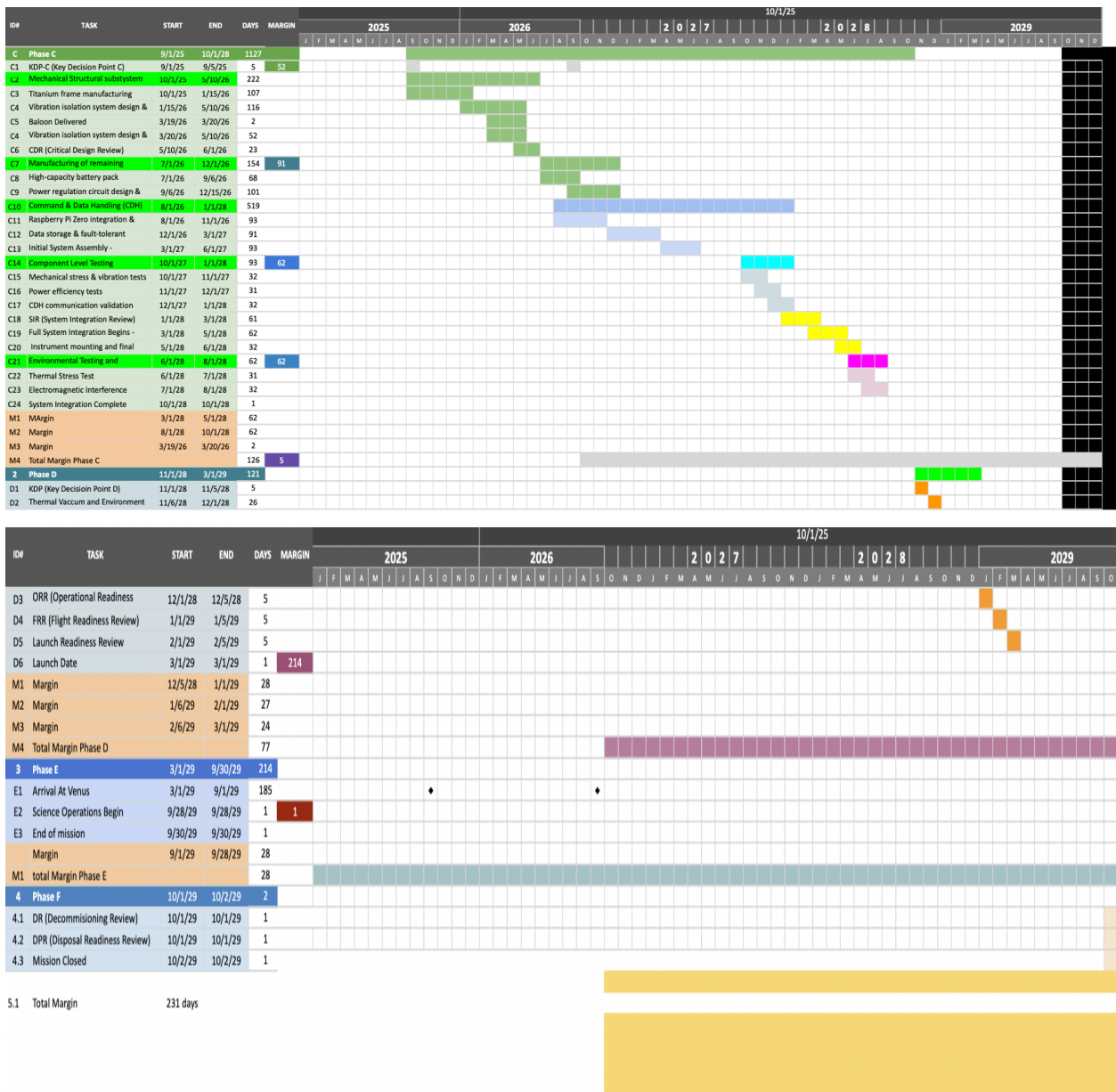
Launch Date	March 1st, 2029	March 1, 2029	Launch to Venus
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Phase E	Date	Justification
Arrival at Venus	September 2029	Arrival occurs roughly 200 days after launch per the mission task document
Science Operations Begin	September 2029	Aerobot descends and record/relays data for 48 hours or until complete system failure
End of Mission	September 2029	Aerobot system is offline

Phase F	Date	Justification
DR (Decommissioning Review)	October 2029	Ensures all systems are offline
DRR (Disposal Readiness Review)	October 2029	Ensures all systems are ideally disposed of
Mission Closed	TBD	Data is analyzed and mission reports are finalized. TBD is decided on mission success.

Table 27

5.2.2 Mission Schedule



Team 28 Gantt Chart Scheduling

Fig.26

Phase C of the Venus mission is focused on the manufacturing, assembly, and integration of the rocket subsystems. The first major task is the manufacturing of the rocket’s structure, which has been allocated 222 days due to its complexity and essential role in supporting all subsystems. The team has selected titanium for the structural framework because of its high strength to weight ratio, superior resistance to corrosion in Venusian conditions, and the ability to withstand extreme temperatures.

The manufacturing process itself is expected to take 107 days, after that, the efforts of the team will shift towards completing the vibration isolation system design over the next four months. This system is crucial in mitigating mechanical stresses encountered during launch and in-flight operations. Once structural fabrication is complete, the team will conduct a Critical Design Review (CDR), a 20-day process ensuring that all design specifications meet mission requirements and that potential risks have been addressed. Upon successful completion of the CDR, the next step is to manufacture the power system, which will take approximately 68 days. The power system is vital for ensuring a reliable energy supply throughout the mission's life, the team will design a power system that includes redundancy and thermal protection. Once the power system is manufactured, work on the power regulation circuit design and testing will begin, a process that has been allocated 101 days to validate efficiency, stability, and system integration. Following power system development, the focus will shift to the Command & Data Handling (CDH) subsystem assembly, which represents one of the most time-intensive aspects of Phase C, spanning 519 days. This subsystem is responsible for executing mission commands, processing critical data, and implementing fault-tolerant measures. The first step involves the Raspberry Pi Zero integration and software validation, taking 93 days to ensure seamless operation and communication between subsystems. Once the software is fully integrated, the team will conduct data storage and fault-tolerant system testing over 91 days to guarantee data integrity and redundancy. After validation, the Initial Subsystem Assembly will take 93 days, incorporating computing units, memory modules, and communication interfaces into the overall system. Once the CDH assembly is complete, the mission enters the component-level testing phase, spanning 93 days. This phase begins with mechanical subsystem stress and vibration testing for 32 days, ensuring the structure can withstand launch and mission stresses. It is followed by power efficiency tests, lasting 31 days, which assess energy consumption and distribution under varying operational conditions. Finally, the CDH communication validation process will take 32 days, verifying seamless data transmission across the system. These tests are critical in ensuring that each subsystem meets performance standards before moving into full integration. The next step is the System Integration Review (SIR), a 61-day process that ensures all subsystems are compatible and ready for final assembly. Following the SIR, Full System Integration will take place over 62 days, during which, each subsystem is installed into the rocket structure. This integration phase ensures proper mechanical, electrical, and software communication between all components. The subsequent step involves Science Instrument mounting and final checks, requiring 32 days to ensure that payload instruments are securely installed and fully operational for Venusian conditions. Before the rocket is deemed "launch-ready", it must undergo environmental testing and validation, scheduled for 63 days. This phase includes thermal stress testing to simulate extreme temperature variations encountered during the mission and electromagnetic

interference (EMI) testing to verify electronic component functionality in a high-radiation environment. These validation tests are essential to confirming mission readiness and ensuring subsystem reliability in spaceflight and planetary operations. Recognizing the potential for unforeseen challenges, the team has allocated a 126-day contingency margin, representing 15% of Phase C's total duration. This buffer period provides flexibility for addressing design modifications, resolving integration issues, and mitigating unexpected technical setbacks. By adhering to this structured critical path, the team ensures that manufacturing, assembly, and testing are executed within the mission's timeline, minimizing risks while maximizing the likelihood of success.

Phase D is primarily focused on final preparations, ensuring that all systems are verified and ready for launch. With the spacecraft having undergone extensive testing in Phase C, this phase serves to finalize assessments, conduct pre-launch verifications, and confirm mission readiness. The phase begins with Key Decision Point - D (KDP-D) in November 2028, a critical meeting where the team will discuss any remaining concerns before granting official authorization to proceed with final pre-launch operations. This step, scheduled to take 5 days, ensures that all stakeholders are aligned on the mission's status and objectives moving forward. Following KDP-D, the spacecraft will undergo its final Thermal Vacuum and Environmental Testing, lasting 26 days. These rigorous tests are designed to validate the spacecraft's ability to withstand the extreme conditions of space, including severe temperature fluctuations, vacuum exposure, and radiation. Ensuring success in this stage is crucial, as failure could result in mission delays or modifications to critical systems. Once testing is complete, the mission team will conduct the Operational Readiness Review (ORR), a 5-day evaluation scheduled for late November to early December 2028. This review provides a thorough assessment of mission operations, including ground support infrastructure and contingency planning. The ORR ensures that all operational components, including mission control and tracking stations, are ready to support the spacecraft throughout its journey to Venus. Following the ORR, the team will proceed with the Flight Readiness Review (FRR) in December 2028, scheduled for 5 days. This review will serve as a final assessment of flight systems, launch vehicle integration, and mission control protocols. Additionally, the FRR will verify compliance with all safety regulations and confirm that the mission is fully prepared for launch. The final step before launch is the Launch Readiness Review (LRR), scheduled for January 2029 and lasting 5 days. This last pre-launch verification ensures that all spacecraft systems, ground operations, and mission contingencies are in place. The LRR is a final checkpoint where any outstanding concerns must be addressed before the team gives final clearance for launch. With all reviews and validations complete, the mission will officially launch on March 1, 2029. This marks the culmination of years of planning, testing, and development, transitioning the mission from preparation to execution. At this point,

Phase D will conclude, and the team will move into Phase E, focusing on spacecraft operations and scientific data collection en route to Venus.

