RASC-AL 2021 Proposal
PROJECT VESPER

Theme #3: Venus Flyby Mission

University of Washington

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Contents

I. Abbreviations

AI	Atmospheric Instruments
ASS	Atmospheric Structure Suite
AWD	ALL Wheel Drive
DI	Descent Imager
DSM	Deep Space Maneuver
EFT	External Fuel Tanks
EME	Mars Flyby
EVE	Venus Flyby
EUV	Extreme Ultraviolet
GPO	Ground Processing Operations
GRS	Gamma Ray Spectrometer
HM	Habitat Module
ICDR	Instrument Critical Design Review
IPDR	Instrument Preliminary Design Review
IRR	Instrument Readiness Review
ISM	Inflatable Space Habitat Module
kg	Kilogram
km	Kilometer
LAS	Launch Abort System
LEO	Low Earth Orbit
LHA	Landing Hazard Avoidance
LHCP	Left Hand Circular Polarized
LHD&A	Landing Hazard Detection and Avoidance
LIBS	Laser Induced Breakdown Spectroscopy
LLISSE	Long-Lived In Situ Solar System Explorer
LOX/LH2	Rocket Propellant based on Liquid Oxygen/Hydrogen
LRR	Launch Readiness Review
m	Meter
MCDR	Mission Critical Design Review
MET	Meteorological Suite/Mission Elapsed Timer
MMH	Monomethylhydrazine
MPDR	Mission Preliminary Design Review
MS	Mass Spectrometer
NASA	National Aeronautics and Space Administration
NTO	Dinitrogen Tetroxide Propellant
OS	Orbiter and Smart Atmospheric Platform
PC	Panoramic Camera
REM	Roentgen Equivalent Man
RHCP	Right Hand Circular Polarized
ROI	Region of Interest
SAP	Smart Atmospheric Platform
SAR	Synthetic Aperture Radar
SEP	Solar Electric Propulsion

SII	Surface Imaging Instrument
SLF	Spring Loaded Feedback
SLS	Space Launch System
SM	Service Module
SRS	Subsurface Radar Sounder
SOI	Sphere of Influence
S&I	Sample and Ingest
TRL	Technology Readiness Level
VAMP	Venus Atmospheric Maneuverable Platform
VASL	Venus All-Terrain Surface Lander
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VIS-NIR	Visible-Near Infrared
VR	Virtual Reality
XFS	X-Ray Fluorescence
XRD	X-Ray Diffraction

II. Quad Chart

Theme 3: Venus Flyby Mission

Objectives & Technical Approach:

Goals

- Landing a rover onto the tesserae highlands
- Discovering the past/present state of Venusian habitability
- Identifying signs of the runaway greenhouse effect

Approach

- Analyze Venus's surface mineralogy and morphology to determine past signs of oceans and to aid future landings
- Identify clues for past and present habitability on Venus through characterization of atmospheric conditions
- Analyze Venus's geological activity to investigate the potential past presence of tectonic plates

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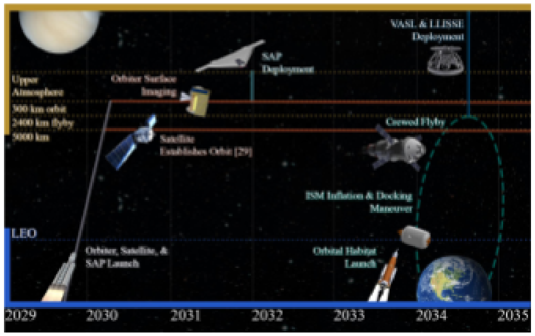

Team & Management Approach:

- Team Lead: Arvean Labib
- Subteams:
  - Surface Team Lead:
    - Mani Sanaiekhah
  - Atmosphere Team:
    - Melissa Peters
    - Anushka Sarode
  - Mission Architecture:
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    - Patrick Rae

Schedule:

- Launch 1: Mid 2029
- Venus arrival: Early 2030
- Aerobot Deployment: Late 2031
- Orbiter achieves Targeted Orbit: Early 2032
- Launch 2: Mid 2033
- Lander Deployment: Early 2034
- Earth Arrival: late 2034

Cost:

- Total proposed budget FY 2021: $10,830,000,000
- Total proposed budget FY 2025: $12,190,000,000

III. Introduction

As climate change on Earth becomes increasingly prevalent, the need to learn more about the factors that sustain and extinguish habitability has never been more important. Venus, a world similar to our own, illuminates the climatic processes on Earth and provides an abundance of information regarding planetary habitability.

Through judgment and real-time interaction, crewed Venus flyby missions "enable mission scenarios not accessible to robotic spacecraft alone, and represent force multipliers in efforts to achieve major Venus exploration goals" [2]. A crewed Venus Flyby will also provide humans with the opportunity to practice deep space operations and to test key architecture at a fraction of the time, energy, and cost of a Mars mission.

Success criteria of this mission include landing a rover onto the tesserae highlands, discovering the past/present state of Venusian habitability, and identifying signs of the runaway greenhouse effect. These criteria strongly influenced the mission approach and the design choices of key architecture, such as the development of an atmospheric platform with high maneuverability and a rover.

A Crewed Venus Flyby will showcase the advancement of humanity and allow NASA to further their goal of pioneering space exploration. With an emphasis on scientific discovery and the enabling of future missions, this proposal introduces innovative architecture and outlines a mission plan for a Crewed Venus Flyby.

