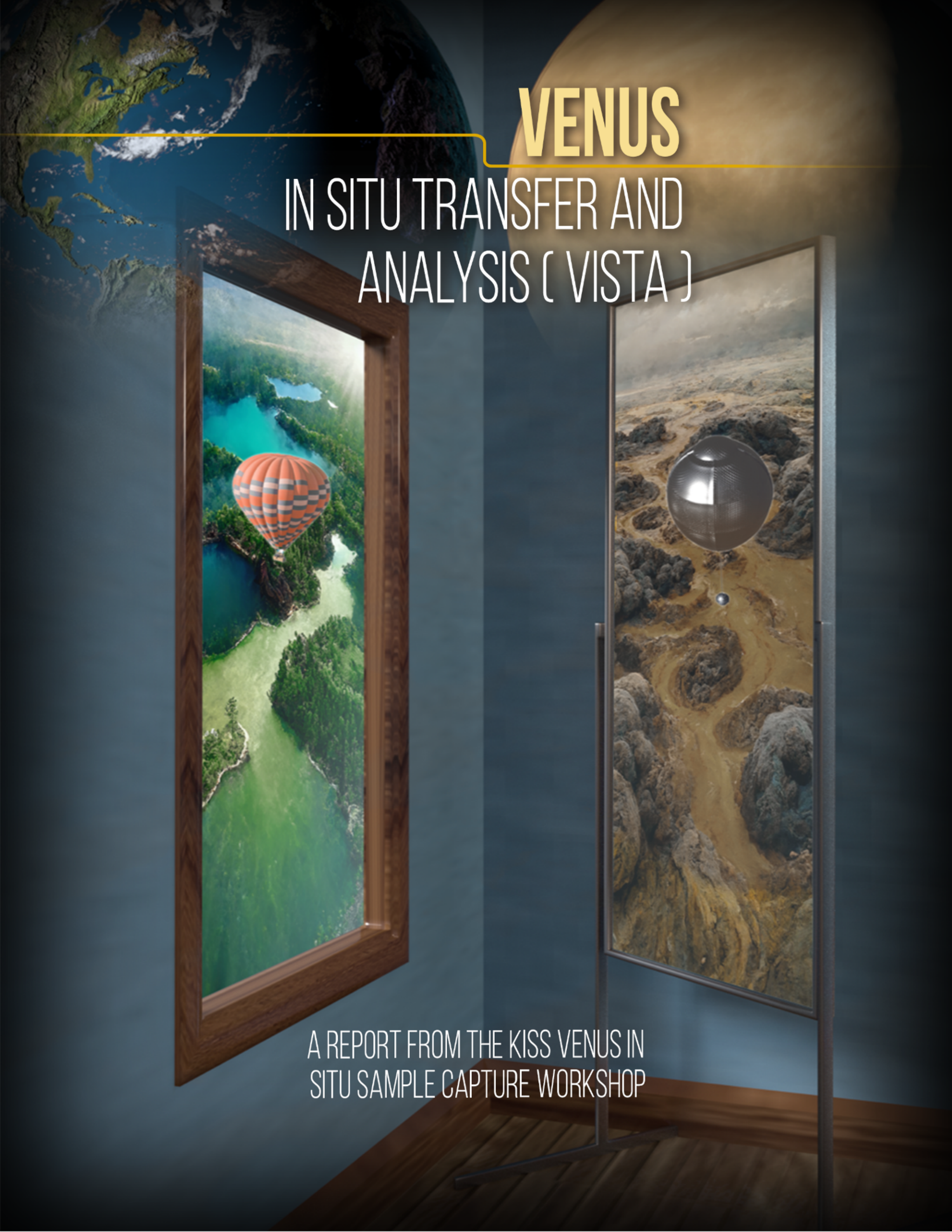

VENUS IN SITU TRANSFER AND ANALYSIS (VISTA)

A REPORT FROM THE KISS VENUS IN SITU SAMPLE CAPTURE WORKSHOP

Study Report prepared for the W. M. Keck Institute for Space Studies (KISS)

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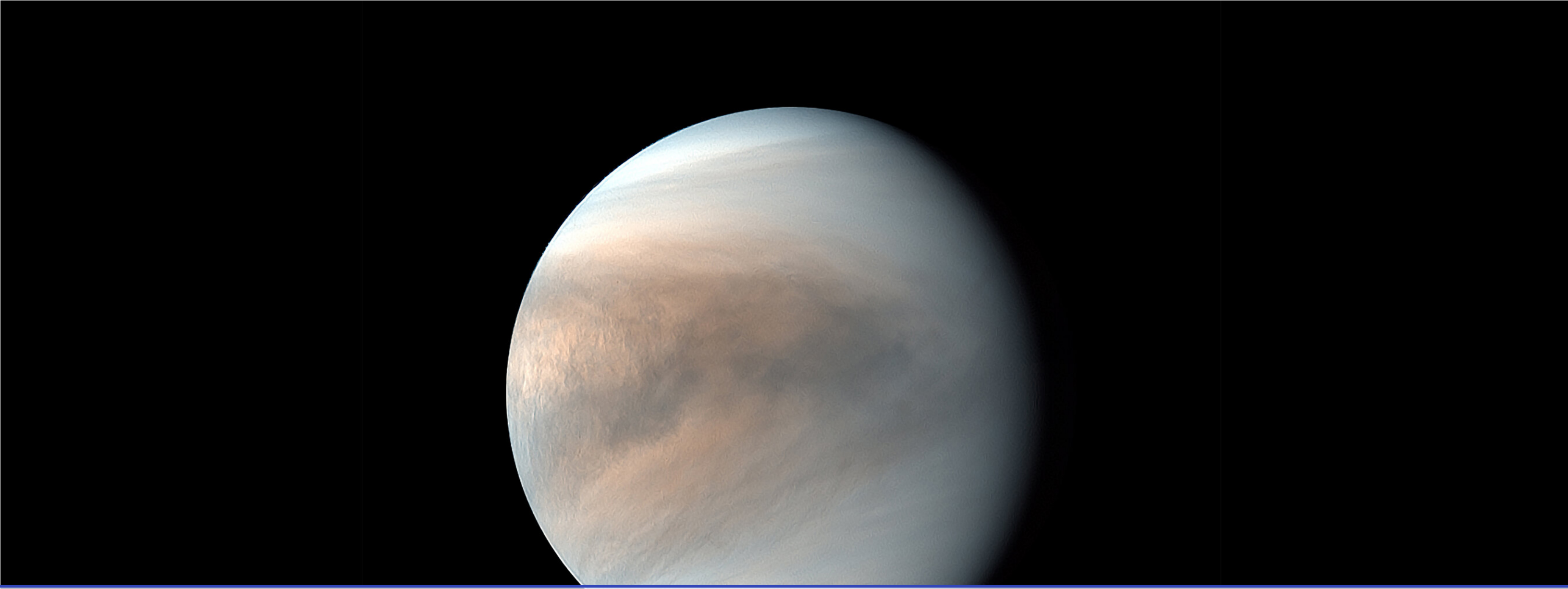

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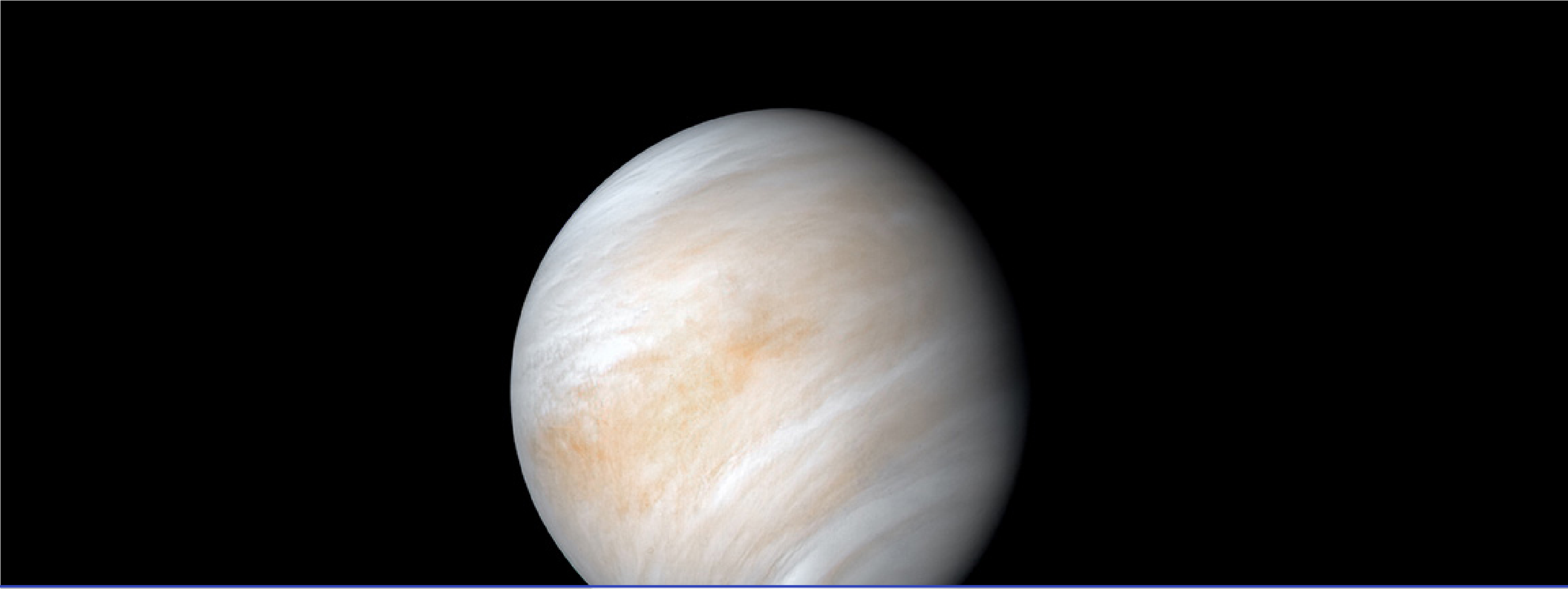

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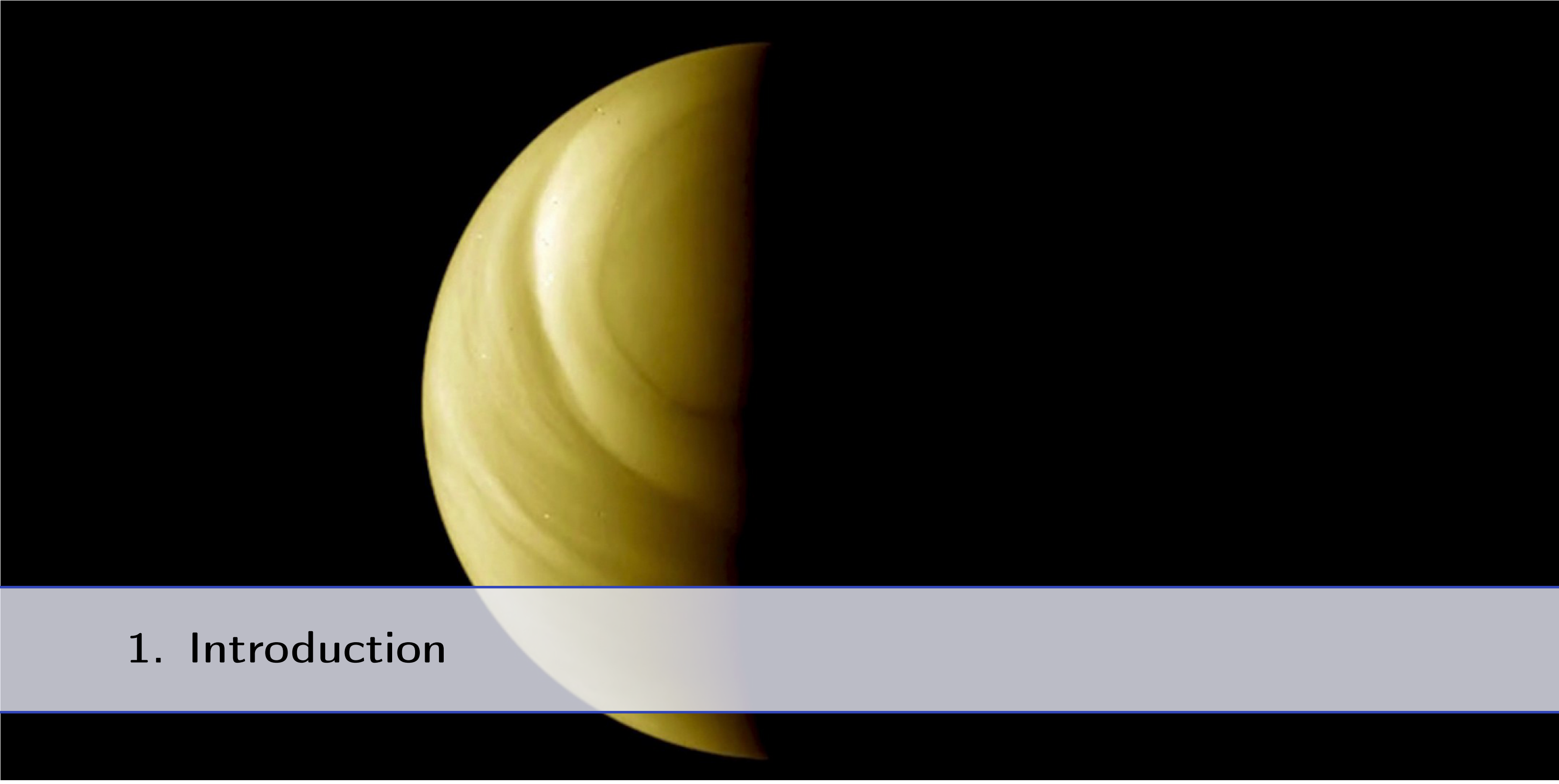


1. Introduction

Venus was the target of the very first interplanetary mission, Mariner 2, and of many subsequent missions through the early decades of interplanetary exploration. After Magellan 30 years ago, US-led Venus exploration has been largely quiescent until the recent selection of NASA Discovery missions VERITAS and DAVINCI, along with NASA's participation in ESA's EnVision. These missions will address a significant number of major science questions about the past and present of Venus. Despite the expected influx of data, many crucial questions about the history of Venus will remain unresolved after the success of these missions, including those that elucidate the divergence of Venus from her sister-planet, Earth (Table 1). Understanding the significant turning points in the evolution of Venus requires knowledge that is not obtainable by the selected suite of upcoming missions, but can be attained by an innovative approach in the next ~20 years with an appropriate strategy in place.