Phase E is dedicated to the spacecraft's flight to Venus and its scientific operations upon arrival of the planet's atmosphere. Phase E provides information on the steps of spacecraft monitoring, trajectory calculations or corrections, and data collection once it has entered the planet. For the journey to Venus, the time allotted is between March 2029 and September 2029, which is roughly 6 months. The spacecraft will have the ability to maneuver for corrections to optimize the trajectory to Venus, as well as give updates on health and performance during this time. Once arrived at Venus, the spacecraft will deploy the aerobot and the science operations will begin on September 29, 2029. From this point, the aerobot will only survive for 48 hours resulting in a mission timeline of 2 days. The mission concludes on September 30 2029, following the completion of all mission objectives. If the aerobot survives longer, further data collection will proceed until complete system failure. Upon a system offline, Phase E is completed.

Phase F is mainly focused on the controlled shutdown and decommission of the mission as a whole. The Decommissioning Review (DR) is scheduled for October 1st 2029 which also aligns with the NASA fiscal year. The DR is to ensure that all systems are safely offline and that no remaining power sources or components pose any risks. Once completed, the team can now start on the DRR or Disposal Readiness Review, which takes place directly after the DR. The DRR is mainly to ensure that the spacecraft is properly disposed of according to the planetary protection guidelines. With Venus being sulfuric acid, a slow descent into the planet should be proper disposal. The final step of the mission is TBD as the team does not know the full length of all of the mission data fully analyzed and findings published. The mission will officially conclude after that.

5.3 Budget

5.3.1 Budget Basis of Estimate

This mission will have a budget of \$180M, which will be allocated across multiple mission categories. The budget estimate from the MDR has been revised to account for new information. Information included is the reallocation of \$20M from the original \$200M budget. This with an additional six months is for the Contractor to deliver the DSS. This change is put in place to ensure the full 48 hours on Venus to collect data and to make sure that the mission's requirements are met without impacting other cost estimates.

Ground Rules

The mission categories included in the budget will be Science Payloads, Aerobot Structure, Materials, Avionics and Communication, Power Systems, Integration and Testing, Travel Cost, Outreach, Personnel, and Margin Reserves. This mission will adhere to the mass constraint of 45kg with a system-wide mass of 34.806kg. The cost

estimate will reflect adjustments for the reallocation of funds to reach mission objectives.

Assumptions

The highest priority for this mission is to meet the science objectives. This is ensured by using higher TRL technology for each subassembly in order to reduce testing time and associated cost. Testing will occur with initial system assembly to give more time by addressing issues early. The mission will also follow an inflation rate of 2.8% per year for phases C through F. Personnel costs are based on industry standard salaries as outlined in the Mission Task Document with scientists and engineers estimated at \$80k annually, technicians and administration at \$60k annually, and project management at \$120k annually. Additionally, personnel costs will include 28% allocated for benefits, onboarding, training, and other expenses. Lastly the travel for the budget will include testing at JPL, KDPs held in Washington D.C., and the Mission Launch seeing all personnel attend at Cape Canaveral, FL.

Drivers

- Personnel
 - Personnel count will fluctuate in need across each phase with an expectation of 30-50 personnel per phase.
 - Personnel count for Phase C and Phase D is equal due to reallocating testing into Phase C. In the budget personnel is not just allocated to each phase but the fiscal year each phase occurs or overlaps. Adjustments in salary is made based on the length of each phase.
 - Phase C: 36 months across the first three fiscal years with full personnel salaries for each year.
 - Phase D: 5 months in fiscal year four, but personnel are allocated for an additional month for the aerobot's flight to Venus. The personnel count for Phase D is halved to account for this shorter duration and then added to Phase E.
 - Phase E: 1 month in fiscal year four, but personnel are allocated for an additional 5 months for overseeing the flight to Venus. Like Phase D the personnel count is halved to account this duration.
 - Phase F: 1 month in fiscal year five, with personnel count multiplied by 1/12 for the one month duration.
- Inflation: 2.8% yearly rate.
- Testing: Early testing because of descoping and cost risks.
- Risk Mitigation: Margin to prevent critical failures and adjust for schedule changes or budget overruns.
- Travel Cost: These are determined via the Mission Schedule and specific personnel requirements for each travel event. Rates for travel are based on the City Pair Program (CPP) for flights, U.S. Government rental car agreements for ground transport, U.S. General Services Administration (GSA) for per diem meals, and FedRooms for hotel costs.
 - KDPs: 5-day visits to NASA Headquarters in D.C. will be \$800 per flight, \$90 per diem, \$275 per night for hotel, and \$60 per day for

ground transport.

- Testing: Conducted at JPL, will be \$800 per flight, \$85 per diem, \$190 per night for hotel, and \$60 per day for ground transport.
- Mission Launch: 5-day visit to Cape Canaveral, Florida, will be \$800 per flight, \$74 per diem, \$170 per night for hotel, and \$60 per day for ground transport.
- Travel Margins: A 20% margin has been applied to travel.

This mission has a revised budget of \$180M in order to reallocate \$20M and 6 months of time to the Contractor delivering the DSS. This ensures that science remains the highest objective by ensuring a full 48 hour window of time for the aerobot to conduct its use of onboard instrumentation and communication. With strict adherence to a 45kg mass constraint, use of high-TRL technology, and early testing the budget will be able to accommodate this reallocation with additional margin to account for changes in scope and risk mitigation.

5.3.2 Total Mission Cost

The table below shows the updated budget for the mission. The budget shows projected costs across each fiscal year, which cover the categories personnel, travel, outreach, and direct subsystem development. Each section has appropriate margins assigned to ensure mission risk mitigation. The total mission cost is **\$174,171,081**, which is under the budget constraint of \$180M.

Table 20

	Phase C	Phase C	Phase C	Phase D-E	Phase F	
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	
Science Personnel:	2	2	2	6.5	0.92	
Engineering Personnel:	27	27	27	18	0.25	
Technicians:	3	3	3	1.5	0	
Administration Personnel:	19	19	19	19.5	1.5	
Management Personnel:	2	2	2	1.5	0.17	

NASA L'SPACE Mission Concept Academy Budget - <i>Aether Solaris</i>						
Mission Phase	Phase C	Phase C	Phase C	Phase D	Phase E-F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Cumulative Total
PERSONNEL						
Science Personnel	\$ 160,000	\$ 164,160	\$ 168,320	\$ 560,560	\$ 81,254	\$ 1,134,294
Engineering Personnel	\$ 2,160,000	\$ 2,216,160	\$ 2,272,320	\$ 1,552,320	\$ 22,080	\$ 8,222,880
Technicians	\$ 180,000	\$ 184,680	\$ 189,360	\$ 97,020	\$ -	\$ 651,060
Administration Personnel	\$ 1,140,000	\$ 1,169,640	\$ 1,199,280	\$ 1,261,260	\$ 99,360	\$ 4,869,540
Project Management	\$ 240,000	\$ 246,240	\$ 252,480	\$ 194,040	\$ 22,522	\$ 955,282
Total Salaries	\$ 3,880,000	\$ 3,980,880	\$ 4,081,760	\$ 3,665,200	\$ 225,216	\$ 15,833,056
Total ERE	\$ 1,082,908	\$ 1,111,064	\$ 1,139,219	\$ 1,022,957	\$ 62,858	\$ 4,419,006
Personnel Margin	\$ 1,389,614	\$ 1,425,744	\$ 1,461,874	\$ 1,312,684	\$ 80,661	\$ 5,670,577
TOTAL PERSONNEL	\$ 6,352,522	\$ 6,687,148	\$ 7,030,362	\$ 6,468,907	\$ 407,083	\$ 26,946,022
TRAVEL						
Total Flights Cost	\$ 8,800	\$ 11,200	\$ 19,200	\$ 52,000	\$ 3,200	\$ 94,400
Total Hotel Cost	\$ 176,500	\$ 280,630	\$ 344,280	\$ 121,340	\$ 4,400	\$ 927,150

Total Transportation Cost	\$ 55,860	\$ 89,460	\$ 110,160	\$ 43,020	\$ 1,200	\$ 299,700
Total Per Diem Cost	\$ 79,260	\$ 126,735	\$ 156,060	\$ 58,155	\$ 1,800	\$ 422,010
Travel Margin	\$ 80,105	\$ 131,161	\$ 167,792	\$ 75,453	\$ 3,004	\$ 457,515
Total Travel Costs	\$ 400,525	\$ 655,805	\$ 838,962	\$ 377,266	\$ 15,018	\$ 2,287,576
OUTREACH						
Total Outreach Materials	\$ 5,700	\$ 5,700	\$ 5,700	\$ 2,500	\$ 400	\$ 20,000
Total Outreach Venue Costs	\$ 21,400	\$ 21,400	\$ 32,100	\$ 9,150	\$ 1,600	\$ 85,650
Total Outreach Travel Costs	\$ 31,600	\$ 31,600	\$ 47,000	\$ 13,600	\$ 2,300	\$ 126,100
Total Outreach Services Costs	\$ 5,000	\$ 5,000	\$ 8,000	\$ 2,200	\$ 400	\$ 20,600
Total Outreach Personnel Costs	\$ 13,000	\$ 13,000	\$ 20,000	\$ 5,500	\$ 900	\$ 52,400
Outreach Margin	\$ 32,871	\$ 34,106	\$ 52,016	\$ 15,749	\$ 2,773	\$ 137,516
Total Outreach Costs	\$ 109,571	\$ 113,687	\$ 173,386	\$ 52,498	\$ 9,244	\$ 458,387
DIRECT COSTS						
Mechanical Subsystem	\$ 253,000	\$ 209,000	\$ 209,000	\$ 429,000	\$ -	\$ 1,100,000
Power Subsystem	\$ 1,380,000	\$ 1,140,000	\$ 1,140,000	\$ 2,340,000	\$ -	\$ 6,000,000
Thermal Control Subsystem	\$ 1,150,000	\$ 950,000	\$ 950,000	\$ 1,950,000	\$ -	\$ 5,000,000
Comms & Data Handling Subsystem	\$ 1,587,000	\$ 1,311,000	\$ 1,311,000	\$ 2,691,000	\$ -	\$ 6,900,000
Guidance, Nav, & Control Subsystem	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Science Instrumentation	\$ 10,833,000	\$ 8,949,000	\$ 8,949,000	\$ 18,369,000	\$ -	\$ 47,100,000
Spacecraft Cost Margin	\$ 12,438,818	\$ 10,771,856	\$ 11,290,221	\$ 24,287,032	\$ -	\$ 58,787,928
Total Spacecraft Direct Costs	\$ 27,641,818	\$ 23,937,459	\$ 25,089,381	\$ 53,971,183	\$ -	\$ 130,639,841
Manufacturing Facility Cost	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -

Test Facility Cost	\$ 1,311,000	\$ 1,083,000	\$ 1,083,000	\$ 2,223,000	\$ -	\$ 5,700,000
Facility Cost Margin	\$ 145,667	\$ 123,820	\$ 127,326	\$ 268,594	\$ -	\$ 665,407
Total Facilities Costs	\$ 1,456,667	\$ 1,238,197	\$ 1,273,263	\$ 2,685,938	\$ -	\$ 6,654,065
Total Direct Costs	\$ 29,098,485	\$ 25,175,656	\$ 26,362,644	\$ 56,657,121	\$ -	\$ 137,293,906
Total MTDC	\$ 27,641,818	\$ 23,937,459	\$ 25,089,381	\$ 53,971,183	\$ -	\$ 130,639,841
FINAL COST CALCULATIONS						
Total F&A	\$ 1,520,300	\$ 1,316,560	\$ 1,379,916	\$ 2,968,415	\$ -	\$ 7,185,191
Total Projected Cost	\$ 37,481,404	\$ 33,948,855	\$ 35,785,270	\$ 66,524,206	\$ 431,345	\$ 174,171,081
Total Cost Margin	\$ 14,087,076	\$ 12,486,687	\$ 13,099,230	\$ 25,959,513	\$ 86,438	\$ 65,718,943
	37.6%	36.8%	36.6%	39.0%	20.0%	
Total Project Cost	\$ 37,481,404	\$ 33,948,855	\$ 35,785,270	\$ 66,524,206	\$ 431,345	\$ 174,171,081

5.3.3 Personnel Budget

In this personnel cost estimate, the personnel is allocated across each phase with an expectation of 30-50 personnel per phase, a fluctuation in personnel count across phases, and a budget constraint of \$20M. Personnel cost is estimated using the schedule estimate and personnel count estimate. Additionally, the beginning of each fiscal year begins in October.

Using the schedule estimate it is apparent that Phase C is 36 months and spans the first three fiscal years. Phase D in fiscal year four will span 5 months, but the personnel will be allocated an additional month while the aerobot is in flight to Venus. Phase E also in fiscal year four will span one month but the personnel will also be allocated the remaining 5 months of flight to oversee. Phase F will begin in the fifth and final fiscal year lasting one month. Considering this the full mission phases C through F will be five fiscal years. The personnel is allocated according to the table Tbl5.1-02 by each need in each Phase and spread across these five fiscal years. Note the personnel count for Phases C and D are equal due to relocation of testing which will occur alongside design and fabrication in Phase C.

Fiscal years one, two, and three will see a team of personnel with a full year's worth of salary thus the number of personnel remains unchanged. Fiscal year four will see the same personnel from Phase C entering Phase D. However Phase D will only be lasting 5 months. To account for this in the cost estimate the personnel count for phase D had been multiplied by the fraction $\frac{1}{2}$ signifying the 6 months out of the year they will be paid for. They will be paid six months because though Phase D will last 5 months the personnel will be kept on between Phases D and E for an additional month within this fiscal year (FY4). For this fiscal year this resulting personnel number will be added to Phase E's resulting number. Phase E will only be lasting one month this fiscal year but the personnel will be brought on 5 months earlier to oversee the remainder of the flight to Venus. Their count will be multiplied by $\frac{1}{2}$ much like Phase D and will be added as mentioned prior. Finally Phase F will be starting in the fifth fiscal year and only last one month so the personnel count will be multiplied by $\frac{1}{12}$ to signify this. With each personnel's expected salary detailed in the Cost Basis of Estimate the personnel margin of 28% is applied and the Personnel cost estimate results in a total of \$26,946,022. While this is over the originally planned \$20M this is an acceptable and expected outcome considering this includes the margin and for the personnel needed for the mission from phases C through F and is resultant of reallocation of resources from the original descope plan of reallocating \$20M and six months. Due to testing times occurring earlier, personnel count increased for Phase C.

	Phase C	Phase C	Phase C	Phase D-E	Phase F	
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	
Science Personnel:	2	2	2	6.5	0.92	
Engineering Personnel:	27	27	27	18	0.25	

Technicians:	3	3	3	1.5	0	
Administration Personnel:	19	19	19	19.5	1.5	
Management Personnel:	2	2	2	1.5	0.17	
Mission Phase	Phase C	Phase C	Phase C	Phase D-E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Cumulative Total
PERSONNEL						
Science Personnel	\$ 160,000	\$ 164,160	\$ 168,320	\$ 560,560	\$ 81,254	\$ 1,134,294
Engineering Personnel	\$ 2,160,000	\$ 2,216,160	\$ 2,272,320	\$ 1,552,320	\$ 22,080	\$ 8,222,880
Technicians	\$ 180,000	\$ 184,680	\$ 189,360	\$ 97,020	\$ -	\$ 651,060
Administration Personnel	\$ 1,140,000	\$ 1,169,640	\$ 1,199,280	\$ 1,261,260	\$ 99,360	\$ 4,869,540
Project Management	\$ 240,000	\$ 246,240	\$ 252,480	\$ 194,040	\$ 22,522	\$ 955,282
Total Salaries	\$ 3,880,000	\$ 3,980,880	\$ 4,081,760	\$ 3,665,200	\$ 225,216	\$ 15,833,056
Total ERE	\$ 1,082,908	\$ 1,111,064	\$ 1,139,219	\$ 1,022,957	\$ 62,858	\$ 4,419,006
Personnel Margin	\$ 1,389,614	\$ 1,425,744	\$ 1,461,874	\$ 1,312,684	\$ 80,661	\$ 5,670,577
TOTAL PERSONNEL	\$ 6,352,522	\$ 6,687,148	\$ 7,030,362	\$ 6,468,907	\$ 407,083	\$ 26,946,022

Table 21

5.3.4 Travel Budget

The teams that span Phases C through F will need to travel for three distinct reasons: Testing, KDPs, and Mission Launch. The fiscal year that each test, KDP, and launch occurs is determined via the Mission Schedule. Fiscal year one will contain Vibration Isolation System Design & Testing and KDP C. Fiscal year two will contain Power Regulation Circuit Design & Testing and Data Storage & Fault-Tolerant System Testing. Fiscal year three will contain Mechanical Stress & Vibration Tests, Power Efficiency Tests, Thermal Stress Tests, and Electromagnetic Interference Testing. Fiscal year four will contain Thermal Vacuum and Environment Testing, KDP D, and the Mission Launch. Finally, fiscal year five will contain KDP F.

Specific personnel will need to attend particular testing, vital personnel will need to attend each KDP relevant to their phase, and all personnel will be welcomed and accounted for in Mission Launch. To estimate each travel cost and to determine rates

the estimate uses the City Pair Program (CPP) for fares, U.S. Government rental car agreement for ground transportation, U.S. General Services Administration (GSA) for per diem meals, and FedRooms for hotel costs.

Each KDP will be a visit of five days in D.C. at NASA Headquarters. The expected rates per individual travel cost are \$800 for a flight to D.C., \$90 per diem meals, \$275 a night for Hotel, and \$60 a day for ground transport. All Testing is expected to occur at JPL and the expected rates per individual travel cost are \$800 for a flight to D.C., \$85 per diem meals, \$190 a night for Hotel, and \$60 a day for ground transport. Finally for the mission launch which is expected to be five days at Cape Canaveral Florida the expected rates per individual travel cost are \$800 for a flight to D.C., \$74 per diem meals, \$170 a night for Hotel, and \$60 a day for ground transport.

All travel rates were multiplied by the number of personnel traveling to that objective and multiplied by the amount of days and/or nights they will be present. All flights are expected to be round trip and the allocated margin for travel is 20%. All expected travel costs are logistically reasonable and a 20% margin provides a comfortable buffer of \$544,316. The use of this margin most likely be allocated towards testing in case personnel need more time to test of which this amount allocates 1,623 additional days that may be distributed accordingly. These days were found by subtracting known fixed JPL travel costs and dividing that outcome by the costs that needed to be multiplied by the days to solve for the variable "days."

The final estimated cost of travel is \$2,287,576. The original budget allocation was 1% of 200M. While the cost estimate is over the original allocation there are other cost categories that are under their allocation of which that budget may be allocated to situations like this. This situation also already accounts for the margin applied thus this is an acceptable outcome.

TRAVEL						
Total Flights Cost	\$ 8,800	\$ 11,200	\$ 19,200	\$ 52,000	\$ 3,200	\$ 94,400
Total Hotel Cost	\$ 176,500	\$ 280,630	\$ 344,280	\$ 121,340	\$ 4,400	\$ 927,150
Total Transportation Cost	\$ 55,860	\$ 89,460	\$ 110,160	\$ 43,020	\$ 1,200	\$ 299,700
Total Per Diem Cost	\$ 79,260	\$ 126,735	\$ 156,060	\$ 58,155	\$ 1,800	\$ 422,010
Travel Margin	\$ 80,105	\$ 131,161	\$ 167,792	\$ 75,453	\$ 3,004	\$ 457,515
Total Travel Costs	\$ 400,525	\$ 655,805	\$ 838,962	\$ 377,266	\$ 15,018	\$ 2,287,576

Table 23

5.3.5 Outreach Budget

The outreach budget was developed by dividing outreach into four Mission Phases (C-F). The expenses were then distributed across five fiscal years (FY1-FY5)

accordingly. The total estimated outreach cost is \$458,387, which is well under the allocated 1% or \$1.8M that was originally budgeted. The final total was allocated based on project needs and cost expectations by validating travel costs with official U.S. Government rates according to the resources within the Mission Task document. Phase C which will span FY1, FY2, and FY3 will focus on initial outreach setup, content development, and early engagement then end with larger expenses. The estimated cost was distributed across FY1 and FY2 to reflect the gradual implementation that will occur. FY3 is the most expensive period of the outreach plan due to the large number of events. Such events will be the 5k races spanning 13 NASA locations, college engagement, and K-12 programs. These events will need higher personnel counts, venues, and travel costs included in the estimate. Finally phases D-F in FY4 and FY5 are a transition into greater social media presence/interaction and final mission outreach. Because of this, there will be a sharper cost decline compared to other fiscal years.