IV. Venus Flyby Mission and Trajectory

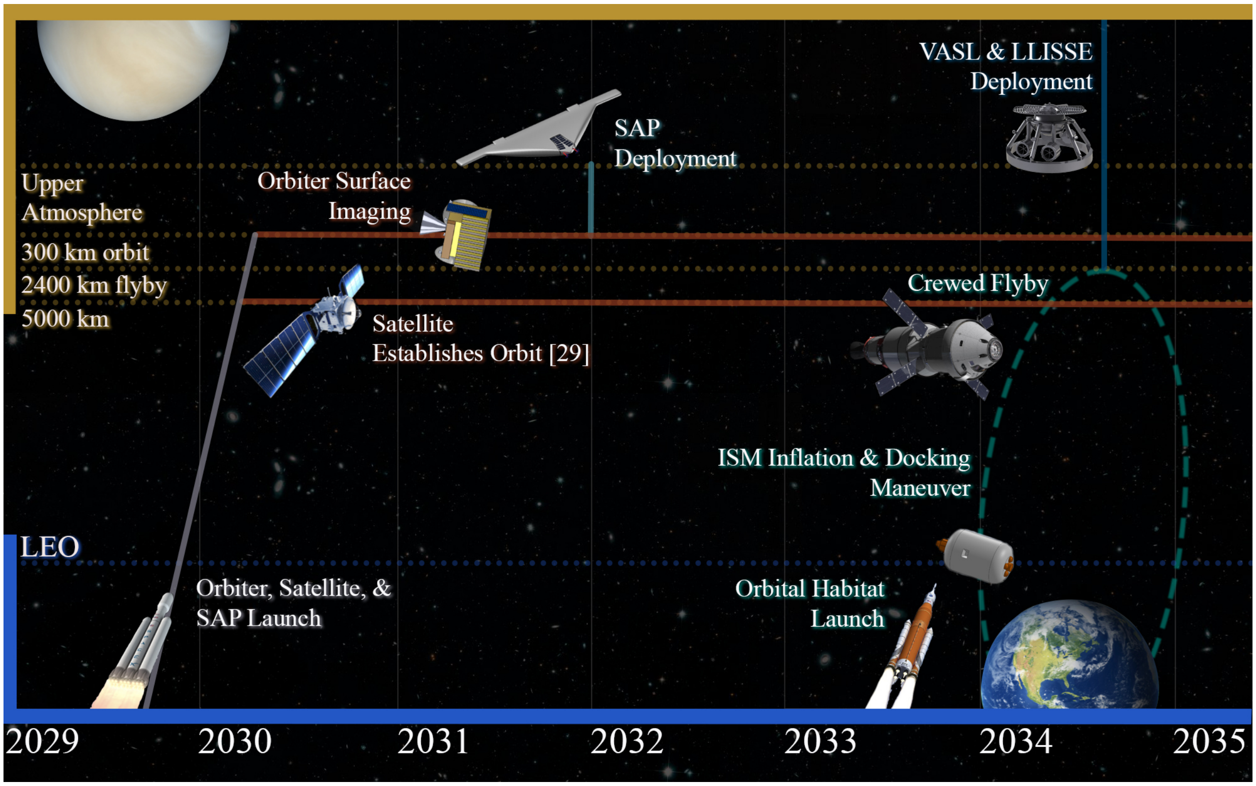


Fig. 1: Concept of Operations

Project Vesper is a Crewed Venus Flyby mission consisting of two launches, the first of which providing mapping of the region of interest in preparation for the second launch.

An Orbiter carrying the Smart Atmospheric Platform (SAP) will be deployed before the Crewed Flyby to collect topographic information regarding the ROI (Region of Interest).

The Orbiter will be equipped with the surface imaging instrument package (SI), which will be in operation throughout the 2-year aerobraking process. The SAP, which will be inflated and deployed from the Orbiter 1.5 years into the aerobraking procedure, will safely glide into the Venusian atmosphere and begin operation of its instruments. Information of the ROI received from the Orbiter and SAP (OS) will identify a safe landing ellipse within a range of 5 km.

Finally, approximately 4.5 years after the first launch, a crew of four will make the flyby transfer to Venus through the Orion and inflatable-space habitat (ISM) where they will deploy the Venus All-Terrain Surface Lander (VASL) and assist in its landing onto the Venusian surface.

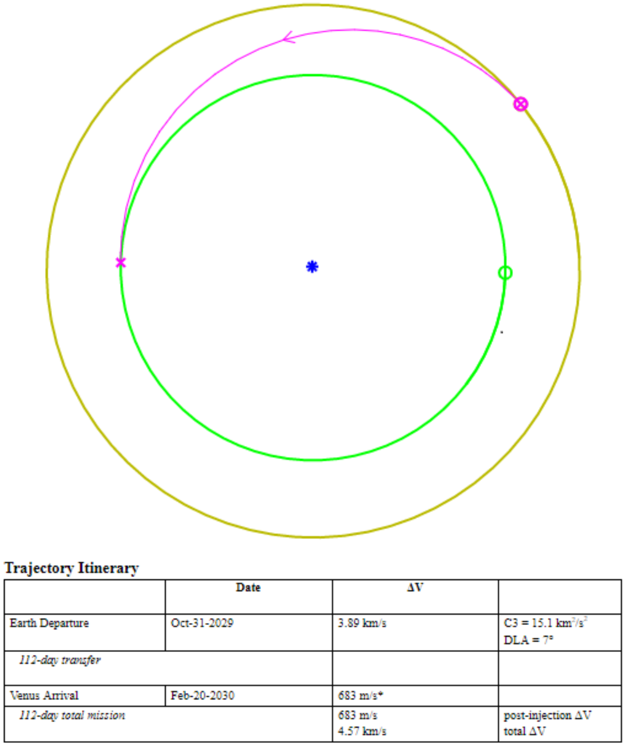
IV.A. Transfer to Venus

Launch 1: Prior to Venus Flyby

Due to the uncertain conditions of the Venusian surface, preparatory measures including high-resolution imaging will be made prior to the Crewed Flyby to safely land the VASL.

The OS and two satellites will be boosted from LEO by the Falcon Heavy upper stage as one unit; the satellites will then break away from the orbiter and SAP in route to Venus. All systems will arrive in the Venusian SOI on Feb. 20 2030. The Orbiter will aerobrake for two years with the SAP still attached. The SAP will be deployed in late 2031 after the orbiter has decelerated sufficiently. This allows for a synergistic approach between the SAP and orbiter data collection as the orbiter will be fully operational during most of the one-year lifespan of the SAP. Research into shortening the Orbiter's aerobraking duration to maximize preparation time is ongoing.

The SAP, which will take key surface and atmospheric measurements, will inflate with H_2 into its buoyant form. The SAP will tentatively release dropsondes over the landing zone, which provide high-resolution imaging of the Venusian surface during descent. Meanwhile, the satellites upon reaching the SOI will begin their SEP maneuvers to attain a highly elliptical orbit of 500 km periapsis and 5000 km apoapsis. The satellites will provide a communication point for the orbiter, SAP, and eventual ground operations.