In the same way that the Mars Exploration Rovers, Mars Science Laboratory, and Mars 2020 have provided measurements that unravel the mysteries of Mars, the Venus In Situ Transfer and Analysis (VISTA) mission concept provides an opportunity to make measurements that cannot be obtained by a single, short-term in situ mission to Venus. The targeted science aims to provide detailed knowledge of the surface and atmosphere to better understand the origin and evolution of Venus, changes in its habitability and the interaction of the surface with the atmosphere. Since the surface environment of Venus is not conducive to long-term (years) surface missions akin to Mars rovers Spirit, Opportunity, Curiosity, and Perseverance, we propose instead a laboratory in the sky.

VISTA is an "in situ sample capture" mission, where atmospheric and geological samples are collected and brought to a laboratory on a platform floating in the Venusian atmosphere for analysis, contrasting with a true sample return mission where samples are eventually analyzed in Earth laboratories. Central to VISTA is the highly-capable Aerial Laboratory that will deliver long-duration (months to years) geologic science from multiple different surface locations, greatly expanding the science return of a surface analysis mission. Critical instruments and electronics can remain at lower temperatures and pressures to extend the mission lifetime. Housing a laboratory in the atmosphere and shuttling samples from the surface also offers unique atmospheric science opportunities.

VISTA is envisioned to be a multi-asset Flagship-class mission concept to collect samples from multiple locations on the planet surface, as well as from within the Venus atmosphere, and deliver them to a highly-capable, long-lived Aerial Laboratory for detailed analysis with modern instrumentation (Figure 1.1). VISTA employs Sampling Landers that are dropped to collect geological samples from the surface and atmospheric samples during transit. The Sampling Lander releases an Ascent Vehicle, which brings the sample into the upper atmosphere. A dedicated Sample Retriever enables rendezvous of the sample with the Aerial Laboratory, where chemical and physical analysis can be done at temperatures near 20°C. Finally, an orbiter provides a communications relay to Earth.

Table 1.1: Expected Science Results from the three missions selected in 2021, mapped to the VEXAG Goals, Objectives, and Investigations. Each investigation is detailed in the GOI document [VEXAG GOI]. Investigations marked in dark blue are substantially addressed by the upcoming selected missions; e.g., the investigation can be substantially incremented or revised after the upcoming selected missions achieve their goals. Medium blue are partially addressed; light blue represents a first look that could be incremented or revised by later missions. The "Achieved by the end of V3NUS" column summarizes the main measurements or observations to be used for each investigation. Bold items in the "Future Achievement" column highlight related or new investigations unanswered by the upcoming scheduled missions that are within the capability of a VISTA-like mission, while the "BP" entries in the Objective column point to evolutionary branch points given in Figure 2.1.

Goal	Objective	Investigation	Achieved by end of V3NUS	Future Achievement
I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets	A. Did Venus have temperate surface conditions and liquid water at early times? **BP2,3,4,5**	**HO. Hydrous Origins**	Near-IR emissivity maps, searching for widespread felsic crust.	**Multilocation measurement of surface rock composition, and mineralogy, particularly in tesserae.**
		RE. Recycling	Radar maps, subsurface sounding, Near-IR emissivity maps.	**Multilocation measurement of surface rock composition.** Follow-up high-res radar & **high res NIR surface imaging**. Age dating.
		A**L. Atmospheric Losses**	-	Orbital measurements of ionosphere & solar wind interaction; **measure winds and transport through lower thermosphere.**
		MA. Magnetism	-	**Magnetic fields measured from orbit and/or balloon**
	B. How does Venus elucidate possible pathways for planetary evolution in general? **BP1,2,4,5**	**IS. Isotopes**	Comprehensively addressed by DAVINCI.	**Next generation MS instruments (gas and solid source) on long-lived cloud platform may be able to achieve even higher sensitivity**
		LI. Lithosphere	Comprehensively addressed by VERITAS & EnVision's SAR & gravity.	Seismometry; Magnetotelluric sounding; **Multilocation measurements of surface material & bulk composition.** Follow-up high-res radar & **high res NIR surface imaging**. Age dating.
		HF. Heat flow	Constraints from gravity/ topography & from detection, characterization of volcanism & tectonism.	Seismometry; in situ heat flow in different provinces.
		CO. Core	Strongly constrained by gravity measurements & spin vector variation monitoring.	Seismometry. **Higher accuracy gravity from e.g. gradiometry Magnetic field measurements from orbit and/or aerobot.**

Goal	Objective	Investigation	Achieved by end of V3NUS	Future Achievement
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus? **BP4,6**	**DD. Deep Dynamics**	Vertical profile of P, T, wind, from; cloud-level winds & waves from cloud tracking; gas mapping & radio occultation from; surface winds from SAR aeolian features.	**Cloud-level 3-D winds & waves from aerobot.** Long-life surface meteorological station. Next-generation cloud tracking from orbit. Sat-to-Sat radio occultations for frequent T profiles at 40 – 90 km.
		UD. Upper Dynamics	-	Ionosphere / magnetosphere / plasma / solar wind interaction orbital measurements. Sub-mm heterodyne to measure winds & transport at 70 – 140 km, or thermal IR sounding of mesosphere (60 – 100 km).
		MP. Mesoscale Processes	Constraints on winds & waves. Winds from camera elements.	**Cloud-level 3-D winds & waves from aerobot. Simultaneous orbital & in situ atmospheric observations. Long-life meteorological station.**
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance? **BP3,5,6**	**RB. Radiative Balance**	Radiative flux measurement from descent probe. New spectroscopy from orbit.	**Radiative flux measurements from descent probes. Cloud-level radiative flux measurements from aerobot. Long-life radiometric/meteorological station.**
		IN. Interactions	Chemical profiles, and maps of key volatile gases, and links to volcanic activity.	**In situ characterization of cloud particles, radiation, microphysics. Search for lighting (aerobot,** orbiter). **Aeolian processes (lander, sampler,** orbiter).
		AE. Aerosols	Orbital mapping of aerosol distributions. Measurement of gaseous volatile species which participate in condensational cloud formation.	**In situ cloud-level aerobot measuring cloud and gas composition, and particle size & shape. Characterization of dust at surface.**
		UA. Unknown Absorber	Orbital UV observations. In-situ chemical inventory in clouds.	**In situ cloud-level aerobot measuring cloud, gas, aerosol composition, especially at altitudes > 60 km, and UV/blue fluxes.**
		OG. Outgassing	Vertical profile of composition including outgassed volatiles; Mapping outgassed volatile species.	**In situ measurements of surface and cloud materials to search for signatures of outgassed volatiles.**

Goal	Objective	Investigation	Achieved by end of V3NUS	Future Achievement
III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere	A. What geologic processes have shaped the surface of Venus? **BP2,3,5**	**GH. Geologic History**	Global SAR imaging & topography, NIR emissivity, gravity & subsurface mapping + high-res imaging.	**Detailed surface properties, composition, and mineralogy multiple locations.** Follow-up high-res radar & **high res NIR surface imaging.**
		GC. Geochemistry	Constraints from NIR emissivity maps (& SAR & radiometry).	**Multisite measurement of surface composition.**
		GA. Geologic Activity	Change detection (repeat SAR imagery), searches for NIR & RF thermal anomalies, volcanic plumes, volcanic tracers.	Systematic surface monitoring with repeat-pass InSAR & radiometry (NIR & RF). Seismometry (surface, **aerobot**, or orbital).
		CR. Crust	Addressed by SAR & gravity, sub-surface sounding, and descent imaging.	Seismometry; Magnetotelluric sounding; **In situ measurements of surface material composition and mineralogy.**
	B. How do the atmosphere and surface of Venus interact? **BP3,5**	**LW. Local Weathering**	Constraints from NIR emissivity maps (& SAR & radiometry). Also measurements of near-surface atmospheric composition.	**Measurement of surface & near-surface atmosphere composition and mineralogy at multiple localities.**
		GW. Global Weathering	Constraints from NIR emissivity maps (& SAR & radiometry) & SAR imagery.	**Measurement of surface & atmosphere composition, global patterns, layering if present.**
		CI. Chemical Interactions	Measurements of near-surface atmospheric composition. Measurements of tropospheric gas abundances. Maps of clouds & low-altitude water vapor. Radar anomaly.	**Surface landers & meteorological stations.** Follow-up high res radar and **other surface mapping/mineralogy**.

This concept provides a new and innovative architecture for in situ sample analysis as a potentially favorable alternative to concepts that have been explored or proposed previously, such as short/long-lived (hours-to-months) surface missions, and long duration (weeks to months) and variable elevation balloon missions. This architecture offers notable benefits over others while also presenting its own unique challenges. These benefits include 1) the ability to include humans-in-the-loop for decision-making, such as for site selection, sample processing pathways, 2) longevity, enabling multiple data sets for repeat experiments, complex or time consuming sample processing or handling, and longer dwell time for measurements because of housing instruments in an ambient environment, which leads to 3) the potential to include more complex methodologies onboard the Aerial Laboratory because of the ambient environment and more relaxed time constraints, 4) smaller and more nimble lander elements, enabling access to important geologic materials that may be located in rougher terrain, 5) multiple sample opportunities for increased redundancy and a greater diversity of surface material locations, and 6) an opportunity for international and/or industrial partnerships for supplying high-impact sampling systems not in the critical path of the mission.

Many Venus mission concepts strive to elucidate information about the surface of Venus, and so VISTA must be compared to these alternatives (Table 1.2). An unspecified multi-lander mission is included in the comparison below as an obvious alternative to VISTA as a mission that could yield samples from multiple sites. The intent of this report is not to suggest that VISTA is the only option to achieve quality science—for example, the hypothetical multi-lander mission was assumed to not include any additional aerial platform, so would not be expected to have aerial platform capability. Instead, we present an alternative architecture with unique benefits and challenges; VISTA is distinct from other concepts. There is a strong case for the type of science enabled by analyzing samples from multiple different surface sites as well as atmospheric profiles (See Science Background/Science Traceability Matrix).

Any in situ Venus mission faces significant technical and operational challenges. VISTA shares many challenges with past and current in situ concepts (e.g., the need to collect surface samples as in previous New Frontier proposals, VISAGE and VICI missions; and the Venus Flagship Mission concept study conducted for the 2023-2032 Decadal Survey), softens others (e.g., shorter surface operations), and presents its own unique challenges (e.g., ascent from surface to middle atmosphere, asset rendezvous, sample processing, and long(er)-lived laboratory platform). Despite the challenges, VISTA is envisioned as a way to exploit as much development in the pipeline as possible. VISTA takes advantage of current robust technologies, and does not require the development of complex, high-capability instrumentation to withstand in situ the harsh environment on the Venusian surface. Further, the technology development that is needed for VISTA shares fundamental technology requirements for a wide range of next-generation Venus (and other planetary) science, from high temperature electronics and mechanics, to autonomy, to communications and more.

The VISTA mission architecture offers an opportunity for a decade-after-next "Capstone" mission to the current revitalized era of Venus exploration, similar to how Mars Sample Return is a Capstone for Mars science efforts of the last 40 years.

Table 1.2: VISTA compared with other Venus mission concepts.

Mission/ Concept	In Situ Duration	Locations	Elevations	In Situ Capability (location of capability)	Humans-in-the-Loop
Venus Flagship	Medium (atmosphere) Short (surface)	Regional (atmo) 1 site (surface)	Atmosphere Profile to Surface	Medium (atmosphere) High (surface)	Yes (for longer-lived assets) No (for surface assets)
VISAGE (NF)	Short (surface)	1 site (surface)	Profile to Surface	High (surface)	No
VICI (NF)	Short (surface)	2 sites (surface)	Profiles to Surface	High (surface)	No
Venus Cloud Explorer (VCE)	Med-Long (atmosphere)	Multiple latitudes uncontrolled	Atmosphere (52–62 km)	High (atmosphere)	Yes
SAEVe (TDO)	Med-Long (surface)	1 or multiple sites (surface)	Profile to surface	Low (surface)	No
Multiple Landers	Short (surface)	Multiple locations	Profiles to Surface	Low (surface)	No
VISTA	Very Long (atmosphere) Short (surface)	Multiple latitudes Multiple locations	Atmosphere Profiles to Surface	Very High (atmosphere) Very High[a] (surface)	Yes

[a]In situ capability on the VISTA surface asset itself is expected to be low-medium, but the impact is high when coupled with the Aerial Laboratory (i.e., delivering on the study of multiple surface samples).