Each cost category was allocated an appropriate amount depending on expected needs. For outreach materials, there was an expected cost for digital flyers, social media production equipment, and educational resources for schools and colleges. Due to the outreach scale, this increases significantly for FY3 but decreases in FY4. The total cost increase in FY3 also is contributed by Venue costs plus Personnel costs amounting to a larger cost estimate. This particularly includes the NASA 5k races and college outreach spaces.

Travel costs needed to be estimated for outreach efforts which is to be a total of \$126,100 accounting all fiscal years. This estimate was determined by using the City Pair Program (CPP) where rates were used to determine airfare. The higher fares averaged \$600 per round trip for domestic travel. Lodging costs were based on FedRooms hotel rates averaging \$150 per night. Ground transportation costs were based on calculations from the U.S. Government rental car agreement, and this caps at a standard rental rate of \$55 per day. Meal costs adhered to U.S. General Services Administration (GSA) per diem allowed amount. This ranged from \$59 to \$79 per day depending on the location.

The determined outreach margin is 30% based upon the given amounts from the Project Management skills module and results in a total margin of \$137,516 distributed uniquely across all fiscal years. As stated previously including margin the total outreach expected costs are well under the 1% budget cap allocated to outreach which leaves flexibility for additional reallocation as necessary. By using federal cost standards, real event pricing, and logical planning, this cost estimate reflects a realistic and cost-effective approach to public outreach and engagement for the Aether Solaris mission.

OUTREACH

Total Outreach Materials	\$ 5,700	\$ 5,700	\$ 5,700	\$ 2,500	\$ 400	\$ 20,000
Total Outreach Venue Costs	\$ 21,400	\$ 21,400	\$ 32,100	\$ 9,150	\$ 1,600	\$ 85,650
Total Outreach Travel Costs	\$ 31,600	\$ 31,600	\$ 47,000	\$ 13,600	\$ 2,300	\$ 126,100
Total Outreach Services Costs	\$ 5,000	\$ 5,000	\$ 8,000	\$ 2,200	\$ 400	\$ 20,600
Total Outreach Personnel Costs	\$ 13,000	\$ 13,000	\$ 20,000	\$ 5,500	\$ 900	\$ 52,400
Outreach Margin	\$ 32,871	\$ 34,106	\$ 52,016	\$ 15,749	\$ 2,773	\$ 137,516
Total Outreach Costs	\$ 109,571	\$ 113,687	\$ 173,386	\$ 52,498	\$ 9,244	\$ 458,387

Table 22

3.6 Direct Costs

Cost Estimation Method for Direct Cost

The direct costs for the Aerobot were estimated using the NASA Mission Concept Cost Estimating Tool (MCCET) and the calculated Cost Estimating Relationships (CERs). These CERs were derived from each subsystem's kilogram mass and with each subsystem's max power draw in Watts. Each subsystem includes the Mechanical, Thermal, Power, Command, and Data Handling (CDH) and Payload (science instrumentation) subsystems. Each subsystem was assessed using the corresponding CER based on the mass and function of the subsystem. For example, the Mechanical subsystem's CER was based on the mass and power draw using the formula $\text{MechMass}^{0.41} \times \text{TotalMaxPwr}^{0.52}$. Another example with the thermal subsystem which followed a formula only on its mass, $\text{ThermMass}^{0.62}$. For the electronic-based systems that were CDH and Power the CERs used the electronic subsystem equations and the masses of both were combined. Inflation, about the 2004 USD, was applied in the MCCET according to the starting year for each subsystem manufacturing and testing. Mechanical and Thermal starting in 2025 had an inflation rate of 170.53% applied and so forth for the other subsystems.

Once the CER was calculated for each subsystem the MCCET was able to generate cost estimates for each Phase in the mission cycle for both manufacturing and testing. These costs were then distributed across the first four fiscal years: Phase B in Fiscal year one, Phase C evenly distributed across fiscal years one, two, and three, and Phase D in fiscal year four. Fiscal year five contains Phase F only which will incur no direct costs resulting in \$0 for both manufacturing and testing. Additionally, no in-house

manufacturing will take place, and no need for navigation subsystems resulting in \$0 for both manufacturing facility cost and Guidance, Nav, & Control Subsystem categories.

Instrumentation Cost Estimation

Science instrumentation followed the same steps within the MCCET as the other subsystems but used different CER equations based on the nature of each instrument. The Time of Flight Mass Spectrometer used the Particles Planetary Instruments equation which incorporated the mass and power draw:

$223 * \text{Mass}^{0.31} * \text{Power}^{0.44} * \text{DsgnLife}^{0.52}$. The design life for all instruments is 6.64 months which is the time from launch to end of mission. This selection was made because of the particle-based data collected by this instrument. The optical instruments, SPICAM and Longwave Infrared Camera used the Optical Planetary Instruments equation: $392 * \text{Mass}^{0.45} * \text{Power}^{0.49} * \text{DsgnLife}^{0.32}$. Lastly, the infrasound detector was estimated using the Fields INstruments CER equation:

$1470 * \text{Mass}^{0.29} * \text{Power}^{0.36}$. This was because the instrument has a passive sensing role in the Aerobot. All instrumentation estimates followed the distribution across each fiscal year as the other subsystems had and inflation was based on the 2028 manufacturing and testing start date with an inflation reflecting this year at 183.64%.

Total Direct Cost Estimate and Margin

The total direct cost estimate is made using a margin of 45%. This is 5% below industry standard though the final total budget estimate lies underneath the max of \$180M where a lot of funds can still be reallocated especially from the outreach budget estimate. The remaining funds of roughly \$5.8M can be reallocated to the total direct cost estimate of **\$137,293,906**.

DIRECT COSTS					
Mechanical Subsystem	\$ 253,000	\$ 209,000	\$ 209,000	\$ 429,000	\$ 1,100,000
Power Subsystem	\$ 1,380,000	\$ 1,140,000	\$ 1,140,000	\$ 2,340,000	\$ 6,000,000
Thermal Control Subsystem	\$ 1,150,000	\$ 950,000	\$ 950,000	\$ 1,950,000	\$ 5,000,000
Comms & Data Handling Subsystem	\$ 1,587,000	\$ 1,311,000	\$ 1,311,000	\$ 2,691,000	\$ 6,900,000
Guidance, Nav, & Control Subsystem	\$ -	\$ -	\$ -	\$ -	\$ -
Science Instrumentation	\$ 10,833,000	\$ 8,949,000	\$ 8,949,000	\$ 18,369,000	\$ 47,100,000
Spacecraft Cost Margin	\$ 12,438,818	\$ 10,771,856	\$ 11,290,221	\$ 24,287,032	\$ 58,787,928
Total Spacecraft Direct Costs	\$ 27,641,818	\$ 23,937,459	\$ 25,089,381	\$ 53,971,183	\$ 130,639,841

Manufacturing Facility Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Test Facility Cost	\$ 1,311,000	\$ 1,083,000	\$ 1,083,000	\$ 2,223,000	\$ 5,700,000
Facility Cost Margin	\$ 145,667	\$ 123,820	\$ 127,326	\$ 268,594	\$ 665,407
Total Facilities Costs	\$ 1,456,667	\$ 1,238,197	\$ 1,273,263	\$ 2,685,938	\$ 6,654,065
Total Direct Costs	\$ 29,098,485	\$ 25,175,656	\$ 26,362,644	\$ 56,657,121	\$ 137,293,906
Total MTDC	\$ 27,641,818	\$ 23,937,459	\$ 25,089,381	\$ 53,971,183	\$ 130,639,841

Table 24

5.4 Scope Management

5.4.1 Change Control Management

Team 28 is tracking and implementing mission changes through a spreadsheet and in specific channels in the team's server. Major changes that require a "Change Request Form" and may potentially involve the Change Control Board (CCB) will be tracked through the spreadsheet and the "Change Request Forms" thread located in the "change-control" channel. The CCB is a group of mentors whom will request "justification for change" verbally through a video call (L'SPACE 2025). Other frequent uses of the CCB may involve meeting with "stakeholders and relevant Subject Matter Experts (SMEs)" in which a request will be stated (L'SPACE 2025).

The Change Request Form is located in the "change-control" channel for easy access. The change request process begins with team members discussing with their specific discipline lead and informing other leads if necessary. This form shall only be completed if a change to the mission is made after it has been baselined. This form shall not be filled out for stakeholder requests and only for internal-team requests. Once a request for change is approved by the internal team, the specific discipline team lead and initiator of the change request will complete the Change Request Form together or with other team members if needed. When completing the form, individuals will make sure to read the instructions at least twice to ensure that the request form's requirements are met. After acknowledging the requirements, members will fill out the required boxes which include: the description of requested change, the reason for change and its impact, its timeline and action plan, and trade study if relevant. Each request shall list the team number, date of request, area of change regarding discipline or in other words science, engineering, programmatic, or multiple categories, and change level indicating the risk of minor, moderate, or extreme. For more specific information, team members shall access the Change Request Form. After completing all requirements for the form, the respective individuals shall send the request to their Student Success Advisor (SSA) and L'SPACE (LSPACE-MCA@asu.edu) by email to be notified for an approval, denial, or a request for a CCB. If a CCB is required, all

individuals who participated in filling the form are highly recommended to attend. In the case of an emergency status, other team leads or specific discipline-based members the change is geared toward will take place to attend. Finally, each request initiated by a discipline member shall be frequently updated onto the “Change Request Forms” thread located in the “change-control” channel as well as the spreadsheet (refer to last paragraph section for more information).