Trajectory Itinerary

	Date	**ΔV**	
Earth Departure	Oct-31-2029	3.89 km/s	C3 = 15.1 km^2/s^2 DLA = 7°
112-day transfer			
Venus Arrival	Feb-20-2030	683 m/s*	
112-day total mission		683 m/s 4.57 km/s	post-injection ΔV total ΔV

Fig. 2: Trajectory Prior to Flyby

Launch 2: Venus Flyby

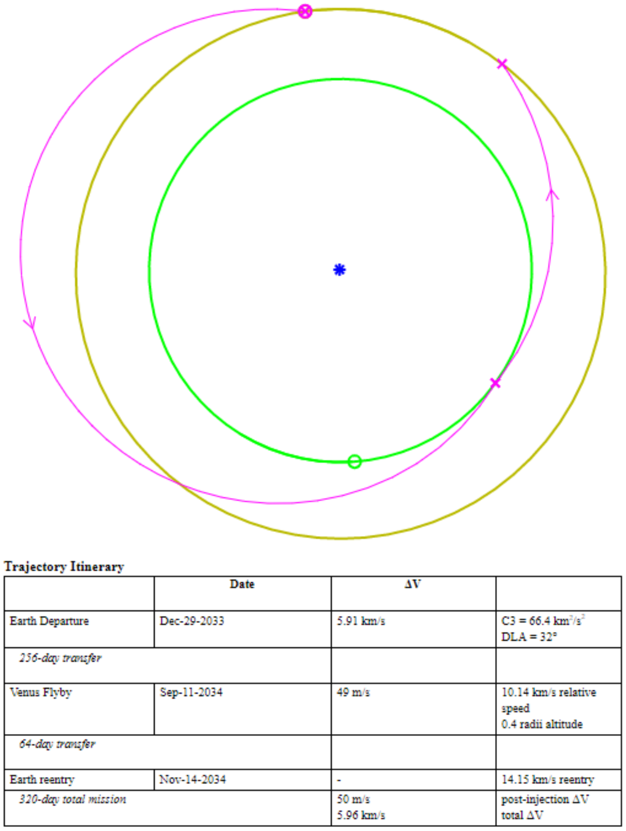
Approximately 4.5 years after the first launch, the Orion, carrying the humans, and the ISM will be launched using the SLS.

The trajectory for this mission was largely influenced with Mars in mind. A Venus Flyby trip would reduce the total time, cost, and energy, thus, serving as a valuable "shakedown cruise for the deep-space transport systems needed for the first human mission to Mars"[2]. The Venus flyby mission also serves as a proving ground for architecture such as the Orion and ISM which could be tested and reused for future missions.

The largest trade-off with regards to a crewed Venus flyby trajectory is minimum ΔV or minimum total flight duration. The minimum ΔV fly-by only requires a ΔV of 3.77 km/s which is significantly less compared to the 5.96 km/s total ΔV from the minimum flight duration trajectory.

However, the benefits come at the cost of increased safety risks. The minimum duration trajectory would take 30 % less time, a safer option for the astronauts due a decrease in time exposed to radiation. Fortunately for both trajectory options, the launch window is during a solar minimum which lower the odds of encountering dangerous levels of solar radiation.

The minimum flight duration trajectory will pass close to Venus allowing for low latency communication for assisting the VASL's safe arrival on the Venusian tesserae. Upon arriving in the SOI of Venus the VASL will separate from the habitat and make a small course correction to enter the Venusian atmosphere near the landing zone. During the flyby, the crew will observe the telemetry data on the VASL to safely land it by performing manual navigation using VR. A small distance to the planet (2423 km) will allow for higher data speeds and reduced landing ellipse error. The direct line of communication to ground operations should be maintainable for roughly 3.47 hours, enough time for the crew to perform the landing operation at near-zero communication latency [2].

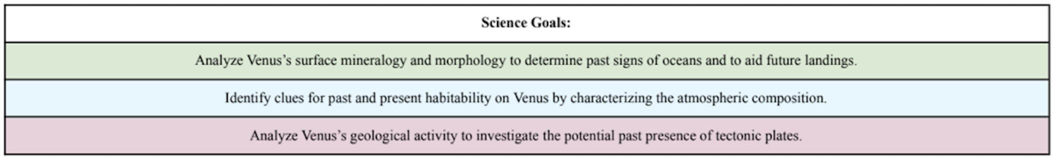


Trajectory Itinerary

	Date	ΔV	
Earth Departure	Dec-29-2033	5.91 km/s	C3 = 66.4 km^2/s^2 DLA = 32°
256-day transfer			
Venus Flyby	Sep-11-2034	49 m/s	10.14 km/s relative speed 0.4 radii altitude
64-day transfer			
Earth reentry	Nov-14-2034	-	14.15 km/s reentry
320-day total mission		50 m/s 5.96 km/s	post-injection ΔV total ΔV