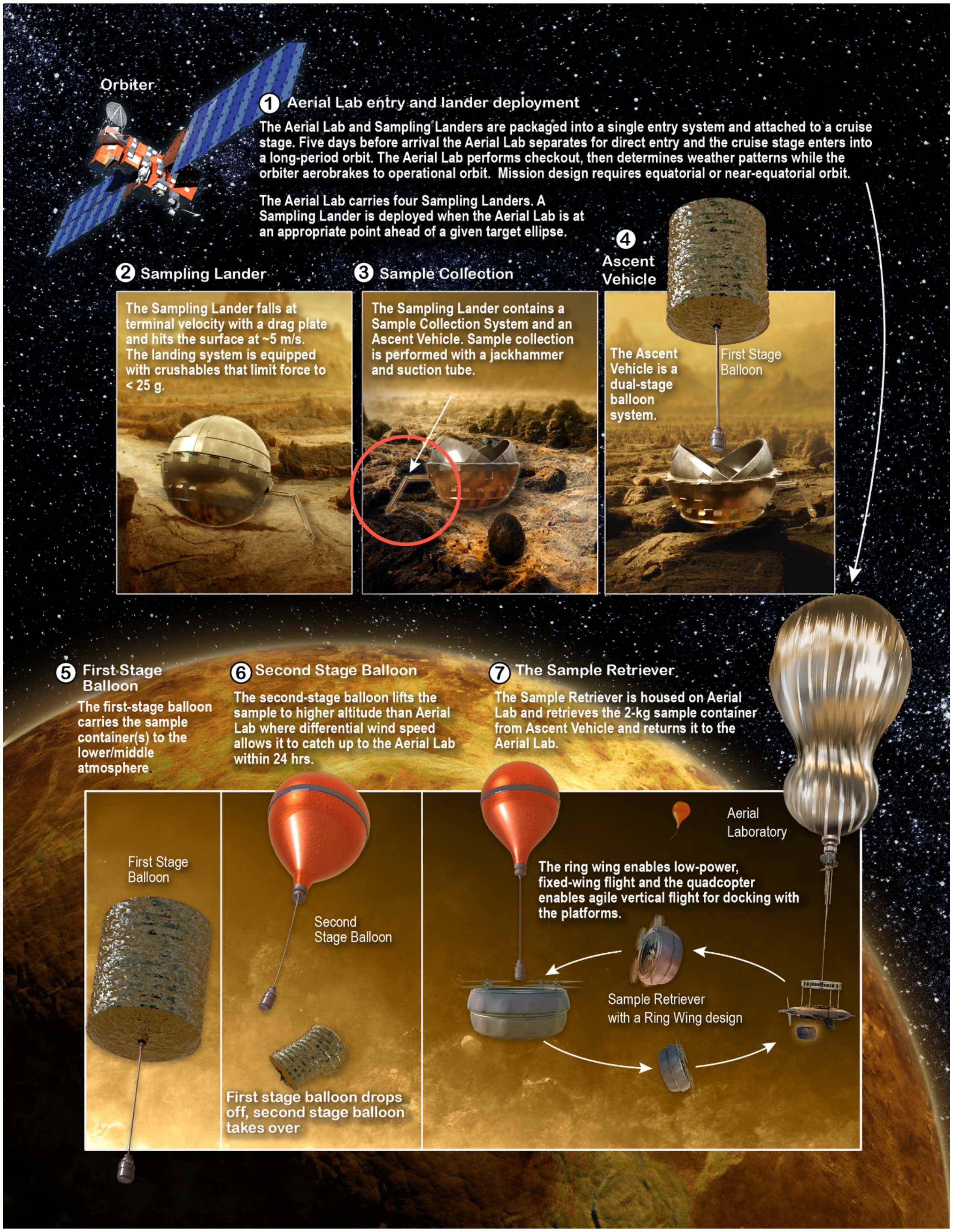


Figure 1.1: High-level VISTA mission architecture

2. Science Background

Mysteries still abound regarding the geologic history of Venus due to the very limited dataset available today. As we currently understand it, Venus is a rocky world shrouded in a thick, greenhouse atmosphere, severely limiting access to the surface. Orbital mapping efforts have shown two major distinct terrain types on the planet's surface—the lowland plains (~80% of the surface) and the high elevation, highly deformed tesserae (~8% of the surface) (Basilevsky and Head, 2003; Basilevsky and McGill, 2007). The highlands are interpreted to be older than the plains, as the tesserae are embayed by plains units and have a higher density of large (>16 km diameter) impact craters than the plains (Ivanov and Basilevsky, 1993; Ivanov and Head, 1996). The only chemical data from solid Venus comes from a series of Soviet landers that visited the plains between 1975–1984. The three landers that could measure more than just the naturally radioactive elements K, U, Th encountered rocks that appear basaltic in composition, in agreement with morphological assessments. However, the data were missing many elements critical to petrology and geochemistry, and the measurements of elemental concentrations were not good enough to be of extensive use (see discussion in Treiman, 2007). These landers did not measure mineralogy, and their landing site locations are not well constrained within their landing ellipse, making difficult any correlation of their measurements to large-scale units (Treiman, 2007). No landed mission has yet visited the highlands, however orbital nightside thermal emission data collected by the Near-Infrared Mapping Spectrometer on the Galileo mission and the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on Venus Express suggest the highlands and plains may be made of different materials as they have different emissivity signatures (Gilmore et al., 2015; Hashimoto et al., 2008). One interpretation of that difference is that these highland materials, specifically the tesserae, may be more felsic in composition than the basaltic plains, which is a tantalizing possibility with implications for liquid water, plate tectonics, and overall Venus evolution (Gilmore et al., 2017).

Orbital radar mapping has revealed a variety of volcanic and tectonic landforms covering the surface of Venus, many of which have been observed within the plains units. These include typical geologic features such as volcanoes, ridge belts, lava flows, and rifts, along with more enigmatic features such as coronae, canali, steep-sided "pancake" domes, and arachnoids that do not have obvious interpretations from imagery alone (Head et al., 1992). The morphologies of these features suggest that lavas of different viscosities have erupted on Venus, with the long, sinuous canali appearing to be formed from a low-viscosity liquid (which cannot be water due to the high surface temperature) and the high, flat-topped, steep-sided domes appearing to have formed from something with much higher viscosity (Baker et al., 1992; Head et al., 1992). This suggests that Venus has a range of igneous processes occurring in its interior, leading to a variety of lava compositions. Additionally, variations in SO_2 gas abundance above the cloud layer observed by both Pioneer Venus and Venus Express (Esposito, 1984; Marcq et al., 2013) and high-emissivity anomalies observed by VIRTIS on Venus Express in volcanic regions thought to be hotspots (Smrekar et al., 2010) collectively suggest that Venus may have been volcanically active into the modern era, or even up to the present day.

More is known about the Venus atmosphere, but even the details of this environment are uncertain in the lower, near-surface elevations. The modern, dense, super-rotating atmosphere is mostly composed of CO_2, also containing N_2 and a suite of other trace gasses, many of which are greenhouse gases and highly reactive or corrosive (summarized in Lodders and Fegley, 1998). The atmosphere provides about 92 bars of pressure at a planetary radius of 6052 km, and the greenhouse effect leads to an average surface temperature of 462°C at this level (Seiff et al., 1985). This environment is far outside the stability field of liquid water, and leads to a different chemical weathering regime than seen on other rocky planets in our solar system (summary in Zolotov, 2018). Conditions such as oxygen fugacity at the surface are poorly constrained due to insufficient precision on gas species measurements at that atmospheric level and uncertainty in thermodynamic data for relevant phases. Oxygen fugacity has been calculated to be between 10–21.7 bars and 10–20.0 bars, which is indistinguishable from the magnetite-hematite phase boundary within the uncertainty of the thermodynamic data, complicating prediction of the stable Fe-bearing mineral phases (Fegley Jr. et al., 1997; Zolotov, 2018).

Present understanding suggests that the clouds are primarily sulfuric acid, though the VEGA data and numerous other studies suggest that other species are present as well. Little is known about the aerosols in the thin haze layers beneath the cloud base at 48 km. Dust and volcanic emissions are expected, and materials vaporized from the hot surface may condense as they rise. The nature of the cloud layer in the Venusian atmosphere has been inferred from limited data obtained with a single-particle light-scattering instrument, the laser cloud particle size spectrometer (LCPS), during the descent of the Pioneer Venus Sounding Probe (Knollenberg and Hunten, 1980) within the upper (66–56 km), middle (56–50 km), and lower (50–48 km) cloud layers. The data extend down into the lower haze layer (31–48 km), with no measurements reported below that altitude. The small particle mode in the data is speculative at best given the low resolution of the light scattering intensity in that size regime and the inability of the instrument to resolve more than the large particle tail of that fine mode distribution. The large particle end of the size spectrum is likely constrained by the measurement range of the instrument. X-ray analysis of filters during descent of the VEGA-1 and VEGA-2 probes through the same region (~70–47 km) provided some elemental analysis of the collected particles. To understand these persistent clouds requires knowledge of the compositions of the droplets, the supersaturations of the vapors that form those droplets, and the cloud condensation nuclei (CCN) on which those droplets form. While the Pioneer data provide important clues about the nature of the clouds, these quantities need to be better constrained. The number, size, and composition of the CCN determine how many cloud droplets are formed. The supersaturation attained within the cloud layer determines which potential CCN activate to form cloud droplets. The absolute condensable vapor concentration determines the rate at which droplets grow. Combined, these factors control the optical thickness of the clouds and hazes. Atmospheric ions (typically produced by cosmic rays) reduce the thermodynamic barrier to CCN activation. The question remains: What are the CCN and how are they formed?

High temperatures in the lower atmosphere are sufficient to dissociate sulfuric acid. As the resulting products from the lower atmosphere are advected into the cooler haze and cloud layers, gas phase reactions may generate sulfuric acid at rates sufficient to produce the supersaturation needed for homogeneous nucleation, or may activate on and grow existing particles. By comparison, sulfuric acid nucleation accounts for roughly half of the CCN in Earth's atmosphere, in spite of its much lower concentration. Initial analysis of the data from the Pioneer LCPS (Knollenberg and Hunten, 1980) suggested that a third, large particle mode in the particle size distribution may include solid particles, though Toon et al. [1984] have suggested that the available data may not support the existence of large solid particles in the cloud layer. That does not exclude the presence of solid CCN which would activate and contribute to the cloud droplets. Measurements within the cloud and haze layer are needed to constrain the properties of the clouds.

Particles within the middle and lower atmosphere are largely unknown, as earlier particle-measurement instruments did not continue to gather data in those hot regions. The particles in the deep atmosphere may, or may not, contribute directly to the cloud or haze layers, but they will provide direct evidence of atmosphere/surface interactions due to emissions from volcanoes, suspension and entrainment of surface dust, erosion, etc. Collection of airborne samples for analysis will provide that direct link. Collection of size-resolved samples will provide critical information for assessing the distances over which suspended particles may be transported. When combined with surface wind data, knowledge of the size and composition of the particles will document the potential for erosion.

Altogether, our current picture of Venus from limited datasets looks very different from Earth, or any other rocky planet in our Solar System. The extreme divergence in evolution of Earth and Venus may seem somewhat surprising, given how similar they are in size and bulk density. Our current Venus dataset cannot begin to answer the complex questions of why, how, and when these two planets began to follow different evolutionary paths, and even the newly selected missions to Venus will not provide all the data needed to solve this puzzle. The long absent, ever critical chemical and mineralogical measurements of pieces of the solid planet cannot be acquired by these upcoming orbital and probe missions. This data gap is what the VISTA mission concept was developed to address, for the purpose of helping us understand how these two sister planets became so different.

> **The central goals of the mission and the science strategy envisioned by this study project are, through analysis of multiple surface, aerosol, and atmospheric samples, to answer two questions (1) When and how did the evolutionary paths of Venus and Earth diverge? And (2) What were the fundamental branch points that set the sister planets on such different paths?**

These questions have implications well beyond the specific cases of Venus and Earth. The terrestrial planets (including Mercury and Mars), accessible to us for detailed study, represent the type examples of uninhabitable, habitable, and perhaps formerly habitable terrestrial planets. It is likely that, beyond the Solar System, there are numerous hot rocky planets, with or without runaway greenhouses, and numerous hot and cold rocky planets with tenuous atmospheres (Kane et al.). There may also be rocky planets precariously balanced in between these hot and cold end-states, maintained like the Earth in a long-term habitable state. If there is extraterrestrial life in the galaxy, then Earth's balancing act must not be unique. Understanding how such a balance can fail to arise or fail to persist is therefore a key question in planetary and exo-planetary science. As the type example of a planet that has ended up in the "hot death" state, Venus merits detailed and focused study of its history, as much as Mars and its "cold death" state (or Earth and its "Goldilocks life" state).

The Science Traceability Matrix (STM) developed by the KISS study group is organized around a series of potential planetary evolution branch points (Figure 2.1), each of which was potentially a stage in Solar System history when the paths of Venus and Earth diverged, and each of which suggests a series of testable hypotheses. Working back into early Solar System history, the deeper branching points require collection of kinds of evidence that could have persisted for longer and longer spans of Venus history, reaching back ultimately to its fundamental building blocks. For all but the last potential branch point (which focuses on the mechanisms that maintain permanent cloud cover on Venus), the evidence that might address the associated hypotheses is to be found in solid material recovered from the Venus surface. In many cases, the measurements needed, at the precision required to make a meaningful hypothesis test, require measurements at the Venus surface that span space, and therefore time, over the arc of the planet's history. The environment is too hostile and the measurements take too long for current rover-based laboratories to reach a sufficient diversity of sites over their expected spatial range and mission lifetime. There is clearly a place for measurements taken at the surface, and many mission designs have been proposed that focus on this approach (e.g., Bullock et al., 2009; Esposito et al., 2017; Glaze et al., 2017). Conversely, the measurements needed to address the deepest branch points (planetary building blocks) are not currently practical with any flight-capable technology and likely will require sample return to Earth for the foreseeable future. While flight instruments are not yet ready to achieve these branch points, the in situ sample capture strategy represents an achievable and likely prerequisite step to informed sample return. We seek to emphasize the areas where VISTA occupies the middle ground of technically achievable measurements that can answer the most fundamental questions about the history of Venus.