Regarding the team’s decision-making process specific to change control besides accounting stakeholder requests, the “decision-making process” in section 1.5 will continue to apply. This process will occur prior and after requests have been processed. The team will ensure that the highest mission risk factors will be a prioritized task. However, various attributes such as costs, schedule, shipment, and more will be considered as well. Other tasks that have lower risks and have high costs, a longer schedule and shipment time, and lack of availability will be prioritized last compared to a change request that is urgent, has a low schedule time to complete, and can potentially alter other processes for instance. Thus, the items will be considered in the following order: risk, science, schedule, cost.

Minor changes that are deemed significant will be uploaded into the “change-control” main directory to keep team members updated on in-progress statuses, changes, and completed sections. For instance, a message like “Inserted Mechanical engineering subsystem requirements (1.5.2.1)” or “Finalized Change Control (1.7.6)” will allow members to note which tasks have been completed or updated. A document or spreadsheet may be created in the future to organize the timeline of updates if necessary. Minor changes will also be tracked in meeting notes. Team members are able to catch up on changes by consistently keeping up with reading meeting notes if meetings are missed. Major changes to deliverables will be documented in the “deliverables” channel. Meanwhile, the “task” channel in the server refers to request for action (RFAs) and advisory (ADVs). RFAs and ADVs shall also be set on meeting notes and discussed in the general team meetings. This ensures the fulfillment of action items which must be implemented in the team’s future deliverables and highly encouraged implementations to be considered. Though this is the procedure for team-requested and internal changes made to the mission during development, this also briefly applies to customer-requested changes. Regarding customer-request changes or feedback from external stakeholders, the team will prioritize requests accordingly and address requests as a top priority in the task channel. This will ensure that the mission’s goals are aligned. Unlike internal changes that will be evaluated and discussed before implementation and documentation, customer-requested changes will be fulfilled and documented.

Additionally, as stated before, request change forms shall be discussed as a team if applicable and updated accordingly based on the “decision-making process” established. Refer to section 1.5 Team Management Overview in the MDR for more information. For request changes directed toward a specific discipline, members should contact the team lead for that discipline and leave a message in the change log channel containing the information required. Members shall also update their message onto the “Change Request Form Tracker” depicted below for simplicity purposes. Again, Team 28 will facilitate this process by posting documents and messages (i.e. section changed [while including if the change is internal or external], name, summary) to indicate

changes. Individuals shall place the date of when the change was made and or approved. A brief summary or indication of what was changed shall also be included. An implementation of discipline task trackers has also been voted as an idea for team organization. This will be used for team leaders to manage subteams to make it easier for the team to be top of assignments and know when to submit extension requests in the future. The tracking system has ultimately been working in-place as current updates to the SRR are frequently updated to ensure that the team is on board. There has been no involvement with the CBB as the team has updated sections where feedback was already given and advised. Discipline Tracking Example (Engineering):

Fig 26

	A	B	C	D	E	F	G
1	Task Name	Subsystem	Person Assigned To	Start Date	End Date	Status	Priority
2	Spacecraft overview	Engineering (all)	TBD	2/26/2025	03/08/2025	Not started	Normal
3	Create CAD/Sketch of Spacecraft Design	Engineering (all)	TBD	2/26/2025	03/08/2025	Not started	Normal
4	Mechanical Subsystem Requirements	Mechanical	TBD	2/26/2025	03/08/2025	Not started	Normal
5	Mechanical Subsystem Overview	Mechanical	TBD	2/26/2025	03/08/2025	Not started	Normal
6	Mechanical Trade Studies	Mechanical	TBD	2/26/2025	03/08/2025	Not started	Normal

Discipline Tracking Example (Template):

Fig 27

Task Name	Subsystem	Person Assigned To	Start Date	End Date	Status	Priority	Notes/Updates
Team Organization	Programmatic (all)	TBD	2/26/2025	03/07/2025	Completed	Normal	
Schedule Basis of Estimate	Program Analyst	TBD			Not started		
		TBD			Not started		
		TBD			Not started		
Cost Basis of Estimate	Programmatic (all)	TBD	2/26/2025	03/08/2025	In progress	Normal	
Salaries/Personnel Costs	Programmatic (all)	TBD	2/26/2025	03/08/2025	Not started		
		TBD			Not started		

Change Request Form Tracker (Example):

Fig 28

Team	Date	Task Section	Description of Change	Document Link
Team 28	2/16/2025	Change Request Form	Tracker (MCA)	1/1 completed
☒	2/16/2025	1-0-1	Example change (Mark off checkmark when approved)	https://docs.google.com/
☐				
☐				
☐				
☐				

5.4.1 Scope Control Management

In the case that a scope change is needed, Team 28 plans to discuss as a whole through general meetings. Each discipline team lead will be responsible for evaluating pre-scope establishments and distributing tasks for research in order to adjust and adapt to any scope changes. After a general idea is gathered, each discipline will

present potential adjustments to the mission to be approved or denied through the “decision-making process” as highlighted in section 1.5 MCA Team Management Overview.

To prepare for situations where the team is met with the task of scoping changes, such as cost or schedule overruns, the team has taken the following precautions. Each Subsystem is analyzed for their cost, TRL, risk level, and other constraints, such as mass and power draw. The TRL consists of various “type of measurement system used to assess the maturity level of a particular technology” (National Aeronautics and Space Administration 2023). In addition, there is an emergency fund kept in case any surprise costs arise. As the science objectives are deemed the highest priority, the decisions of the team will be based on ensuring that all of the data needed is still collected. While there are redundant systems on board, some of the lower risk components’ redundancies can be dropped.

Due to excess and emergency funding, team leads will work with the program manager and the insurance fund manager to distribute any funding toward disciplines that urgently need assistance. Each discipline will reach out to the team leads and notify them about any assignments that will need more allocated time, funding, and commitment. Extra resources to benefit the mission could include hiring more personnel to speed up the efficiency of tasks or addition of more powerful or reliable resources and materials to meet mass or certain requirements. This will highly depend on the direct costs section when updated respectively. See section 1.10.6 Direct Costs.

Any scope ideas and adjustments will be documented thoroughly and any changes will be tracked through a potential spreadsheet for easy readability and the “Scope Control Management” thread located in the “change-control” channel. Major changes will be listed as RFAs in the “task” channel as listed in the change control as well as ADVs for less urgent duties.

In the case of downscoping, the team will ensure that there will be effort to maintain and preserve the core mission objectives as a number one priority. Safety requirements are fulfilled and met as an urgent task. Cost and schedule adjustments will include reallocating resources to high-priority tasks to fulfill mission goals. An evaluation of ensuring that Team 28 only acquires the necessary tools or instruments aboard will be crucial. Any miscellaneous instruments will be removed to reduce costs and current components may be compared and substituted for cheaper but suitable materials. The effects of manufacturing time will also be taken into account.

In the event where an increase in scope is needed, Team 28 will reassess the budget to determine how areas can be improved with additional or better resources to mitigate risks further while attempting to achieve more goals.

Moreover, Team 28’s business handlers or deal makers will take charge in negotiating with vendors and suppliers for potential price reductions. The main job is to determine if there are alternative options that Team 28 can explore to reassess plans while fulfilling the quality and standards of the mission goal. The vice versa shall apply in the case of expanding a scope where more time and funding is given to validate testing, reliability, and to enhance the mission’s success.

Nonetheless, scoping methods will differ at different points in the mission life cycle. For instance, during the development phase where changes have not been fully baselined, scope changes will be implemented with more ease and successfully.

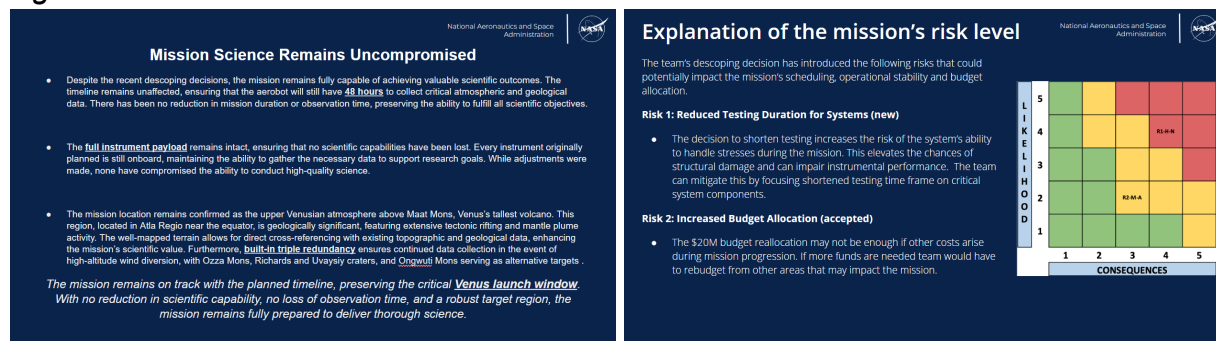
However, when systems have already been built and are in the process of testing, it will become more challenging for Team 28 to adjust accordingly. Through the later phases of the mission life cycle, it will be the team's job to keep the core of the system design together unless in the case of fatal errors and risks beyond recovery which may cause the mission to be cancelled.

An example of descoping that Team 28, Aether Solaris, has had to handle for the mission includes an unforeseen issue with the Aerostat's balloon material. The manufacturer gave and provided the team two options: a reduction of 12 hours of operational time, or an additional 6 months, \$20 million dollars, and a reduction of 5 kg of the team's system, to avoid a 12 hour decrease in operational time. To make this decision, the team looked at the emergency budget, current mass of the system, and the schedule to determine what option was best. With approximately a 40% emergency budget, an underweight system, and some wiggle room in the schedule, the team decided to allocate the necessary resources to the contractor to keep the original mission operation time of 48 hours.

To help ensure this choice did not affect the current launch date, the team will move forward with choosing technology with higher TRL's in order to reduce testing time, as well as beginning testing earlier alongside initial system assembly. This will be an instance in where extra funds may be utilized as it will allow Team 28 to opt for higher TRL components and invest in extra testing or research to reduce risks.

Example Risk Scope Documentation:

Fig 1.11.2-01



5.5 Outreach Summary

The Aether Solaris mission is redefining outreach by implementing an interactive and immersive approach to public engagement. The goal is to ignite curiosity and interest by blending entertainment with education. Through immersive activities, exclusive digital content and collaborative experiences, a passion for STEM and Space will reach a global scale. This mission aims to fulfil the human desire to belong and connect with something greater than oneself. Creating a movement that people will seek to be involved in, signifies the dawn of a revolution in space exploration. It will make Aether Solaris more than just a single mission, it will dare to incite passion and forge a foundation for the emerging wave of innovators.