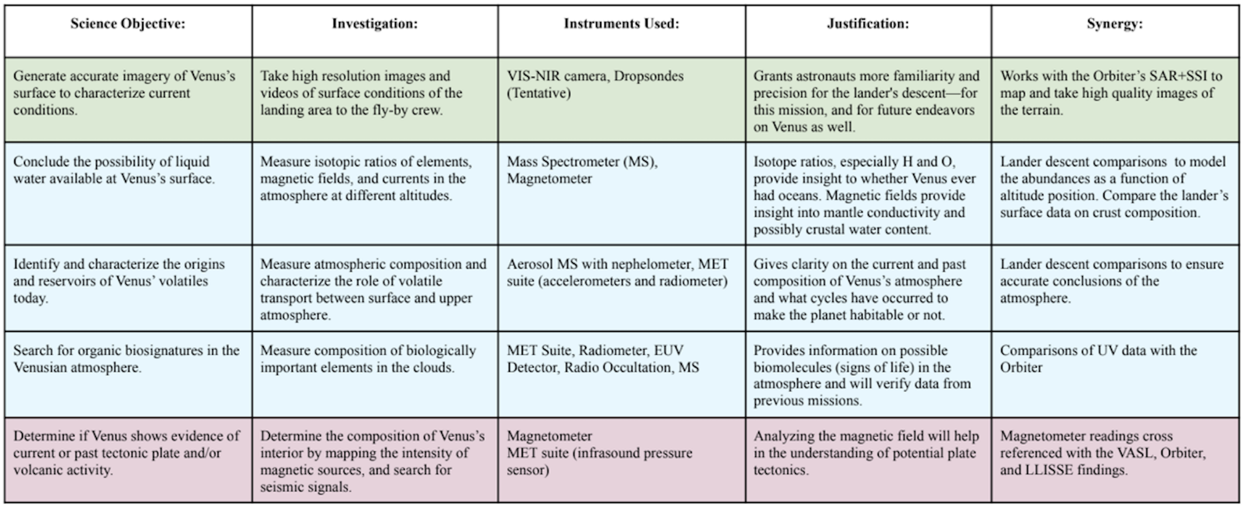
Fig. 3: Trajectory of the Crewed Flyby

V. Venus Surface and Atmosphere Mission



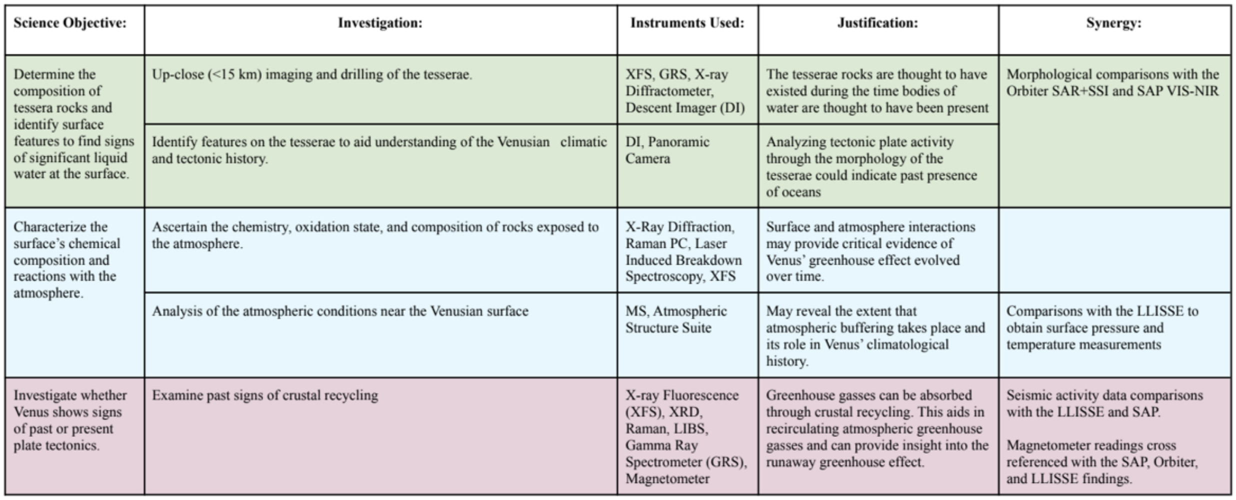
Science Goals:
Analyze Venus's surface mineralogy and morphology to determine past signs of oceans and to aid future landings.
Identify clues for past and present habitability on Venus by characterizing the atmospheric composition.
Analyze Venus's geological activity to investigate the potential past presence of tectonic plates.

Fig. 4: Science Goals



Science Objective:	Investigation:	Instruments Used:	Justification:	Synergy:
Generate accurate imagery of Venus's surface to characterize current conditions.	Take high resolution images and videos of surface conditions of the landing area to the fly-by crew.	VIS-NIR camera, Dropsondes (Tentative)	Grants astronauts more familiarity and precision for the lander's descent—for this mission, and for future endeavors on Venus as well.	Works with the Orbiter's SAR+SSI to map and take high quality images of the terrain.
Conclude the possibility of liquid water available at Venus's surface.	Measure isotopic ratios of elements, magnetic fields, and currents in the atmosphere at different altitudes.	Mass Spectrometer (MS), Magnetometer	Isotope ratios, especially H and O, provide insight to whether Venus ever had oceans. Magnetic fields provide insight into mantle conductivity and possibly crustal water content.	Lander descent comparisons to model the abundances as a function of altitude position. Compare the lander's surface data on crust composition.
Identify and characterize the origins and reservoirs of Venus' volatiles today.	Measure atmospheric composition and characterize the role of volatile transport between surface and upper atmosphere.	Aerosol MS with nephelometer, MET suite (accelerometers and radiometer)	Gives clarity on the current and past composition of Venus's atmosphere and what cycles have occurred to make the planet habitable or not.	Lander descent comparisons to ensure accurate conclusions of the atmosphere.
Search for organic biosignatures in the Venusian atmosphere.	Measure composition of biologically important elements in the clouds.	MET Suite, Radiometer, EUV Detector, Radio Occultation, MS	Provides information on possible biomolecules (signs of life) in the atmosphere and will verify data from previous missions.	Comparisons of UV data with the Orbiter
Determine if Venus shows evidence of current or past tectonic plate and/or volcanic activity.	Determine the composition of Venus's interior by mapping the intensity of magnetic sources, and search for seismic signals.	Magnetometer MET suite (infrasound pressure sensor)	Analyzing the magnetic field will help in the understanding of potential plate tectonics.	Magnetometer readings cross referenced with the VASL, Orbiter, and LLISSE findings.