In order from oldest to most recent, the branch points listed in the STM are:

- ***Branch Point 1 Hypothesis:*** *Venus and Earth accreted from different mixtures of primitive solar system materials ("building blocks"), and these differences determined their divergent evolution from the very beginning.* In this hypothesis, the radial architecture of the solar nebula and the different heliocentric distances of Venus and Earth drive subsequent evolution. That is, we need not identify a planetary process that led to divergence because the planets were different already as a result of nebular processes. The evidence to test this hypothesis lies in cosmochemistry. The isotopic study of samples from Earth, the Moon, Mars, meteorites, and comets has revealed mass-independent gradients in the relative abundances of isotopes with different nucleosynthetic origins or energetic particle irradiation histories (Warren, 2011; Dauphas and Schauble, 2016; Kleine et al., 2020). Because these isotopic differences are apparently systematic functions of heliocentric distance, they are likely tracers of differences in the initial abundance of life-essential volatile elements (Mezger et al, 2020; Render et al, 2017; Bermingham et al, 2020). The ability to place Venus on this gradient represents a key test of the radial hypothesis for these differences. The mass-independent isotopic signals themselves are essentially immune to modification by planetary processes and so are much more persistent over time and global in character than actual differences in the volatile contents of particular planetary samples available today. They are also challenging to measure, often at the forefront of the capability of terrestrial laboratories, and so addressing this branch point may only be possible with informed sample return (see Treatise on Geochemistry, Volume 15, 2014 for discussion of methodologies; Greenwood and Anand, 2020). If all the later branch points can be eliminated with data from this mission, the case for true sample return will be made that much stronger. Although mass-independent isotopic signatures may be the most definitive indicators of planetary building blocks, there may be other, more easily measured, indications of the differences in bulk composition between Earth and Venus. With sparse Martian and lunar samples, geochemists have been able to constrain the crustal and mantle compositions of these bodies and define models for their bulk composition (e.g., Dreibus and Wanke, 1985; Jones and Delano, 1989). Similar lines of reasoning would allow a select number of solid igneous rock samples from Venus to be generalized to a model of bulk silicate Venus composition, which can be compared to that of Earth to determine if differences in their bulk chemistries could cause their divergent evolutions.

- ***Branch point 2 Hypothesis:*** *The events of the giant impact era of accretion led to major differences in the timing of core formation, degassing history, and the loss of volatiles from Venus and Earth.* The era of giant impacts has plainly left different imprints on Earth and Venus. Earth has a large Moon and the Earth-Moon system has a large prograde angular momentum, both thought to be traceable to the particular size, geometry, and timing of the last giant impact on Earth (e.g., Canup and Asphaug, 2001). Venus has no moon and a slow retrograde rotation, indicating essential differences in size and geometry (and likely timing) of any giant impacts it experienced (Gillmann et al., 2016). Here, we ask how these highly energetic events affected the interior and surface reservoirs of Venus and Earth and whether the differences set the stage for the divergent evolution of the two planets. Giant impacts are intimately associated with planetary differentiation, core formation, core-mantle equilibration, mantle mixing, and magma ocean formation (e.g., Jacobson et al., 2017; Nakajima and Stevenson, 2015; Rubie et al., 2015). Primordial atmospheres are developed by vaporization during impacts and lost by sufficiently energetic impacts. Later atmospheres are developed by degassing from the interior, most efficiently from magma oceans (e.g., Elkins-Tanton, 2012; Gillmann et al., 2022). Hence any signatures of core formation that can be discovered in Venus rocks can address the initial state for subsequent atmospheric evolution and the potential role of that state in determining the planetary path. Persistent, planetary-scale geochemical evidence with memory of this era includes isotopes of Pb, W, and Sr isotopes in rocks and Xe isotope differences between atmosphere and interior. These isotopes can potentially be studied with in situ measurement technologies under development, but there is room for the development of capable and flexible instrumentation.

- ***Branch Point 3 Hypothesis*** *Venus' smaller heliocentric distance prevented condensation of a liquid water ocean, leaving CO_2 in the atmosphere and exposing H_2O to early loss.* The essential difference between the surface environments of Venus and Earth is the quantity of carbon dioxide in the atmosphere. Venus, with a column abundance of 92 bars of CO_2, has a runaway greenhouse effect that keeps the surface too hot for life (Lodders and Fegley, 1998). Earth, with a column abundance of ~3 x 10–4 bars of CO_2, has just enough of a greenhouse effect to maintain liquid water at the surface (Cockell et al., 2016). But it is likely that the initial quantity of CO_2 in the Earth system was at least as large as that of Venus, now mostly stored in solid form, as carbonate minerals (Lecuyer et al., 2000). Carbonate minerals require aqueous chemistry, i.e. liquid water, to mediate their precipitation. The presence of abundant carbon on Venus suggests that there was significant delivery of volatile-bearing objects during its formation, implying also significant initial water, which is also required to explain the elevated D/H ratio of the Venus atmosphere through H_2O loss (Gurwell, 1995). Hence, in the early history of both Venus and Earth, it is possible that there were H_2O-rich steam atmospheres, likely degassed from magma oceans (Elkins-Tanton, 2012 and references therein). Hence there is a possible branch point where this H_2O either condensed to a liquid ocean or did not condense (Hamano et al., 2013; Lebrun et al., 2013). If it condensed, then CO_2 could dissolve in the ocean and begin the process of sequestration as solid carbonate, leading to an Earth-like path. If the steam atmosphere did not condense, the CO_2 also would not condense to form carbonates and, moreover, the H_2O would remain in the atmosphere where it is comparatively easy to lose to space (Lammer et al., 2006). This leads to the Venus path. If neither of the previous branch points had already set Earth and Venus on different paths, then the simple difference in heliocentric distance and solar irradiation of the steam atmospheres on Venus and Earth may have made the difference. Differences from this era that might persist in rocks available to sample today include C and H isotopes, and the presence or absence of hydrated and carbonated minerals or their decomposition products in ancient rocks (e.g., we might expect a total absence of hydrated minerals in the case where H_2O never significantly condensed). Addressing this branch point ideally requires sampling fresh, ancient sedimentary rocks, but the recycling of sedimentary source material into igneous rocks preserves (at least on Earth) a record of the early condensation of an ocean and the same may be true on Venus (Harrison, 2009; Hansen, 2018). Sampling strategies that seek to collect material whose hydrated or carbonated minerals may not have had time to fully react with the atmosphere would be key targets to address this branch point. Intact samples with petrographic context are important for assessing the progress of such weathering reactions, or determining if weathered mineral assemblages represent the breakdown products of hydrous minerals.

- ***Branch Point 4 Hypothesis:*** *Venus once had abundant surface water but lost it to space.* If the steam atmosphere on Venus did condense and form a liquid water ocean, then it is evident that that ocean has been lost. Where did it go? One obvious possibility is loss to space. For a planet with as much gravity as Venus, such loss is challenging as long as the planet is shielded by a magnetic field (Driscoll and Bercovici, 2013). Today, Venus has no global magnetic field. We do not yet know whether it ever had such a field, or if so when it was lost. This branch point is intimately tied to Venus' magnetic history. It can be addressed with an aeromagnetic survey for crustal remanent magnetism and with paleomagnetic data on collected rocks of various ages (depending on the magnetic mineralogy of fresh and weathered rocks on Venus; the surface conditions today are below the Curie point of magnetite but not of hematite). Paleomagnetic measurement is a good example of something that can be done in an aerial laboratory under clement conditions but would be exceptionally difficult to do at the surface. The water loss question can also be addressed by searching for H isotopes and hydrous minerals in rocks; we might expect to find hydrous minerals in the oldest rocks with distinctively different H isotope compositions from the modern Venus atmosphere.

- ***Branch Point 5 Hypothesis:*** *Venus never developed or failed to maintain plate tectonics and is today in a stagnant lid convective state.* A strong case can be made that the persistent habitability of Earth is dependent on continuous exchange between the surface and interior reservoirs, mediated by the processes of plate tectonics (Korenaga, 2012). It is thought that plate tectonics creates numerous cycles that refresh the atmosphere's budget of life-essential volatile elements (H, C, N, O, S) and regulate their abundance. Emission of volcanic gases at spreading centers is compensated by subduction of altered rocks when the cycles are at balance, and steady-states can emerge (Foley, 2015). We do not know whether Venus has or ever had plate tectonics, but many plausible scenarios place Venus in the stagnant lid convection regime (e.g., Rolf et al., 2022). The mantle of Venus may be transporting heat by convection, but the "last mile" of heat loss is achieved by conduction through the lithosphere or by volcanic heat pipes rather than by breakage of the lithosphere, plate spreading, and subduction (e.g., Smrekar et al., 2018). This question has been studied using radar imagery and altimetry, looking for geomorphological and geophysical evidence of Venus' convective regime (e.g., Phillips and Hansen, 1998), and will continue to be studied by the upcoming VERITAS mission (Smrekar et al., 2022). It can also be productively studied using the petrology of Venus rocks, an approach which would strongly complement the orbital measurements from VERITAS. From volcanic rocks, petrologists can infer the temperature and pressure of melting and hence the state of the interior below the lithosphere (e.g., Lee et al., 2009; Herzberg and Asimow, 2015; Brown Krein et al., 2021). Sampling provides chemical and petrological indicators of heat loss, whereas inferences from morphological and structural data, or even from remotely sensed spectroscopy, may be more indirect. Sampling is much more promising.

- ***Branch Point 6 Hypothesis:*** *Venus entered a self-maintaining persistent state of permanent global cloud cover.* As hot and hostile as Venus surface conditions are, they could be worse. Because of its permanent global cloud cover, the albedo of Venus is 2.5 higher than that of the Earth (Moroz, 1983). Hence, despite being exposed to twice as much solar radiation, Venus absorbs less sunlight per unit area than Earth. How persistent is this distinct cloud state, and how did it arise? We hypothesize that the cooling effect of the clouds is necessary to maintain the middle atmosphere in the stability field of liquid H_2SO_4 droplets and hence that the cloud layer is self-sustaining. This implies another branch point, where the current state of Venus, with its permanent global clouds, diverged from that of Earth, with transient partial cloud cover. We intend to address this hypothesis by studying the mechanism of cloud droplet formation in the modern Venus atmosphere, and the role of surface-derived solid particles as cloud condensation nuclei. The mission architecture of VISTA provides, as a matter of course, natural opportunities to sample particles from the lower atmosphere, in and below the clouds and down to the surface. Capture and study of these particles offers opportunities beyond nephelometry to determine their nature and distribution. Understanding how the clouds form directly informs the question of how the cloudy state originated and why it persists.

The science achievable by VISTA has broad impact, helping us understand not only Venus, but also the evolution of terrestrial planets and the history of our Solar System as a whole. As such, the above listed Branch Points map into both the VEXAG GOI (Goals, Objectives, and Investigations) document (GOI ref), as shown in Table I, as well as the recently completed Decadal Survey (Decadal Survey ref below).

Figure 2.1: A peek into the diverging evolution of two sister planets leveraging the VISTA mission architecture.

3. The Science Traceability Matrix

The table on the following pages captures the Science Traceability Matrix in pursuit of the key Science Goal:
How does Venus' history compare with that of the Earth's? What are the branch points where the evolution of these two sister planets diverged?

Hypothesis	Prediction	Science Objectives (Architecture Needs)	Observables & Physical Parameters	Instrument Parameters	Instrument Requirements
Branch Point 1: Venus and Earth accreted from different mixtures of primitive solar system materials ("building blocks"), and these differences determined their divergent evolution from the very beginning.	Nucleosynthetic, stable, and radiogenic isotopic differences from terrestrial standards will be measurable in Venus surface samples.	Characterize enough surface samples to define Venus fractionation lines and nucleosynthetic anomalies and calculate a bulk composition of Venus (1b)	isotopes in rock (O, S, Ti, Cr, Mo), bulk rock chemistry (major/minor/trace elements)	solid-source Mass Spec	0.1 ‰ on O d S, 100 ppm/amu n Ti, Cr, and Mo
Branch point 2: The events of the giant impact era of accretion led to major differences in the timing of core formation, degassing history, and the loss of volatiles from Venus and Earth.	Pb isotope composition of Venus preserves a different U/Pb ratio and a different age of U-Pb fractionation	Determine the age of the core. (1a/b)	isotopes in rock (Pb)	solid-source Mass Spec	1% $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$
	Venus atmosphere closure age distinctively older than Earth	Determine the age of the atmosphere (2)	Xe and Ar isotopes in the atmosphere	gas-source Mass Spec	±10%

Hypothesis	Prediction	Science Objectives (Architecture Needs)	Observables & Physical Parameters	Instrument Parameters	Instrument Requirements
Branch point 3: Venus' smaller heliocentric distance prevented condensation of a liquid water ocean, leaving CO_2 in the atmosphere and exposing H_2O to early loss	Surface samples will contain no evidence of an aqueous environment and the C/H/N/O/Noble gas elemental and isotopic ratios will reflect a loss history	Determine whether evidence of an aqueous history is preserved in surface samples. (1a/b, 2)	bulk chemistry	XRF	$\pm 1\%$ relative on major elements, $\pm 5\%$ relative on minor elements
			mineralogy (non-detection of amphibole or other hydrous silicates at 2%)	XRD	Detection limit for OH bands $\leq 1\%$
			Fe oxidation state	Mössbauer	Fe^{3+}/Fe^{2+} to ~20% relative in samples with ~10% total Fe
Branch point 4: Venus once had abundant surface water but lost it to space.	Surface samples will contain mineralogical and chemical evidence of this past environment	Determine whether evidence of an aqueous history is preserved in surface samples. (1a/b, 2)	bulk chemistry	XRF	$\pm 1\%$ relative on major elements, $\pm 5\%$ relative on minor elements
			mineralogy (detection of amphibole or other hydrous silicates at 2%)	XRD	Detection limit for OH bands $\leq 1\%$
			Fe oxidation state	Mössbauer	Fe^{3+}/Fe^{2+} to ~20% relative in samples with ~10% total Fe
			hydrogen/deuterium ratio in rock	solid-source Mass Spec	100 permil on D/H
			Remanent magnetism	Magnetometer	<10–20 nT sensitivity