In today's technologically advanced world, it is easier than ever now to connect with a global audience. With 69.3% of the world's population using social media, online platforms have become a valuable tool for outreach (Chaffey). Research shows that the top platforms among users today are Youtube, Instagram, Facebook and Tik-Tok (Chaffey). In Phase 1 of the social media outreach plan Aether Solaris will be utilizing these top social platforms in order to promote this extraordinary Venusian mission. The goal of this social media outreach is to engage a wide range of audiences, promote STEM resources, and educate the public on the Aether Solaris mission. This will be done by creating an intimate experience for users where they feel just as part of the mission as the team members actively involved. On Instagram, Tik-Tok and Facebook fun interactive themed content days will be created. This allows the public to directly engage with the team. Monday-Thursdays and Saturdays will focus on the Aether Solaris mission and details involving the progression of the mission. Mechanical Monday will be hosted by the team's mechanical engineers, beginning with introductions where they share their educational and career journey along with personal insights to connect with the audience. Every week the segments will progress, featuring interactive elements like live Q&A sessions, interesting facts, and short behind the scene content from the engineers and scientists. The rest of the themed days will follow a similar structure. Thermal Tuesdays will focus on heat protection, while Wired up Wednesday will dive deep into power systems and energy. Technical Thursday will highlight software and AI advancements. Frontier Fridays will showcase previous NASA missions, in order to educate on foundational aerospace journeys. Science Saturdays will explore subjects such as planetary science, with Venus as the center. Sundays will be a bit different and focus on the social aspect of this mission. Sundays will be used to promote outreach events and opportunities for in-person engagements happening in different cities across the U.S. These in-person events will also be live streamed in order to allow others to still be involved virtually. Youtube will be the platform where longer video content will be posted with behind the scene details throughout the development of the mission, along with more in-depth and detailed information about the different subsections involved in the mission.

Similar to that of the Lucy Ambassador program, Aether Solaris will introduce the Solaris Scholars program. Under the umbrella of the Solaris Scholars Program there will be two different tiers. Through these multiple sections individuals that have multiple backgrounds can become involved in the mission. There will be an academic tier and a community tier.

The community tier will be called the Social Solaris Program, intended to coalesce local business and the common space enthusiasts through grassroots engagement. Local venues such as bookstores, museums, and coffee shops can become Social Solaris Facilitators. They can achieve this by completing a short onboarding process, where they complete short modules which will result in them

earning a Certified Aether Solaris Social Venue certificate. These businesses can then host space themed events like poetry nights, info sessions, trivia games and open space jamming days. They can also create and offer mission themed items like Aether Lattes, Hot Venusian Paninis or Solaris Snickerdoodles. All these events and goodies will help build enthusiasm and awareness within the community! This community program introduces an artistic and fun way to spread the word. It allows individuals to showcase their talents and creativity with our mission and planet Venus being their muse.

The academic tier of the Solaris Scholars Program involves a unique opportunity for STEM undergraduate and graduate students who are interested in space exploration and communication. The Solaris Internship program is an unpaid, volunteer initiative that will allow selected students to work directly with a specific subsystem based on their academic interest. Their primary tasks and responsibilities will be to synthesize the complex knowledge of their domain by producing easy to digest content. These interns will be in charge of the content creation of the social media theme based days. Implementing digital media production skills is a great way to cross train in communication and presentation skills, which are valuable to have in the current technical climate. This model is essentially a modern version of powerpoint presentations. Instead of presenting to a panel of individuals that already know the program and mechanics involved in the mission. Students will be able to showcase content to people who may have no knowledge in anything space or engineering related. It will enhance their ability to adapt knowledge for diverse audiences, creating equity and bridging the gap between society and STEM. While the program is unpaid, participants will receive a strong letter of recommendation from the NASA team. This will offer them strong credential support for their career and academic growth.

The K-12 outreach initiative will consist of after school workshops, classroom engagement, and digital learning tools in order to foster accessibility for students across different grade levels. A teacher training and certification program will be implemented in order to provide STEM teachers educational resources and materials. The Mini Scholaris program will be for elementary school students. It will focus on animated content videos, fun worksheets and hands-on activities. They will have access to online modules where they can earn badges after completing mini quizzes and they can unlock fun rewards like printable posters. For middle school students the Junior Solaris program will consist of learning modules, interactive activities and challenges. They will also be able to earn badges and a certification once they complete the online and in-person sessions. High school students will be able to participate in a more in-depth program where they can learn more about specific subsystems of interest. They will be able to be part of a team where they can create their own simulated Venusian mission. A virtual end of the year program will be available to participating students where they

can showcase their mission to a panel of Aether Solaris interns and team members. After school classes that participate in these workshops will be invited to tour their local NASA facility if they are located within range of that area. Virtual tours will be offered to students in locations without direct NASA facility access. This outreach plan aims at planting the seed for younger generations to lean into their curiosity and passion for STEM.

The college outreach initiative will be designed to inform and educate students on mission objectives and opportunities. Through hands-on experiences, guest speakers and interactive sessions the mission team will build connections with students in order to inspire interest. Guest speaker sessions will be the main component to college and university outreach. Through pre-recorded videos and live Q&A sessions through Zoom, team members will be able to discuss the ongoing process of the mission and answer questions in real-time. Other ways that the Aether Solaris will be integrated into college communities will be through STEM clubs, Career Fairs and STEM Engagement events. At these events there will be a booth set up providing information materials, demonstrations and networking opportunities. Students will also have access to learn about the Aether Solaris Scholars program and how they can contribute to the mission.

Community 5K

Post pandemic public mass behavior has trended towards more physically centered events. The United States currently holds the largest number of people who run in the world (Crane). So much so, that popularity of running has increased by 57% in the last 10 years (Crane), making it an ideal event for community involvement. In order to foster enthusiasm and a spirit of collaboration there will be an Aether Solaris 5K walk/run. This event will take place across 13 cities that are home to NASA facilities, with the grand finale being at the mission's launch site. Aside from the race, this event will give participants the opportunity to actively contribute to the mission through a fundraising opportunity. The top five financial contributors will earn access to attend the mission launch in person. To ensure inclusivity, the top racers from each age division will also receive an invitation to be part of the launch. This creates an athletic achievement and fundraising balance. The slogan for the event will be "Finish Strong Before Takeoff", runners and walkers will be encouraged to dress in their favorite space-themed attire.

Merchandising

The outreach team has designed a logo for the Aether Solaris mission. This logo will allow the public to have a visual representation of this journey. The color scheme of the logo involves bright gold, along with chic tones of grey and white. Aether is the name of the god of the light in Greek mythology. With this in mind the logo was designed to emphasize a divinely elegant visual. Making it appealing to wear and in any setting. Through a pay for print website the team will have merchandising options for

sale, such as t-shirts, sweatshirts, hoodies, tote bags and hats. The team will act as the models during their content videos and will sport the Aether Solaris branded apparel.

Fig 1.12-01



6. Conclusion

In this mission a specialized aerostat will be conducting research on Venus's atmospheric composition and determining whether Venus is volcanically active. The aerostat will feature two different spectrometers (Time-of-Flight and SPICAM UV), infrasound sensor, and a long wave infrared camera to gather metrics to determine volcanic activity and composition of gases in the Venusian atmosphere. The risk levels and TRL for the project are mature and show high promise for a successful Discovery Expedition. After the PDR, the team will work on creating a presentation to explain the contents of the deliverable and transition towards receiving feedback to include in the following Critical Design Review.

Design Reference

Component: Wire Rope Isolator (Placeholder for IDC SM3-070-A)

Model Source: GrabCAD

File Type: STEP (.stp)

Link: <https://grabcad.com/library/wire-rope-isolator-1>

Note: Used as a placeholder geometry pending official model from manufacturer (IDC).

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

- No AI was used in this Document

Appendix (No page limit)

Resources and Examples

Spacecraft System Hierarchy

The [NASA Work Breakdown Structure \(WBS\) Handbook](#) has defined a standard system for the different levels of a mission. Your mission will primarily focus on the Payload and Spacecraft elements of the WBS, but there are many more elements that a full mission would consider. You should expand these elements to a minimum of level 4, but ideally level 5, which are the subassembly levels of a spacecraft design, when you come up with requirements and design your spacecraft. The NASA WBS system can be seen below, as well as an example of requirements following this hierarchy. For more information, please see the handbook linked above.