Fig. 5: SAP Science Traceability Matrix



Science Objective:	Investigation:	Instruments Used:	Justification:	Synergy:
Determine the composition of tessera rocks and identify surface features to find signs of significant liquid water at the surface.	Up-close (<15 km) imaging and drilling of the tesserae.	XFS, GRS, X-ray Diffractometer, Descent Imager (DI)	The tesserae rocks are thought to have existed during the time bodies of water are thought to have been present	Morphological comparisons with the Orbiter SAR+SSI and SAP VIS-NIR
	Identify features on the tesserae to aid understanding of the Venusian climatic and tectonic history.	DI, Panoramic Camera	Analyzing tectonic plate activity through the morphology of the tesserae could indicate past presence of oceans	
Characterize the surface's chemical composition and reactions with the atmosphere.	Ascertain the chemistry, oxidation state, and composition of rocks exposed to the atmosphere.	X-Ray Diffraction, Raman PC, Laser Induced Breakdown Spectroscopy, XFS	Surface and atmosphere interactions may provide critical evidence of Venus' greenhouse effect evolved over time.	
	Analysis of the atmospheric conditions near the Venusian surface	MS, Atmospheric Structure Suite	May reveal the extent that atmospheric buffering takes place and its role in Venus' climatological history.	Comparisons with the LLISSE to obtain surface pressure and temperature measurements
Investigate whether Venus shows signs of past or present plate tectonics.	Examine past signs of crustal recycling	X-ray Fluorescence (XFS), XRD, Raman, LIBS, Gamma Ray Spectrometer (GRS), Magnetometer	Greenhouse gasses can be absorbed through crustal recycling. This aids in recirculating atmospheric greenhouse gasses and can provide insight into the runaway greenhouse effect.	Seismic activity data comparisons with the LLISSE and SAP. Magnetometer readings cross referenced with the SAP, Orbiter, and LLISSE findings.

Fig. 6: VASL Science Traceability Matrix

V.A. Surface and Atmosphere Mission

Although the final landing ellipse is subject to change based on the data received from the OS, a preliminary landing ellipse was selected at 96.0 E, 5.5 S in the Ovda Fluctue. The choice to make the West Ovda Regio the primary ROI was due to its scientific value and flatter slopes compared to other regions. The Ovda Regio's high elevation regions, evidence of folds, ribbons, and syncline/anticline formations could answer the question of a period in Venus' geological history where there was active plate tectonics. Additionally, its 1.5 Byr age may reveal older mineralogical samples to a surface VASL than Venus' comparatively younger surface.

However, the rough tesserae surface lends itself to potential landing complications. Its high topography is rife with fold-like formations, cracks, and steep surface angles that are difficult to land on. With many boulders potentially strewn around as well, it could be fatal if the VASL were to land on one and possibly end surface operations. Human interaction with the landing will be key to making sure the VASL arrives safely, being able to quickly parse incoming information of the surface, and making split-second decisions on the safest place to land.

During the hour-long descent, the VASL will make a series of atmospheric measurements. When the lander arrives on the surface, the crew will maneuver the VASL to a secure location for sampling. With limited time on the surface, it is crucial to gather a broad range of data. The lander's sample and ingest system (S&I) will drill into the regolith about 30 cm, and return a core sample into the lander, where it will be crushed or ionized for input into the various instruments. Interior mechanisms then transport the sample to where it can be imaged, passing through different equipment for identification. After 20 minutes, samples are disposed of, equipment is secured, and the lander will be guided at least 5m away from its prior sampling location to repeat the SI process.

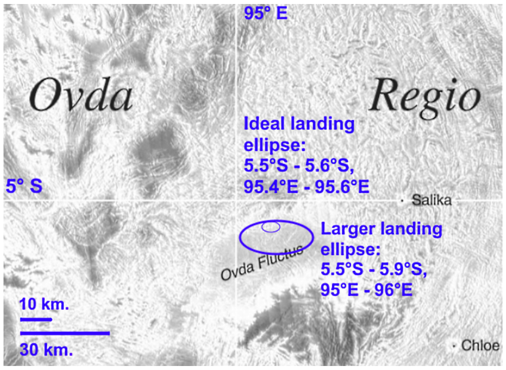


Fig. 7: Landing Region

The orbiter will provide fundamental imaging and data of tesserae regions, specifically the landing sites chosen. Information and data on the terrain and topography of these sites will be recorded using S-band SAR with up to 1 m resolution of targeted regions, and 30 m mapping. The SRS will obtain images of the vertical structure and properties of the tesserae. Using a spectrometer suite, data on the albedo, winds, thermal fluxes, and the interaction of surface and atmosphere will be analyzed. This could lead to clues on the history of Venusian superrotation which will aid in the understanding of climate change.

The SAP will cross-reference imaging and atmospheric data with the Orbiter. The maneuverability of the SAP will allow it to vary in altitude on the day-side of Venus. The long-lasting SAP provides important measurements of the Venusian atmosphere to determine its composition, potential for past magnetic fields, and forms of habitability. Over the SAP's long duration in the mid-cloud region, the understanding of factors that sustain and eliminate life will become realized with the scientific data from the mission to improve models of other similar inner solar system planets. Although research is still ongoing, the deployment of dropsondes over the ROI would provide further context for the landing of the VASL.

VI. Design Overview

VI.A. Crew Vehicle & Habitat Module

Although it is unlikely that the astronauts will encounter a severe solar storm, previous models indicate that 300 days on an EVE or EME trip surpasses the 30 day REM limit [32]. As a precautionary measure, Orion's storm shelter will be retrofitted with a graphite-epoxy lining. The exterior will be modified to include a carbon-nanotube reinforced aluminum composite, and storage equipment and water supplies will be placed around the Orion to increase shielding density. In the event of a solar panel malfunction, a Tesla Powerwall battery will supply power until the astronauts repair the panel.

If an emergency occurs during launch, the astronauts will be brought to safety by the launch abort system (LAS) of the SLS. Should an emergency arise after the LAS is jettisoned, the Orion, which will be stocked with the consumables, will be capable of separating itself a safe distance away from the ISM and the Orion's SM module.

The European Service Module will also be altered to suit the needs of the mission. While more research needs to be conducted, the new service module will feature two ports on the exterior to support two External Fuel Tanks (EFT). Approximately 80 % percent of the stored fuel will be reserved for emergencies, capable of providing a 0.50 km/s ΔV if needed.

The ISM is an inflatable habitat connected to the Orion to be reused for future trips to Mars. The ISM features fitness equipment, personal quarters, entertainment, a refabricator, and storage. The total volume when inflated is 110 m^3, including, 95 m^3 of habitable space and 15 m^3 for storage. Further details regarding the ISM will be included in the technical paper

Human Factors

The astronauts will closely monitor their health during transit, including performing daily medical inspections. The data provided through these inspections will indicate the efficacy of the Orion's radiation protection measures and serve as a proving ground for the safety of future Venus Flybys to Mars using the ISM. Astronaut scheduling will be discussed further in the technical paper.