Hypothesis	Prediction	Science Objectives (Architecture Needs)	Observables & Physical Parameters	Instrument Parameters	Instrument Requirements
Branch point 5: Venus never developed or failed to maintain plate tectonics and is today in a stagnant lid convective state	Venus' lithosphere is thicker than Earth's and its convective upper mantle is much hotter than Earth's	Determine the distribution (1b) and composition (1a/b) of rocks, minerals, and soils on the Venus surface with sufficient precision to estimate mantle source parameters for volcanic samples.	geological composition (lava plains, tessera, active volcano, mountain tops, coronae...)	Microimaging, XRF, IR/Raman/XRD	±1% relative on major elements, ±5% relative on minor elements
			isotopes in rock	solid-source Mass Spec	1% on $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{207}Pb/^{206}Pb$
			Fe oxidation state	Mössbauer	Fe^{3+}/Fe^{2+} to ~20% relative in samples with ~10% total Fe
			carbon in rocks	Elemental Analyzer	detection limit for C < 100 ppm
	The interior remains hydrated even though the surface is dry	Interrogate mantle-derived igneous rocks for evidence of hydration in the source	bulk rock chemistry, mineral chemistry	XRF	±1% relative on major elements, ±5% relative on minor elements
	Venus did not undergo a massive surface renewal event in recent geological history and hence rock samples from different regions on Venus will have dramatically different compositions and ages.	Determine the igneous and exposure ages of the surface. (1a/b, 2)	isotopes in rock	solid-source Mass Spec	1% on $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{207}Pb/^{206}Pb$
			Fe oxidation state	Mössbauer	Fe^{3+}/Fe^{2+} to ~20% relative in samples with ~10% total Fe

Hypothesis	Prediction	Science Objectives (Architecture Needs)	Observables & Physical Parameters	Instrument Parameters	Instrument Requirements
Branch point 6: Venus entered a self-maintaining persistent state of permanent global cloud cover	Solid particles are needed to nucleate cloud droplets and help maintain the cloud cover. These particles are derived from explosive volcanic eruptions, implying that Venus is volcanically active at the present day and unweathered rocks can be found near the summits of active volcanic centers	Determine the igneous and exposure ages of the youngest surfaces (1a/b, 2) and obtain fresh volcanic ash particles from atmosphere (3)	geological composition (K_2O vs SiO_2)	XRF	±1% relative on major elements, ±5% relative on minor elements
			He isotopes in rock	solid-source Mass Spec	10% on $^3He/^4He$
			Fe oxidation state	Mössbauer	Fe^{3+}/Fe^{2+} to ~20% relative in samples with ~10% total Fe
			micro-nanoscale texture	Microimaging	10 μm resolution, 5 mm field of view
			particle composition particle size	laser ablation Mass Spec? laser scatterometer?	
			density of particles in atmosphere	laser scatterometer?	
	Solid particles are derived from the surface by wind entrainment and can be found at all elevations from surface to cloud base, independent of locations of volcanic activity	Determine how the particulates in the atmosphere drive and support cloud formation. (3)	particle composition	laser ablation Mass Spec?	
			particle size	laser scatterometer?	
			particle composition	laser ablation Mass Spec?	

4. VISTA Architecture Trade Space

4.1 High-Level Architecture Trades

At the highest-level, the broad architecture and vision investigated in the workshop was:

- "In situ Sample Capture" is leveraged to retrieve multiple samples from the surface (and possibly lower atmosphere) for analysis at an Aerial Laboratory.
- The long-lived Aerial Laboratory houses sensitive instruments at altitudes where temperatures and pressures are closer to Earth-ambient.

The workshop focused on the potential methods of achieving the envisioned in situ sample capture and the science potential for these options as compared with other mission architectures. The main benefits identified for this concept over other architecture options are 1) humans-in-the-loop, 2) mission duration, 3) sophistication of measurements, 4) diversity of sampling sites, 5) number of sampling sites, and 6) a partnership opportunity.

A wide variety of potential methodologies were explored to achieve the envisioned mission, with a focus on the most challenging piece: the sample capture chain. This includes areas such as sample collection system delivery to the surface, return to the Aerial Laboratory, sample capture technique, type of sample collected, features and capabilities of the Aerial Laboratory, etc. A trade tree (Figure 4.1) was developed to help organize and characterize the mission option space, focusing primarily on the sample capture chain, and this tree was further refined and evaluated. The version of the tree shown here includes a high-level assessment of the relative level of technical difficulty for each option. A more complete discussion of pros and cons of each of the entries in the trade tree was developed to support the trades and is included in the Appendix. A key finding is that although the tree includes a comprehensive listing of the possible elements and options discussed, only two entries (fully reusable sampler and rocket for sample ascent) were determined at this stage to be likely to prove impractical as viewed at this time. **There are several feasible solutions to meet the intent of the mission concept.**

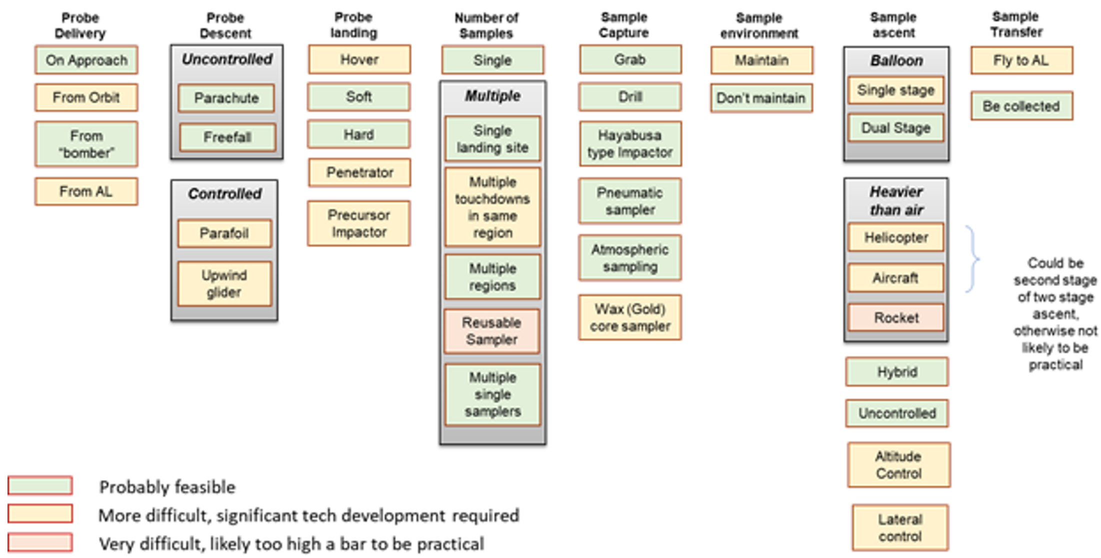


Figure 4.1: Mission Trade Tree that shows options for the sample capture chain. Probe refers to any element reaching the surface, which is encompassed by the Sampling Lander in the Example Architecture.

Of the remaining options, a number of possible architectures remain, varying in difficulty and performance. The use of such a tree allows a comparison of both architecture elements as well as complete architectures. For instance, when exploring which architecture might be the simplest to implement, one option could be to choose a probe delivered on approach, with an uncontrolled freefall descent and a hard landing. In this version (Figure 4.2, shaded elements), a single probe would be delivered to a single landing site, taking a sample using a system that does not preserve the surface environment and ascending to the altitude of the Aerial Laboratory via a dual-stage, uncontrolled balloon. The Aerial Laboratory would then send a vehicle to retrieve the sample and return it for analysis. This "simplest" architecture was also determined to be uncompetitive with other mission architectures—as compared with a single landed mission, the possible gain in science is unlikely worth the increase in complexity and cost. While this is likely the simplest implementation, it does not meet the minimum science requirements for the mission (i.e., requires sampling from multiple regions to significantly distinguish the science from a lander/probe mission architecture).

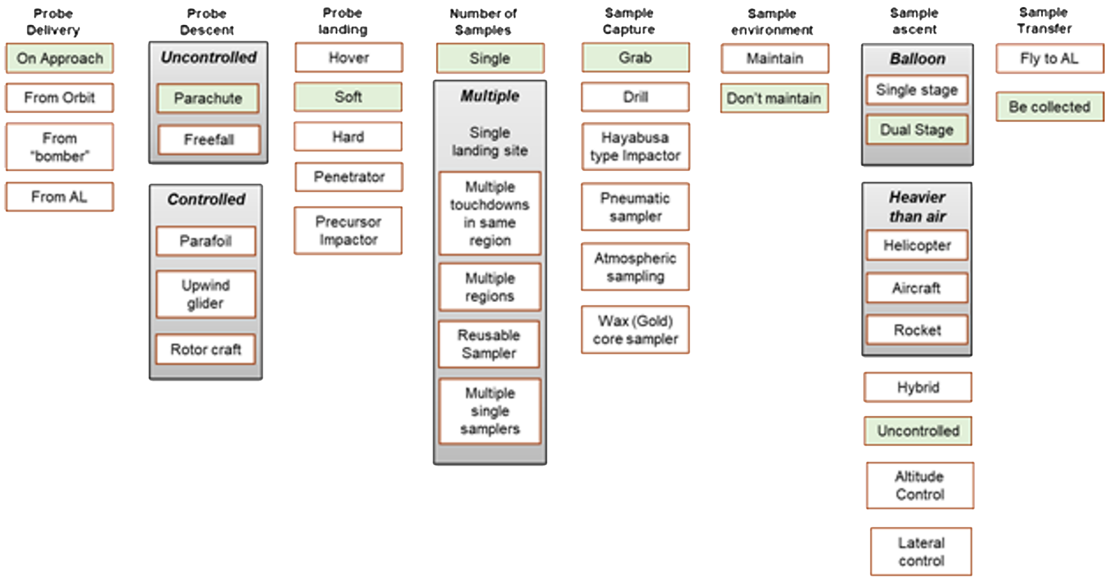


Figure 4.2: Trade Tree for Simplest Mission with green shading showing the selected elements.

Certainly, many different variations of these basic elements can be combined to develop alternate architectures with different features and differing levels of science return. The trade space for VISTA is large, and additional efforts are required to truly close on a more detailed mission design.

4.2 Elements

The VISTA mission concept leverages a multi-element architecture in order to achieve flagship-level science on a uniquely-challenging planetary body. At the close of the workshop, it was determined that with the information in-hand, the key elements involved include (See Figure 1.1 for reference):

- Aerial Laboratory: houses instrumentation and sample processing equipment onboard, floats in the relatively ambient upper atmosphere
- Sampling Landers: (i.e., "probe" in Trade Tree) carry sampling equipment and Ascent Vehicles, and carry out surface operations
- Ascent Vehicle: carries the collected sample from the surface to the upper atmosphere
- Sample Retriever: deploys from the Aerial Laboratory and fetches the sample from the Ascent Vehicle
- Orbiter: acts as a communications relay between VISTA and Earth