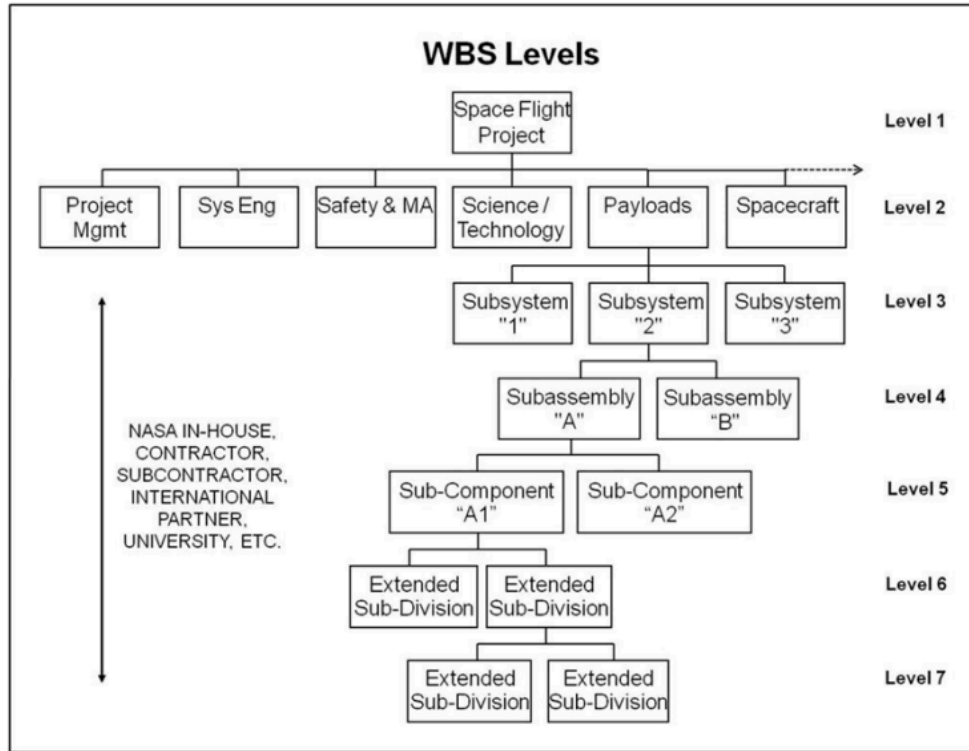


Figure 2-2: WBS Levels Illustration

WBS Level	Requirement ID	Requirement	Parent Req	Child Req	Notes
Level 1	MIS-1	Mission X shall investigate the Lunar South Pole for volatiles that will be valuable to future surface operations.		MIS-1.1	Derived from the Science Traceability Matrix
Level 2	MIS-1.1	Mission X shall be accomplished with a mobile spacecraft on the surface of the Lunar South Pole.	MIS-1	SYS-1	The spacecraft
Level 3	SYS-1	The spacecraft shall contain a thermal control system that maintains necessary operating temperatures.	MIS-1.1	TCS-1	The subsystems that make up the spacecraft
Level 4	TCS-1	The thermal control system shall use an active heating source to maintain the operating temperature ranges	SYS-1	TCS-1.1	The subassemblies that make up the subsystems

		between A and B degrees Celsius.			
Level 5	TCS-1.1	The active heating source shall not utilize radioactive material with a mass greater than C grams.	TCS-1		The sub-components that make the subassemblies

Requirements

Requirements at the sub-system level should be quantifiable and as detailed as possible. They should be a child requirement based on an already established top level requirement.

Having well defined and quantifiable requirements gives the team a numeric value to design and test for. See the requirements skill module for more information on developing well written requirements.

Recovery and Redundancy

Redundancy: Critical systems may require a backup system, composed of duplicate components, to ensure that if a failure occurs in the primary system, the mission critical requirements can still be met. Not every system will have a physical redundant system, and some components (such as the antennas or solar panels) would need to be documented as Single Point Failures (SFPs).

Recovery: If a system error occurs, what steps will you take to return to a safe configuration? For example, if a thermal sensor shows that a component is too hot, what will the spacecraft do to bring that component back to a safe operating temperature? Most recovery plans will be autonomous and therefore must be controlled by the software on the spacecraft (In the example above, software will need to execute something to fix the thermal issue, such as opening vents to allow heat dissipation into space, or swapping to your redundant backup system and powering off the primary components). Each system must work with the software team to create a recovery plan. (Note: "autonomous" here means that the commands are not coming from mission control (ie you). You need to be confident that your system can fix itself without your direct control since a lot of the time you will not be in contact with your spacecraft)

Manufacturing and Procurement

Describe your team's plans to manufacture your design, including estimated time it would take, the resources/people hours required, and whether or not your team will need to outsource the work to a manufacturing shop or will manufacture in-house at a

NASA center. Be as detailed as possible! Also, you should discuss your plan for integrating all of the vehicle system components. How will you ensure that all of the parts fit together? Explain your timeline for assembly and integration. Also, describe why the team has decided to either manufacture in house or contract out an external facility. If the team is manufacturing in house, which NASA center will handle the build. If the work is being outsourced, who will be contracted and why? Does the contractor have heritage with NASA/space missions? For integration, where will components be assembled? Try to think strategically. For example, think about where certain testing centers are or launch sites.

Verification

A preliminary verification plan should be made while a requirement is written. Typically this plan is no more than establishing the technique (Inspection, Demonstration, Analysis, or Test) that will be used for verifying a requirement.

After deciding on a verification method, a more detailed plan, including the requirements to complete that method, are developed. This can be done to a preliminary level at the PDR using a verification matrix.

Verification testing is often completed in controlled environments to ensure that the system, subsystem, component, or part meets the predefined requirements. Your team needs to outline how you plan to answer the question, “Did I build the product right?”. Verification should be conducted starting at the development stage, and should be completed before launch. Provide a detailed description of the necessary steps and tests needed to verify your design meets the system requirements you have defined.

If “Test” was chosen as a verification method, these are the key tests that may need to be performed.

Key Space Environmental Tests

Test	Purpose	Equipment / Facilities Needed
Vibration & Shock Testing	Ensure product will survive launch	Vibration table and fixture enabling 3-axis testing, and/or Acoustic chamber
Thermal Vacuum Testing	Induce and measure outgassing. Ensure product will perform in a vacuum under extreme flight temperatures	Thermal vacuum chamber. Equipment to detect outgassing (e.g. coldfinger or gas analyzer) as needed Instrumentation to measure temperatures
Electromagnetic Interference / Compatibility (EMI / EMC)	Ensure product does not generate EM energy that may interfere with other systems. Verify that the product is not susceptible to external EM energy	Radiated test: Sensitive receiver, anechoic chamber, antenna with known gain. Conduction susceptibility matched "box"

More information can be found here:

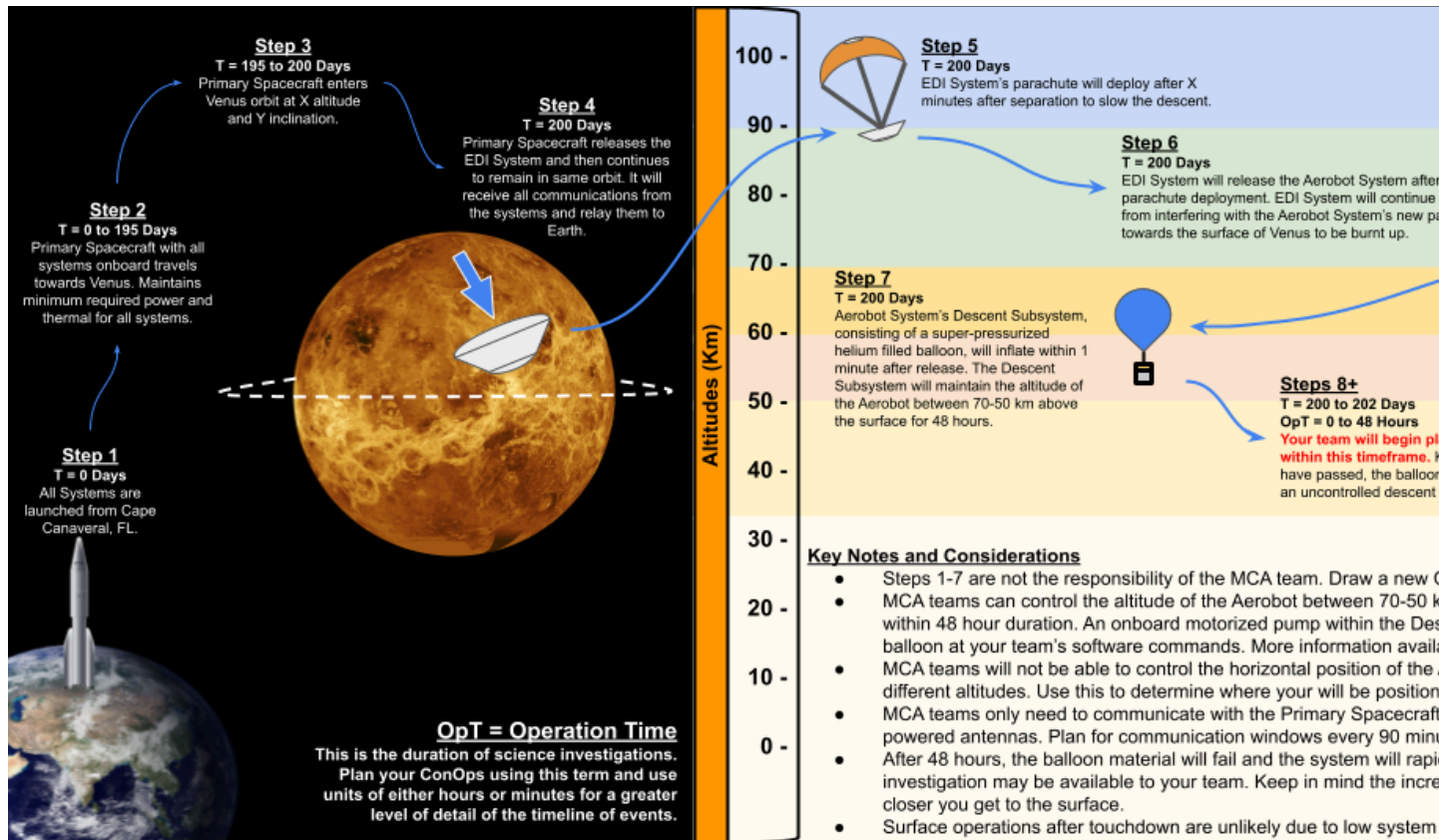
<https://www.nasa.gov/seh/5-3-product-verification>