As humans venture farther into the solar system, NASA continues to consider alternate options for spacecraft supplies [33]. 3D printers will dramatically reduce the time it takes to get parts to orbit, decrease costs, and improve the reliability and safety of space missions. Onboard the ISM, humans will gain experience utilizing a refabricator through the manufacturing of critical maintenance supplies and completion of projects such as constructing and delivering a CubeSat into the Venusian SOI. More details regarding the refabricator projects will be included in the technical paper.

VI.B. Orbiter and Satellite

Orbiter

The orbiter structure will have a baseline 2x2 m square bus, with the constraint of the Falcon Heavy's structure. The fairing envelope will house the orbiter with the SAP attached by a payload adapter to one face with the satellites attached under it. Each remaining plane of the orbiter will have attached systems such as the propulsion and attitude control systems, antennas, solar arrays, and other instrumentation. The orbiter will be able to accomplish complex maneuvers to combat the large inertia associated with the stacked payload.

Communication systems will be in the form of two 2 m high gain antennas, and two low gain antennas. X-band and Ka-band systems will be used for communication with earth, and S-band for the SAP.

In the case that the VERITAS mission is selected, a much cheaper orbiter with limited capabilities will deploy the SAP. Budget will be allocated towards the development of more VASLs.

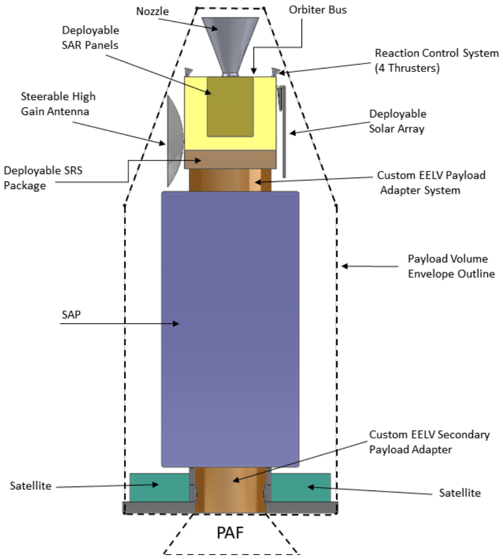


Fig. 8: The Orbiter, SAP, and satellites prior to deployment, outlined by the Falcon Heavy Fairing

Satellite

There will be two satellites orbiting Venus opposite to each other. Each satellite will be 1x1x1.5 m with high gain antennas. Two satellites maximize communication time over the VASL and provide a safety option in case of a satellite failure.

VI.C. SAP

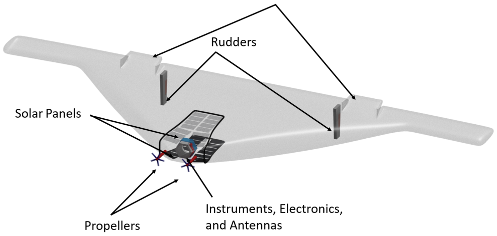


Fig. 9: Key features of the SAP

Based on the Northrop Grumman VAMP, the SAP is a long-lived atmospheric platform, unprecedented in its approach for data collection. Lasting up to a year, it will both maneuver to different altitudes and supplement surface imaging collected during the first launch to the crew. When inflated, the SAP has a wingspan of 36 m, a volume of 600 m^3, and a mass of 540 kg.

Buoyancy enables the SAP to vary in altitude in the dense cloud layer between a range of 55-70 km, and to maneuver over areas of interest on the surface due to controls for the rudder, ailerons, and front propeller. The solar panels on the SAP provide sufficient power to travel on the night side of the planet, and at its 100% buoyant altitude of 55 km, will allow us to better understand unexplained phenomena such as the UV-absorbers.

Other platforms considered included a variable-altitude balloon. Although the balloon allows for a simplistic design, it lacks maneuverability, which is critical for surface and atmospheric cross-referencing with the Orbiter.

VI.D. VASL

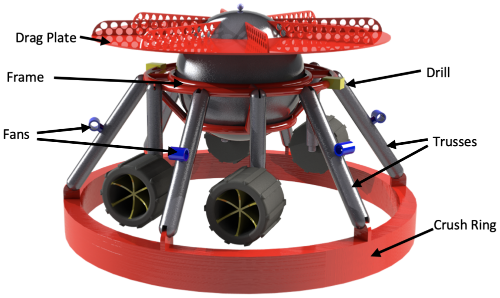


Fig. 10: Key features of the VASL

The VASL plays a vital role in scientific data collection. It has been designed to overcome the overwhelming temperature and pressure on the Venusian surface, roughly 470 °C and 93 bar respectively. Additionally, its design will enable the VASL to handle difficult terrain and inclines of 30°, or 57.7% grade, on the tessera surface. The 0.8 m diameter sphere is built to withstand the inherent implosion from high pressures and protect the internal instruments. Heat resistant materials, namely zirconium dioxide and titanium, along with phase-changing materials aim to slow down the heating process. The expected lifetime of the rover on Venus' surface is approximately 6 hours, with research still ongoing to extend its lifespan.

The drag plate is 1.8 m in diameter and works to slow down the velocity of the VASL during its descent. The impact of the landing itself will be absorbed by a crush ring, which will be attached to the frame via trusses, taking an 8 m/s impact. This will be left behind after the landing occurs and the wheels are deployed.

The VASL will have an effective AWD and Spring Loaded Feedback (SLF) system to increase its maneuverability when encountering difficult terrain. Utilizing a spring-loaded system, the SLF provides degrees of freedom about the wheels and along the legs. The frame gives additional rigidity and support to the changing directions of the axial forces imposed on the VASL body by the wheels. The operating ground clearance ranges from 0.1 to 0.7 m.

The demand for low latency is critical for the landing of the VASL. To achieve a high data rate under S-band, two Endurosat S-band transmitters are used to achieve a maximum of 40 Mbps. By using two of them and two orthogonal antennas, one RHCP and one LHCP, instead of using two antennas of the same polarization, the data rate of a single bandwidth can double.