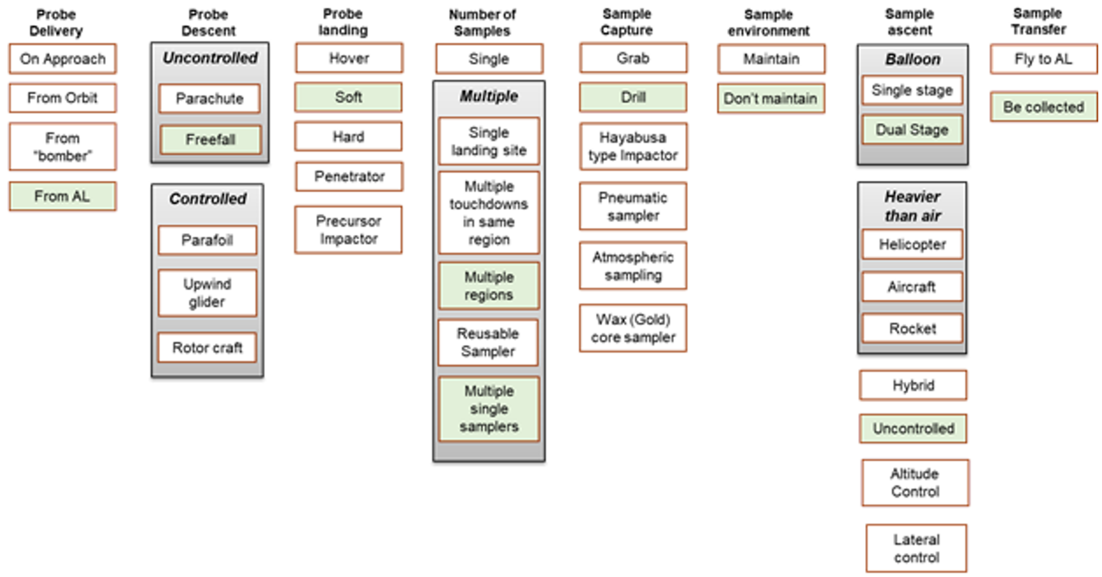
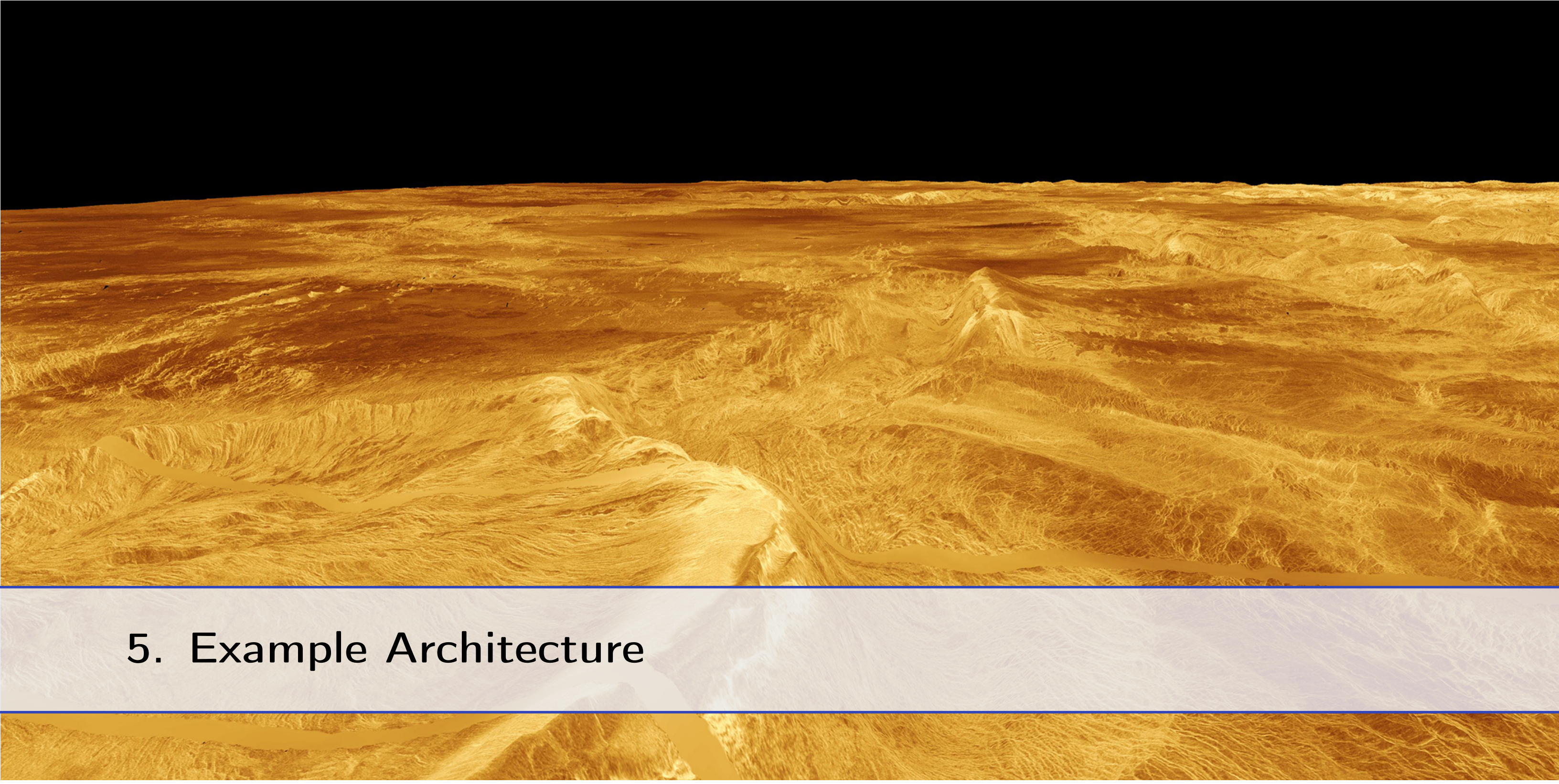


Figure 4.3: Trade Tree for Example Mission with green shading showing the selected elements.



5. Example Architecture

The trade space on achieving the VISTA mission remains open, and a dedicated mission concept study is needed in order to both close on a design and understand the benefits and challenges relative to other mission architectures. Also, the technology landscape is rapidly evolving, which can be expected to make some alternatives more or less attractive as our capabilities change. Because VISTA is expected to be viable in the 10–20 year timeframe given appropriate investments and maturation efforts, the solution described below is likely to evolve, perhaps significantly, as technologies mature. What is described here is not intended to prescribe a specific solution, but to highlight feasibility. While VISTA is a complex multi-asset mission, all operations described below have solutions currently in the technology pipeline. Table 3 shows a preliminary estimation of mass by asset, and Table 4 shows how these estimations propagate to the complete mass stack determining launch capabilities.

5.1 Concept of Operations

1. **Venus arrival and orbit:** The Aerial Laboratory and Sampling Landers are packaged into a single entry system and attached to a cruise stage. Five days before arrival the Aerial Laboratory separates for direct entry and the cruise stage enters into a long-period, elliptical orbit, which reduces Venus-orbit insertion ΔV. The Aerial Laboratory performs checkout and determines weather patterns while the orbiter aerobrakes to operational orbit. Mission design requires equatorial or near-equatorial orbit. At least one satellite is needed for communications relay and navigation. Instrumentation on the orbital platform offers an opportunity for additional science, but is not required.

2. **Aerial Laboratory entry and deployment:** The Aerial Laboratory, housing the Sampling Landers and Sample Retriever, is contained in a single entry, descent, and landing (EDL) system. The Aerial Laboratory deploys and the balloon inflates in the middle atmosphere. The Aerial Laboratory stabilizes at ~52 km where the atmospheric properties are: temperature of 10–50°C, density of 0.2–1.0 kg/m^3, and winds of 50–70 m/s E and $\pm$ 20 m/s N/S. The entry deceleration requirement is $<$ 50g for instruments.

3. **Sampling Lander deployment:** The Aerial Laboratory carries four Sampling Landers. A Sampling Lander is deployed when the Aerial Laboratory is at an appropriate point ahead of a given target ellipse. The ellipse is defined by the navigation uncertainty of the Aerial Laboratory and uncertainty of the wind profile to surface. The Sampling Lander falls ballistically with a drag plate at terminal velocity into the lower atmosphere, and eventually, hits the surface at ~5 m/s. The landing system is equipped with crushables that limit force to $<$ 25 g. During the ~1-hour descent, the Sampling Lander takes context images from a descent camera. Deployed small booms can collect aerosols on descent, for example, by impacting particles into a Au substrate for later analysis at the Aerial Laboratory. Staged vacuum canisters can collect air samples on descent. These atmospheric sample collections can alternatively be done on ascent if this is necessary for the science (i.e., if the surface temperature and preservation is a concern); the rationale behind collection during descent is to enable the Ascent Vehicle to be as simple (and light) as possible.

4. **Sample Collection:** The Sampling Lander contains a Sample Collection System and an Ascent Vehicle. Sample collection is performed with a jackhammer and suction tube. The surface is imaged again for context, then the suction tube collects the initial sample. The sample is delivered to a sample container via pneumatic flow and deflector plate. A simple fill sensor on the sample container determines whether additional sample is required. If no rocks are detected in the container, the jackhammering will commence, followed by the suction collection. This process repeats until the sample container is full or until surface sojourn time reaches its limit. An image is taken of the surface and sample container before and after each collection for contextual comparison. Surface duration is <1 hour; for comparison, Mars Sample Return (MSR) coring drill and caching system takes up to a few hours for collection and storage, but VISTA science does not need the carefully collected cores required by MSR. Other robotic collection systems (described in the Appendix) are capable of collecting faster.

5. **Ascent:** The Ascent Vehicle is a dual-stage balloon system. The first-stage balloon inflates and carries the sample container(s) to the lower/middle atmosphere with an ascent over ~3 hours. The Sample Collection System is left behind so that lifted mass is only ~2 kg. For relevant comparison to MSR, the sample vessel without sample is ~62g, with collected samples on the order of 5–20 g, far less in mass than the VISTA 2-kg

estimate.. The second-stage balloon lifts the sample to higher altitude than the Aerial Laboratory where differential (eastward) wind speed allows the Ascent Vehicle to catch up to the Aerial Laboratory within 24 hrs. The Ascent Vehicle passively rides the winds. The Aerial Laboratory changes altitude to control local winds plus outboard propellers for finer latitude/longitude control. The Aerial Laboratory has ~1kW available to run pumps to change altitude and/or run propellers, scaled by how fast the Aerial needs to descend; an ascent rate of 10 km/hour is assumed here.

6. **Sample Retrieval and Rendezvous:** The Sample Retriever is housed on the Aerial Laboratory and retrieves the 2-kg sample container from the Ascent Vehicle and returns it to the Aerial Laboratory. The Sample Retriever, currently leveraging the Ring Wing Drone (see Appendices for more details), utilizes a quadcopter propeller arrangement and a novel nonplanar ring-wing design to improve flight control characteristics during hover and to improve structural rigidity. The ring wing enables low-power, fixed-wing flight and the quadcopter enables agile vertical flight for docking with the platforms. The Sample Retriever range was assumed to be 60 km with a mass of 30-kg Sample Retriever. This estimate is quite conservative—the current design scales to carry a 1-kg sample package with a 10-kg drone over 100 km range. The use of the Sample Retriever may enable even faster rendezvous times as compared to the plots above.

7. **Sample Processing/Analysis within Aerial Laboratory:** Because the Aerial Laboratory is highly equipped, with the ability to have humans-in-the-loop, there is time for detailed sample analysis, processing, and secondary analyses. The sample chain takes ~2 weeks per sample to proceed through all desired analyses. Imaging and selection of samples from the containers, and cutting, polishing, or powdering can happen onboard. Instruments may include an X-ray fluorescence spectrometer, X-ray diffractometer, a Mössbauer spectrometer, a solid-sampling mass spectrometer, infrared spectrometer, and Raman spectrometer. There is convenient overlap between instruments for impacted aerosol analysis and geochemistry, and a similar analysis chain may be leveraged.

8. **Repeat steps 3–8 until all Sampling Landers are exhausted.**

Table 4.1: Vehicle Mass and Power

Asset	Mass (kg)[a]	Notes
Aerial Laboratory	800–1000 kg (power <1.5 kW; 1 kW altitude control (assumes 10 km/hr ascent requirement) and <500 W payload needs)	Drops four Sampling Landers
Sampling Lander (total)	50 kg	2-kg sample & container
Sample Collection System	35 kg	4x sample sites
Ascent Vehicle	15 kg	
Sample Retriever	25 kg	10% payload 2x for redundancy
Orbiter	400 kg (power ~500 W)	Telecom/Nav

[a]Add 50% to all of these for contingency and margin.

Table 4.2: Mass Stack

Aerial Laboratory	Mass, kg[a]	Method
Sample analysis	100	estimate
Structure/subsystems	150	estimate
4 Sampling Landers + 2 Sample Retrievers	250	estimate
Carried Mass	**500**	**subtotal**
Balloon	500	1:1 with carried mass (incl. 125 kg He)
Tanks	750	6× He mass
Delivered to Atmosphere	**1750**	**subtotal**
Aeroshell/TPS	1750	1:1 with delivered mass
Entry Mass	**3500**	**subtotal**
Orbiter	400	WAG
Propellant	400	1500 m/s monoprop
Launch Mass	**4300**	**Launch vehicle req.**

[a]Add 50% to all of these for contingency and margin.

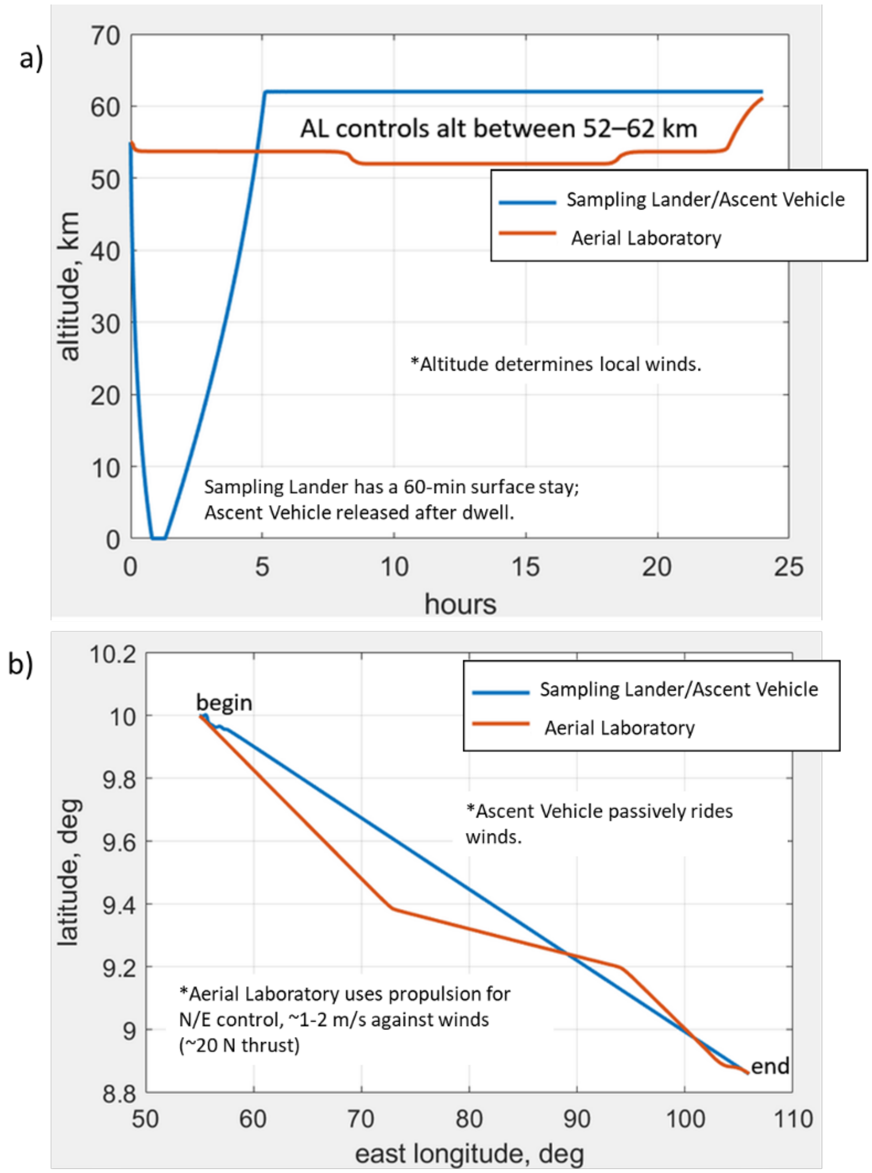


Figure 5.1: Altitude (top) profile over time and the resultant latitude/longitude (bottom) of sample capture chain elements. The Sampling Lander (SL) is dropped from the Aerial Laboratory (AL) and takes about 1 hour to reach the surface, followed by a 1 hour dwell for collection. During this collection time, the Aerial Laboratory continues to move with the winds. Ascent of the sample in the Ascent Vehicle takes about 3 hours to reach an altitude higher than the Aerial Laboratory, where the wind speeds are faster. The Aerial Laboratory actively controls altitude in order to match latitude/longitude of the passive Ascent Vehicle, and the Ascent Vehicle is able to catch up to the Aerial Laboratory in less than 24 hours.