<https://www.nasa.gov/seh/appendix-b-glossary>

L'SPACE Requirements Skill Module

Concept of Operations (ConOps) Example*

**Example for reference only, will not reflect your team's exact ConOps*



Trade Study Example

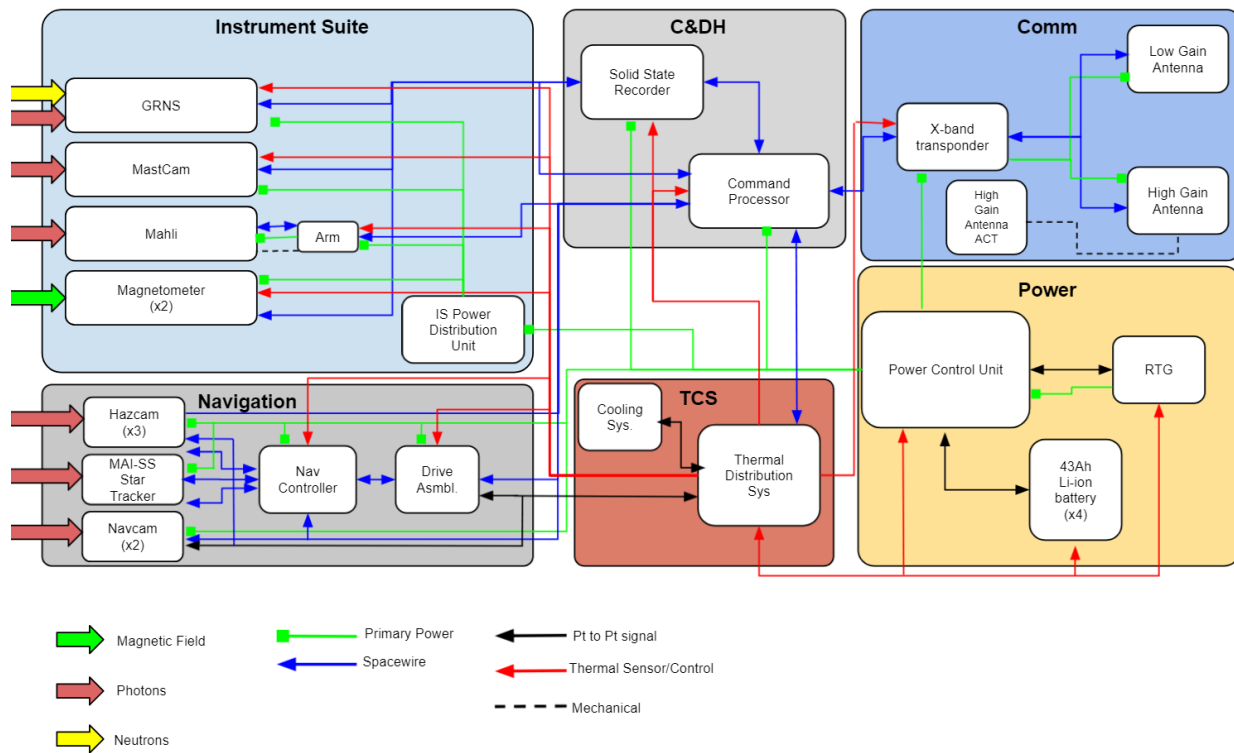
Mechanical - Deployment Actuator Trade Studies						
Criteria	Explanation	Grade	Weight	Stepper Motor	Hydraulics	Pneumatics
Supporting systems	DEP-3	1: Complicated supporting system 4: No supporting system	15%	3.5	2	2.0
Position control	DEP-1 & DEP-2	1: Deployment is locked during launch and after deployment. 2: Deployment locked during launch and had adjustability in deployment method 3: Deployment can be locked in multiple positions 4: Deployment can be deployed locked and repositioned	30%	4	3	2
Reliability	DEP1	1: Minimally reliable 4: Very reliable	35%	3	3	3
Temperature	MAT-4	1: Does not fall within temperature range 4: Falls within requirements range	20%	3	2	1
		TOTAL	100%	84.38%	66.25%	53.75%

Interface Control

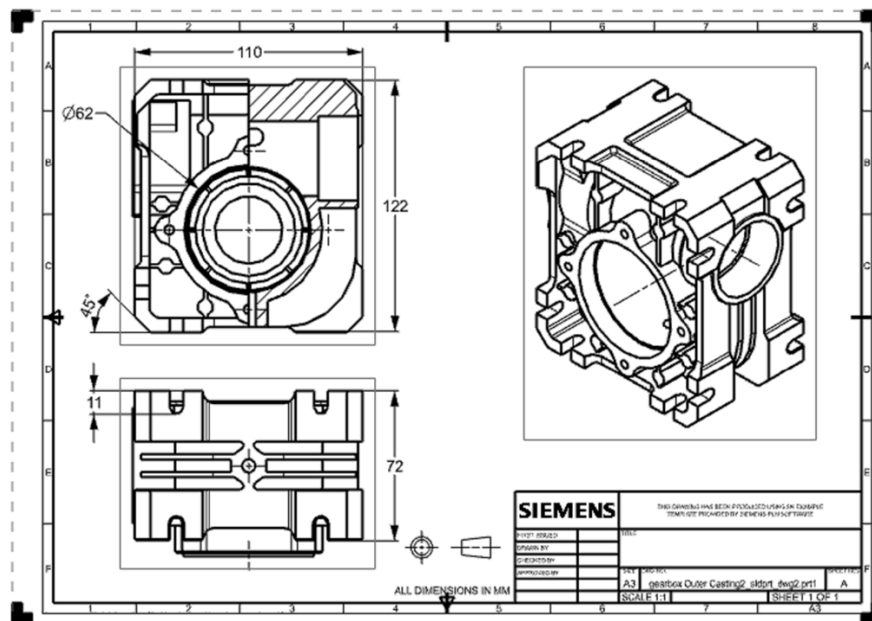
N² Chart Example

Payload Instrument Suite	Instrument Science Instrument Heartbeat				
Commands to begin/end collection	Data Handling Solid State Recorder	Instrument data Heartbeat check Telemetry data Autonomous check	Navigation plan	Rover thermal state	
	Inbound Transmissions and Terrain Data	Comm			
	Telemetry		Navigation		
TCS	TCS Telemetry	TCS	TCS	Thermal	TCS
Power	Power	Power	Power	Power	Power 6

Block Diagram Example



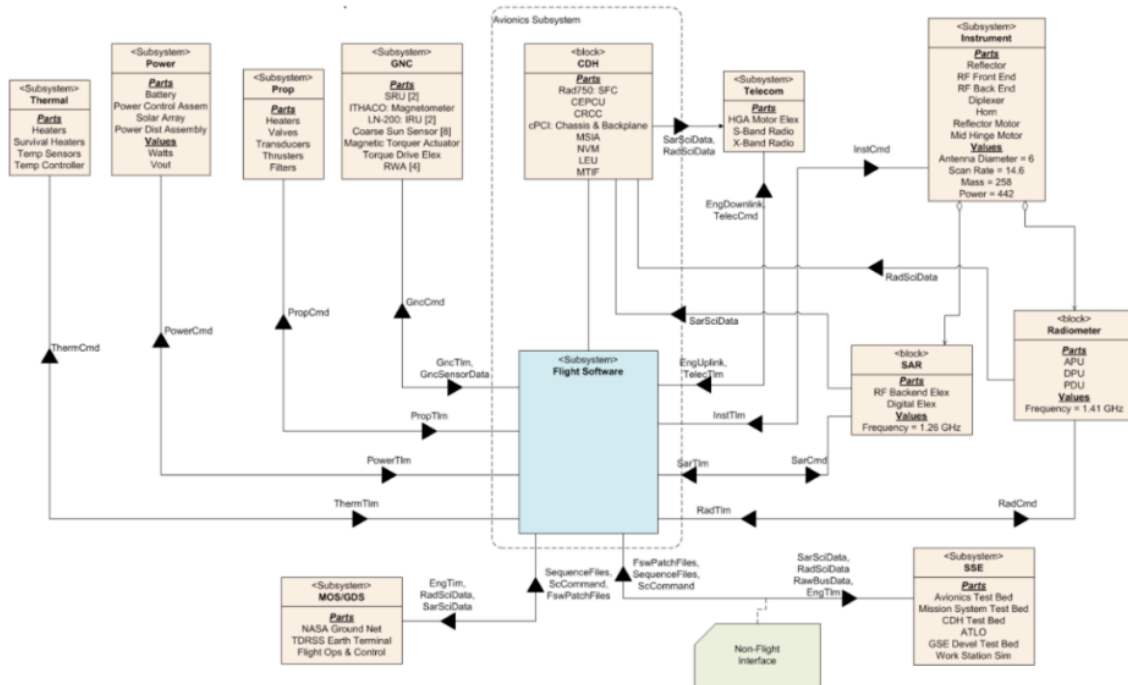
Engineering Drawing Example



Siemens NX Drafting Example

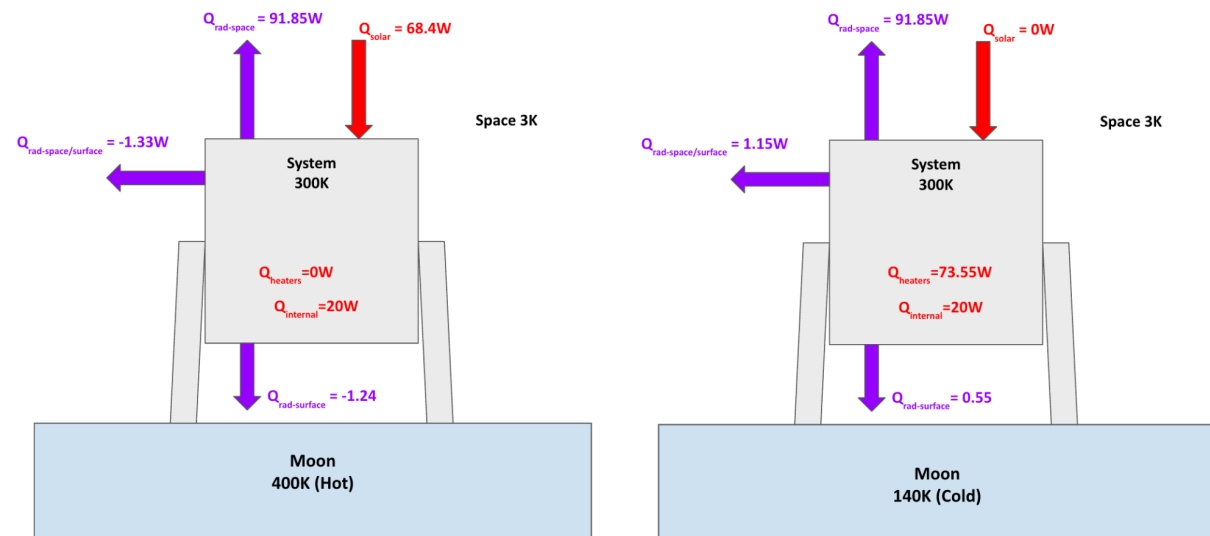
Software Architecture Flowchart Example

Example:



Found in the [NASA Software Engineer Handbook](#) under the “Recommended Contents” section

Heat Flow Map Example



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