The terrain relative navigation, hazard detection, and avoidance subsystem are together meant to provide a targeted landing zone while assisting in the maneuvers to avoid landing obstructions. Testing this subsystem in an extreme environment such as the Venusian tesserae could provide a reference for future NASA projects requiring autonomous landing onto challenging terrain.

The LLISSE, a payload of the VASL, is a low-cost, 0.2x0.2x0.2 m cubic lander. Utilizing high-temperature silicon carbide-based electronics, the LLISSE can survive on the Venusian surface for at least 60 Earth days. Although further specifications need to be researched, the LLISSE serves as a proving ground for long-duration technology on Venus' surface.

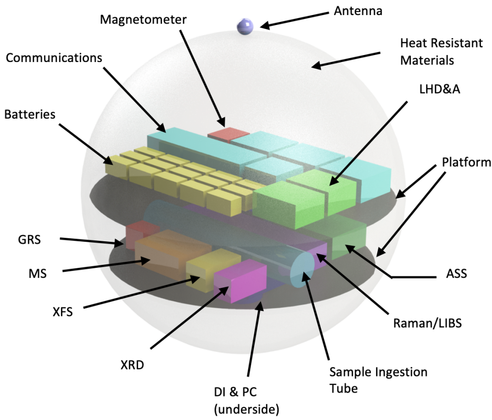


Fig. 11: VASL Instrumentation

VII. Budget and Project Schedule

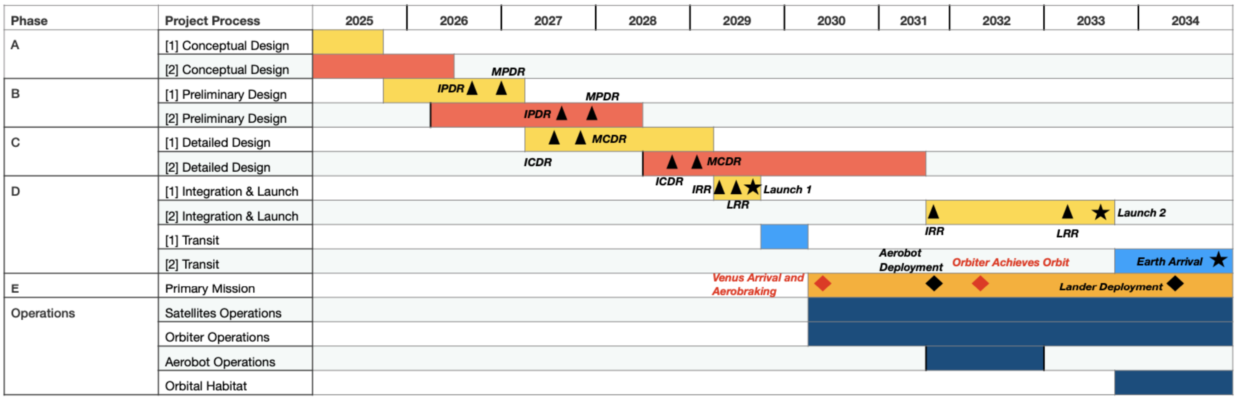
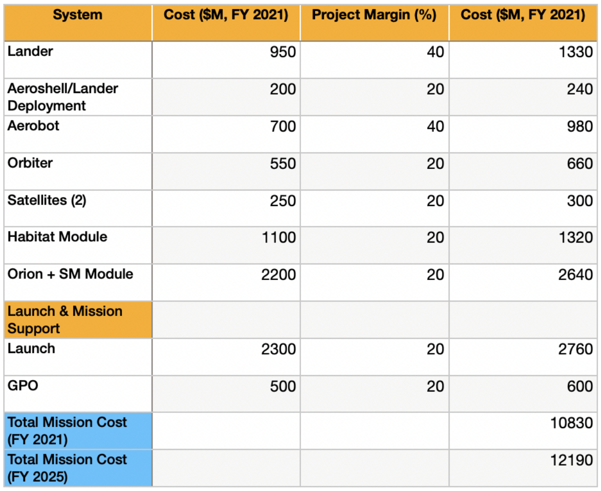


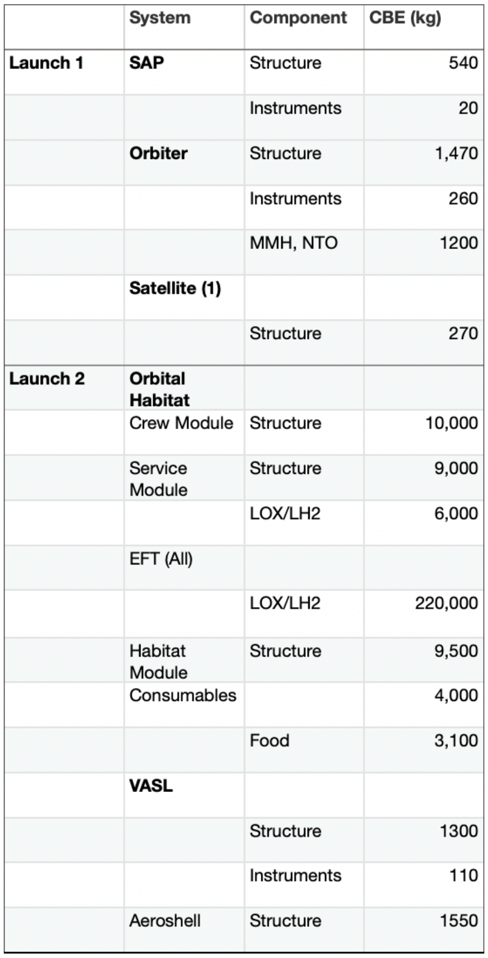
Fig. 12: Gantt chart with IPDR, MPDR, ICDR, MCDR, IRR, and LRR mission reviews. [1] Launch 1 [2] Launch 2



System	Cost ($M, FY 2021)	Project Margin (%)	Cost ($M, FY 2021)
Lander	950	40	1330
Aeroshell/Lander Deployment	200	20	240
Aerobot	700	40	980
Orbiter	550	20	660
Satellites (2)	250	20	300
Habitat Module	1100	20	1320
Orion + SM Module	2200	20	2640
Launch & Mission Support			
Launch	2300	20	2760
GPO	500	20	600
Total Mission Cost (FY 2021)			10830
Total Mission Cost (FY 2025)			12190