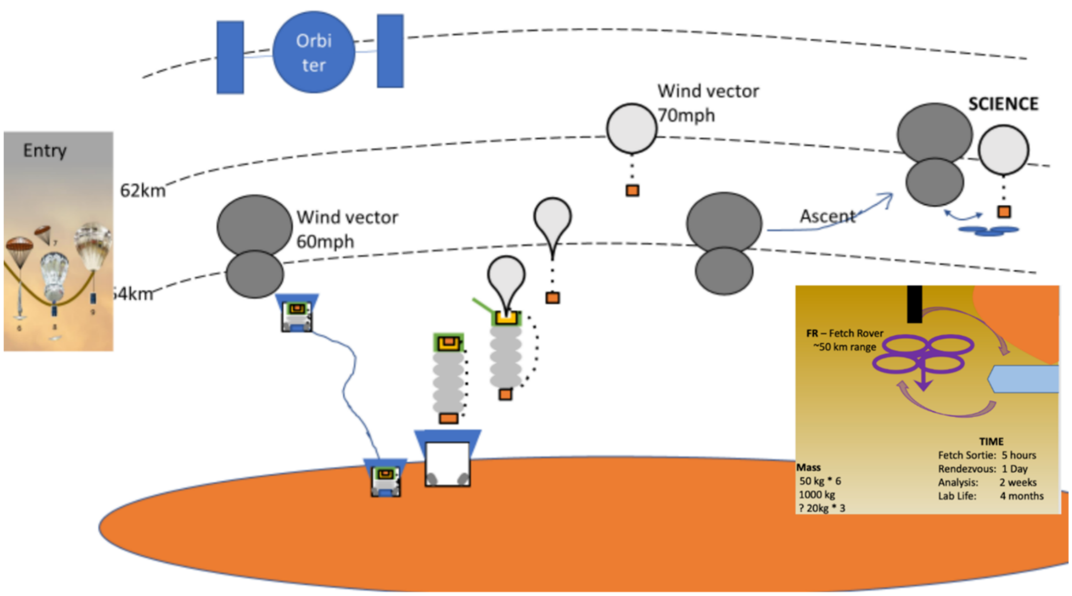


Figure 5.2: Diagram illustrating how the Ascent Vehicle, Aerial Laboratory, and Sample Retriever work together to achieve sample capture and rendezvous.

6. Investment Needs

6.1 Technology Investments

The technology needs associated with the VISTA mission concept depend on the details of the implemented architecture, however, there is a high level of overlap with different implementations of VISTA, as well as with those required by other Venus mission architectures. The 2019 Venus Technology Plan (vexag$_{\mathrm{t}}$ech$_{\mathrm{c}}$over-6$_{0}$90619 (usra.edu)) provides a vision for the status of Venus technology development by the year 2042 assuming appropriate technology investments take place. While a VISTA-like mission was not identified in this report, much of the mission capabilities identified in the 2019 Venus Technology Plan are necessary to achieve any implementation of the VISTA architecture.

The technology investments needed for VISTA that are already noted in the 2019 Venus Technology Plan include:

- **Venus Communications and Navigation Infrastructure:** VISTA will require a robust communications infrastructure to limit risk and enable humans-in-the-loop for real-time decision making. The Venus Technology Plan recommends a study of the feasibility of and methods for establishing a Venus communications and navigation infrastructure.

- **Aerial Platforms:** The Aerial Lab is a critical piece of the VISTA architecture. It must survive for months to years, and will require some level of maneuverability. The Venus Technology Plan calls out the development of a range of targeted aerial platform technologies as enabling capabilities.

- **Advanced Descent and Landing:** While the accuracy requirements for VISTA sampling landers are not well-defined at this point, the landers are expected to target a variety of terrains, making descent and landing a critical step in the VISTA concept of operations. The Venus Technology Plan calls for new concepts for adapting precision descent and landing hazard avoidance technologies to operation in the dense, hot Venus atmosphere.

- **Autonomy and Automation:** There is a significant need for the development of autonomous operations to achieve VISTA (e.g., surface operations and rendezvous). What is necessary for VISTA goes beyond what was envisioned in the Venus Technology Plan, but this area was highlighted in the report as a way to enhance the science delivered and mission success.

- **In Situ Instruments:** The Venus Technology Plan calls out specifically for in situ instruments for use on landers—VISTA will perform sensitive chemical analyses on the Aerial Lab, however, the Sampling Landers would be served by, at minimum, imaging capabilities for sample context.

- **Small Platforms and High-Temperature Subsystems:** The definition of the VISTA Sampling Landers is currently an open trade-space, ranging from as simple and fast as possible to more complex and somewhat longer duration (ultimately driven by delivery and rendezvous methods). Because the lander is exposed to the surface environment regardless of complexity, VISTA would benefit from the development of electronics, sensors, and power sources designed for operating in the Venus surface ambient environment. In fact, many of the capabilities called out in the Venus Technology Plan go beyond what is ultimately necessary for VISTA, and the development of these capabilities would limit VISTA risks overall. Many of these technologies are already under development, such as the Long Lived In situ Solar System Explorer, the Venus In Situ Surface Imager (VISSI) and the HOTTech 1 and 2 projects.

- **Environmental Modeling and Simulation:** VISTA requires an improved understanding of Venus winds and surface properties to ensure appropriate sampling technology capabilities. The Venus Technology Plan calls for establishing and maintaining a broad but interdependent infrastructure for Venus modeling and laboratory experiments, overlapping well with the specific needs for VISTA.

Because VISTA does not yet have a detailed point design, there are several specific technologies that would enable different versions of this concept. By mission phase, these include:

- Aerial Science Platform Deployment and Operations
    - Flight trajectory and control throughout multiple atmospheric conditions

  - Communications/tracking through descent/ascent
  - Regional and local characterization upon descent
  - Sampling methods for collection of aerosols
- Sampling Lander Operations
  - Localized cooling/ Insulation for selected components/functions
  - High temperature control, power, and communications
  - High temperature surface visualization and selection
  - High temperature actuation/manipulation
  - High temperature surface drilling/impaction into hard structures in supercritical environments
  - High temperature in situ sample extraction, preparation, and handling
  - Sample packaging and encapsulation
- Ascent and Retrieval
  - Two-stage balloon materials and technology
  - Atmospheric sampling
  - Balloon flight trajectory throughout multiple atmospheric conditions
  - Sample transfer operations and rendezvous
  - Automated sample retrieval and docking
- Aerial Platform Analysis and Operations
  - Sample delivery and exchange
  - Instrument adaption for mission parameters
  - Sample processing
- Mission Architecture
  - Orbiter/aerial platform interactions
  - Communications infrastructure

All of this is no small undertaking, but with the rapid pace of material design and the development of technology, including drones and other autonomous vehicles, we can envisage engineering studies that yield tenable solutions enabling sample acquisition from the surface (with contextual information as the vehicle descends and at the site), transfer from the surface to upper atmosphere, sample handoff to the Sample Retriever, and docking with the Aerial Laboratory for sample analysis. Importantly, much of the technologies and materials needed for these subsystems and vehicles are already in progress, but need maturation and coordination into systems in parallel with pending mission information and laboratory experiments.

In order to achieve the ambitious mission described here, it is imperative that technology development continue. Venus technology needs are often unique, and the Planetary Science Division (PSD) should continue and expand support for programs such as HOTTech and CloudTech, as well as identify where joint sponsorship and dual-use development can be leveraged that would result in new mission capabilities. For operation in the Venus clouds, variable altitude balloon technology needs to be developed. The Planetary Science and Astrobiology Decadal Survey Report (Decadal survey) states that *"Balloon platform technology can address Strategic Research but needs advances this decade to meet the requirements of in situ atmospheric explorations on Venus and other planetary atmospheres. This technology requires the capability to inflate after storage in their parent spacecraft while remaining ultralight and resisting damage during deployment and controlling altitude during long-term operation."* A program following the PSADS recommendations would provide a sound foundation for the VISTA mission.

The development and evaluations of technology requires laboratory testing, simulations, and analysis on Earth, which in turn requires the support of capable facilities (such as GEER and the Venus Cloud Simulator being developed at the Caltech campus to test materials that are resistant to Venus' sulfuric acid clouds). An overall development schedule is difficult to specify because, unlike the case for Mars, NASA does not have a Venus Exploration Program so the missions and technologies are developed in an ad hoc manner within PSD. The Planetary Science and Astrobiology Decadal Survey (OWL Report) has urged NASA to take a more strategic approach to planning the future exploration of Venus that might facilitate technological infusion, laboratory studies, and mission collaboration/cooperation for Venus, but the Planetary Science Division has so far expressed its reluctance to do so. Alternatively, the community needs to develop the technologies and mission concepts within existing programs, such as Simplex, Discovery, and New Frontiers. HOTTech can be leveraged to advance some of the surface technologies, but new programs would have to be initiated to further technologies for the aerial, sampling, and fetch vehicles as well as the system- and functional-level autonomy that is required to perform the operational scenarios. These technologies could be funded either from new PSD and/or Space Technology Mission Directorate (STMD) programs (with advocacy from the Science Mission Directorate (SMD)).

6.2 Science Investments

A primary goal of VISTA is to quantify global, regional, and local geologic diversity by selecting landing sites and samples that are representative of the full range of Venus' surface composition and processes. In order to achieve this, several science investments would benefit VISTA development and risk reduction. Science investments described here are in *addition* to support regarding data analysis from upcoming missions and the science returned by them.

6.2.1 Laboratory measurements of reaction rates of representative surface rocks

Thermodynamic modeling indicates most minerals within fresh exposures of volcanic rock are not stable at the Venus surface, chemically weathering to produce surface rinds of various sulfates, sulfides, or oxides. The rates and mechanisms of these reactions and the morphology of the secondary mineral layer are not yet constrained, making it difficult to predict the expected thickness of weathering rinds on Venus. Initial experimental studies suggest these reactions may begin quickly, but there is not presently sufficient data to determine if reaction progress is ever stopped or slowed by a protective coating of secondary minerals. Weathering rates of geologic materials in the Venus surface environment will be useful in constraining the likely required depth of sampling in order to obtain samples from the planet's surface that represent both weathered and unweathered material in this mission. These rates can only be constrained by laboratory experiments (see discussion in Zolotov, 2018).

6.2.2 Observations for sampling site reconnaissance sediment loading

The laboratory experiments described above reveal the weathering rates of undisturbed rocks on the surface of Venus. However, soil and regolith layers on Earth and Mars are much thicker than simple weathering rinds, up to ~100 m thick in extreme cases (e.g., Greenberger et al. 2012). Processes such as bioturbation, wind and water erosion, and groundwater flow cause weathering at various depths on Earth today. There is little current evidence for similar global processes on Venus for exposing fresher, unweathered (unreacted) materials at the surface (aeolian processes do form features, but it is unclear if wind erosion of significant extent occurs), meaning that chemical diffusion from the atmosphere to the subsurface could limit the rate of weathering. Analyses of Magellan data should be able to indicate, and observations from new missions should be able to determine if, for example, tectonic exposure and/or physical weathering processes might facilitate regolith production, and therefore rapid weathering at particular locations. Discriminating between larger scale physical processes and chemical weathering is also important, since unweathered regolith sites have their own advantages and disadvantages to consider in sampling strategies. With reconnaissance information in hand, sampling missions can then target locations with the lowest chances of regolith formation and enhanced weathering.

6.2.3 Laboratory measurements of atmospheric reaction rates

A comprehensive model of the formation and destruction of minor reactive species in the atmosphere, and of the clouds themselves, remains elusive due in large part to the dearth of kinetic data for dozens of photochemical and thermochemical intermediate reactions (Mills et al., 2020). Obtaining the rate constants in question are within the capabilities of existing laboratory processes and instruments. Obtaining these empirical data creates testable hypotheses for the VISTA atmospheric measurements (e.g., related to Branch Point 6) and provides more robust requirements for instrument targets and sensitivity.

7. A Venus Mission and Science Strategy

While VISTA, as described above, is a single flagship-class mission, the far-reaching science objectives coupled with the multi-asset architecture offers an opportunity to map out a longer-term Venus science strategy that can deliver an even richer set of science objectives while simultaneously lowering the risk of the eventual VISTA mission. Rather than immediately striving for the ambitious mission described here, precursor missions to Venus (including those already selected) are an important strategy to collect the necessary data and demonstrate the critical technologies ahead of VISTA. Specific items that were identified to make a VISTA-like mission more likely to succeed include:

- Improved knowledge of winds on Venus
- Improved knowledge of the Venus surface
- Improved atmospheric compositional knowledge
- Demonstration of longer-lived aerial platform
- Demonstration of surface operations/sample collection
- Demonstration of rendezvous of two aerial assets

Fortunately, with the decade of Venus at hand, this proposed mission concept can build upon past knowledge, as well as learn from upcoming approved missions. VERITAS, DAVINCI, and EnVision successes will help to lower VISTA risks by offering insights into both the Venus surface and the atmospheric composition. Beyond what has already been selected, VISTA could benefit from future New Frontiers, Discovery, or even SIMPLEx mission selections.