Fig. 13: Cost Budget

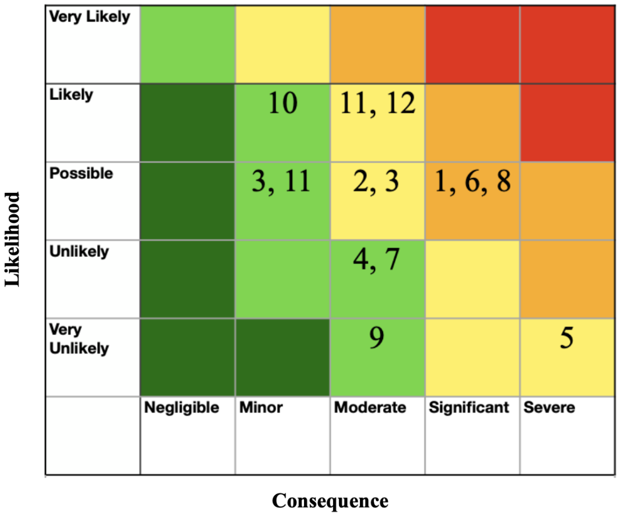
Cost estimations were made using the 2020 Venus Flagship Mission Study [5] and NASA's Life Cycle Cost Estimation model [30]. A large portion of the available budget was reserved to supplement a 60:40 beta curve for development costs [31] and an expected gradual increase in budget allocation from 2025-2027. A project margin of 20-40 % was determined based on risk and TRL levels. Currently, only preliminary costs have been estimated, and subsystem costs still need to be researched. Costs for technology development including the LHDA and the SAP entry mechanism are embedded within the cost of the project.



	System	Component	CBE (kg)
Launch 1	**SAP**	Structure	540
		Instruments	20
	Orbiter	Structure	1,470
		Instruments	260
		MMH, NTO	1200
	Satellite (1)		
		Structure	270
Launch 2	**Orbital Habitat**		
	Crew Module	Structure	10,000
	Service Module	Structure	9,000
		LOX/LH2	6,000
	EFT (All)		
		LOX/LH2	220,000
	Habitat Module	Structure	9,500
	Consumables		4,000
		Food	3,100
	VASL		
		Structure	1300
		Instruments	110
	Aeroshell	Structure	1550

Fig. 14: Mass Budget

VIII. Technology Readiness and Risk Analysis



	Negligible	Minor	Moderate	Significant	Severe
Very Likely					
Likely		10	11, 12		
Possible		3, 11	2, 3	1, 6, 8	
Unlikely			4, 7		
Very Unlikely			9		5

Mission Operating Risks

Lander

1. VASL Landing Failure
2. SAP Entry Failure

Orbiter

3. Orbiter DSM Maneuver Failure

Habitat

4. Habitat Inflation Malfunction

Human

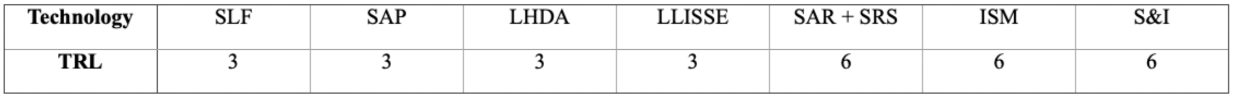
5. Fire Hazard
6. Medical Emergency
7. Large Solar Particle Event
8. Crew Psychological Problems

Other

9. Crew Launch Vehicle Failure

Project Development Risks

10. Over budget, Schedule Overrun
11. Productions Issues
12. Technology Readiness Issues



Technology	SLF	SAP	LHDA	LLISSE	SAR + SRS	ISM	S&I
TRL	3	3	3	3	6	6	6

Fig. 15: Risk & TRL chart

“Further technology investment can surmount many of the previous challenges of Venus exploration and enable new frontiers in Venus science and exploration” [9]. The VASL pressure vessel hardware integration and test complexity [5], low TRL of the LHDA Divert System, and low TRL of the mobility and SLF system call for risk mitigation. To reduce the likelihood of system failure and the chances of project delay, 40 % cost reserves were made for the VASL. A second VASL, which is currently being researched, would drastically reduce the likelihood of a mission failure in the case of a malfunction or failed landing.

Cost reserves of 40 % were made for the SAP in the case more research and testing needs to be made before launch. Further mitigations to combat the low TRL of the technology proposed in this mission include a detailed technology development plan that will ensure all TRL are up to a 6 prior to Phase C.

Along with the technology proposed, the overall mission complexity remains a source of risk. Integrating all flight elements may delay the launch and a large number of flight elements increase the number of failure points in the mission. Mitigations include extensive planning, integration, and testing phase before the second launch, and redundancy of key instruments, communication mechanisms, and high-value scientific data to reduce the risk of critical failure.

IX. Conclusion

The NASA RASC-AL Theme #3: Venus Flyby Mission requirements have been addressed through the following: utilization of low-latency through humans-in-the-loop control; development of thorough safety precautions, a reusable habitat, and the use of a refabricator to enable future missions to Mars; and the use of emerging space capabilities through the Orion and SLS.

Project Vesper outlines a low cost, low risk mission to answer fundamental questions regarding planetary habitability while pioneering space exploration.

X. Appendix

X.A. Equations Used

Tsiolovsky Rocket Equation	$I_{sp} g ln(\frac{m_0}{m_f})$
ΔV	Velocity Change
$I_s p$	Specific Impulse
g	Earth's Acceleration $= 9.81 m/s^2$
m_0	Initial/Wet Mass
m_f	Final/Dry Mass
Cost-Estimating Formula	$C = k * aW^b$
k	Multiplicative factor of Technology
b	Coefficient (slope)
a	coefficient (first pound cost)
Cost Estimation	$DDT\&E = aQ^b W^c d^S \frac{1}{e^{(IOC-1900)} B^f g^D} * inflation$
Buoyant Force	$B - \rho_f V g$
B	Buoyant Force
ρ_f	Fluid Density
V	Volume of Displaced Liquid

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