Such a long-term strategy would significantly augment our understanding of Venus in key ways that fills science gaps and lowers knowledge risks for VISTA, as well as demonstrating critical technologies. Furthermore, a strategy like this offers an opportunity to involve and engage the entire Venus community, with a pathway that hits each scientific area while demonstrating key technologies needed for the next step along the path. We propose one potential science and mission strategy that has opportunities for key risk reduction for VISTA specifically, but also paves a road to target key remaining unknowns for Venus. While one goal of the workshop was to identify a path to ready the mission concept for submission to the next Decadal Survey, it is important to note that this type of strategy has value with or without VISTA as the endpoint. There are other Venus flagship concepts, and other ways to target the same questions over time, but an agreed upon strategy to decrease risks of the next missions through both measurements and technology demonstrations can deliver Program-level science without a dedicated Program. The strategy described here progresses in a logical way by the implementation challenges faced by a given mission, while offering different science opportunities at each step. It also allows for time to fully mature and develop VISTA and other large-scale mission concepts (and their corresponding technologies) so that the appropriate information is available when it is time to make a decision. In doing so, VISTA, or a VISTA alternative, becomes a capstone to a broader strategy of Venus exploration significantly increasing science impact.

7.1 Achieving VISTA: Strategic Precursor Missions and Science

VISTA (or another similarly ambitious Venus mission concept) is not expected to be the next mission to Venus, and a viable strategy must deliver critical scientific information that will lower risk of each next step along the path, with critical knowledge gaps being winds, the surface, and atmospheric composition. An effective strategic approach to achieving a complicated architecture is to sequentially lower risks by level of complexity, while offering distinct scientific opportunities. The opportunities could achieve the information to lower the risk of VISTA or similar mission concepts, as well as yield additional exciting Venus science. The team specifically decided against prescribing detailed science to each identified architecture in the strategy. Instead, an architecture strategy of increasing complexity, including opportunities for technology demonstrations, was outlined, and specific precursor science needs were identified separately.

7.1.1 Mission Opportunities

1. **Communications Infrastructure:** First, it would be beneficial to have approved orbiting assets in place at Venus to give VISTA (and other missions) a communications and navigation network similar to that at Mars. This could come from the already selected missions, and be an added component to any of the additional mission opportunities described below. It would be valuable in the long-term to ensure that a

long-lived (years) orbiter with communications capabilities is included for each (any) early mission in the strategy. Depending on the details of the mission, these required platforms could also offer an opportunity for remote sensing science, such as wind characterization, which would greatly impact VISTA's risk posture.

2. **Aerobot Mission:**Especially valuable to VISTA could be an aerobot pathfinder mission to Venus to better understand the environment at 55 + 5 km, to determine the concept of operations of such a vehicle, and demonstrate longevity. This aerobot mission also offers the opportunity for a Technology Demonstration of a second asset (i.e., the Sample Retriever precursor) to show that departure and rendezvous with the Aerobot is possible. Scientifically, the Aerobot offers a possible long-lived mission (several months with current expectations of capabilities) that can do both in situ measurements of the atmosphere and weather, while giving a platform for remote sensing of the surface. The Tech Demo opportunity can also be leveraged for science and risk reduction; for example, imaging in the NIR allows for inspection of the Aerobot when above the cloud ceiling and imaging of the surface of Venus when below the cloud deck.

3. **Surface Operation:** Surface missions, long- or short-duration, could be leveraged to demonstrate surface operations and capabilities while lowering risk by giving an improved understanding of specific surface regions. From a technology demonstration standpoint, a surface-based mission would provide an opportunity to show survival, and possibly sampling and sample transfer capabilities. From a science perspective, these types of missions could both provide high resolution images of the surface structure, and depending on the details of the mission science, could offer some preliminary insights into physical properties of the surface, degree of weathering, and possible surface chemistry/mineralogy.

7.1.2 Precursor Mission Science Needs

1. **Winds and Lightning Hazards:** Predictive models of global winds are required for accurate navigation of the aerial platform, and for retrieval of the surface sample ascent platform. Current global circulation models use data from orbital cloud motion tracking and the limited number of descent profiles from deep atmosphere and surface probes (Lebonnois et al., 2010, 2016). However, contributions to the winds from vertical currents, solar fluxes, interactions with the surface, and temporal variability of both horizontal and vertical winds, remains poorly constrained. Retiring these knowledge gaps, for the dual purposes of improving atmospheric flight navigation and for fundamentally improving our understanding of global weather, requires a large number of vertical profiles throughout the atmospheric column, over a range of geographic locations and local solar times (Mills et al, 2021; Brecht et al., 2021; Balcerski et al., 2021), and/or long duration in situ atmospheric platforms that are capable of

measuring the relevant meteorological data. These data would provide valuable inputs to future global circulation models and, critically for our platform, provide insight into the timeframe over which the predictive models are reliable.

As the lifetime of an aerial platform increases, so does its exposure to environmental hazards. Lightning on Venus has been a subject of debate for decades (e.g., Lorenz et al. 2018). Briefly, various electromagnetic observations have been interpreted to signal frequent lighting originating somewhere below the ionosphere (e.g., Russell et al. other UCLA guy's recent work). Lighting could originate in the cloud layers (due to atmospheric convection and charge build up on something) or, perhaps, near the surface (due to volcanism and/or triboelectric charging of sediment). If lighting existed in the clouds at the maximum rate indicated by interpretations of claimed observations of putative Whistler-mode waves by Venus Express, then an aerial platform would have a high chance of being struck by lightning after an Earth-year. However, searches for optical flashes by ground-based telescopes and the Akatsuki spacecraft imply that lighting in the clouds is rather rare (e.g., Lorenz et al. 2019; Akatsuki preprint). If the $<$10 observed flashes originate from meteor fireballs, then the rate of lighting in the clouds might be zero. Continued observational campaigns to determine the rate of lightning on Venus are scientifically useful to models of the atmosphere and surface. These studies would also help assess if lighting is an environmental hazard for mission concepts featuring a very long-lived aerial platform.

2. **Surface Knowledge:** Beyond the already-planned missions, information prior to a VISTA-like mission might be possible during the next decade that would provide further information on landing sites. The orbital missions that are currently planned encompass the kinds of observations of Venus that are possible from orbit. The Venus atmosphere is so effective in blocking radiation across most of the electromagnetic spectrum that many of the observations that have been so useful in characterizing airless bodies and Mars are not feasible at Venus. To acquire new information, it is necessary to observe from below the clouds and for some types of observation within a few kilometers of the surface. These data could be acquired on a precursor mission to VISTA or by deployment of vehicles from the aerial platform prior to the beginning of the sample acquisition phase. Observations from below the clouds can eliminate the cloud scattering that limits the spatial resolution of near infrared images that will be observed by the VEM instrument on VERITAS and EnVision. Targeted coverage at high spatial resolution would greatly reduce landing site selection risks. Multiple imaging probes capable of gliding at a shallow angle to the surface would provide more useful data than the nested images produced by DAVINCI.

Data from radar and imaging instruments aboard the Magellan and Venus Express missions provide valuable indications of regional (i.e. > 10 km scale) diversity in surface rock composition and texture. The upcoming VERITAS, DAVINCI, and EnVision missions will further enhance measurements of this diversity through significantly higher resolution radar and (N)IR emissivity maps of the Venus surface. Detailed analysis of these archived and future mission data products will significantly improve sampling site selection for our concept, as it will show where units of different composition are on the surface, provide insight into possible composition based on formation morphology, provide relative age information for different units and features, and allow better assessment of landing site hazards. Descent images from the DaVinci probe at one location on Venus will provide higher resolution insight into the morphology, and possibly composition, of a tessera terrain than available from orbital data. Correlation of the findings from the descent probe and panoramic images from Venera landers with signals in the new, higher-resolution global scale imaging, may allow better assessment of which tessera or plains terrain to sample with the current mission, and any associated landing hazards there.

The architectural choices for VISTA will determine what precursor data is needed beyond that to be provided by the currently approved missions. Sampling concepts that are more robust to surface conditions and sites that are free from complex topography may obviate the need for some of the precursor data described above. Nonetheless, this information will remain a valuable addition to reducing risk to VISTA, at least until all of the trades are closed.

7.2 Venus Mission and Science Strategy

Figure 8 illustrates the arc of the Venus Mission and Science Strategy and the proposed advances that can be undertaken to lead to VISTA. The notional missions along the path to VISTA offer opportunities to advance our understanding of Venus in meaningful ways, while making critical progress towards demonstrating key technologies necessary for VISTA. Importantly, none of these prior missions detract from the science posed by VISTA; pieces of the story may be addressed by an earlier Aerobot or surface mission, but they do not offer an option of multiple samples from multiple sites, and importantly, Venus hosts an entire planet's worth of geological features to measure. This proposed mission arc allows for science gaps remaining in the current Venus Roadmap to be strategically filled, and gives a vision for the science beyond the current roadmap. While this is beyond the scope of this report and workshop, this path also sets up for a viable Venus Sample Return mission in the decade beyond VISTA. Importantly, the strategy proposed here could set the stage for VISTA or other ambitious Venus flagship mission concepts. A detailed mission concept study is needed to elucidate the benefits of one concept relative to another, but the overall strategy can remain the same. A mission architecture of this type is a natural progression of the reinvigorated Venus exploration strategy at NASA, and a logical conclusion of several technical development ladders in aerial technology and mobility, high-temperature operations and survival, autonomous operations, and more.

> Required technical developments and precursor science are all achievable in a reasonable time and cost scale to produce a viable VISTA flagship concept for the next Decadal cycle (2033–2042). It is therefore recommended that resources be dedicated to 1) a long-term, strategic Venus Flagship mission in concert with 2) an evolving Science Strategy with buy-in from the Venus science community.

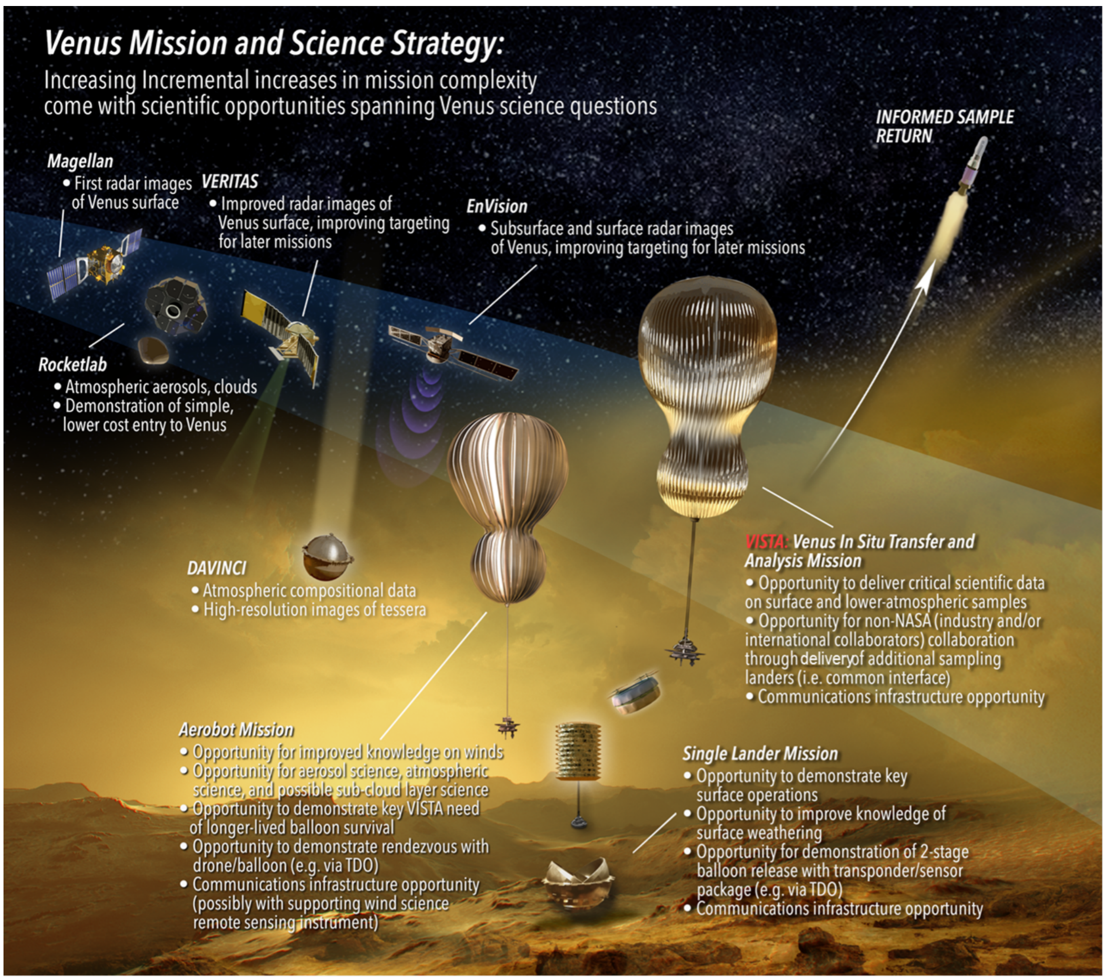


Figure 7.1: Venus Mission and Science Strategy Framework

Appendix: Assessment of Trade Tree Elements

The high level trade tree discussed in Section 4.1 was evaluated at the element level to assess the pros and cons of each architectural element. Results of that evaluation are shown in the following figures.

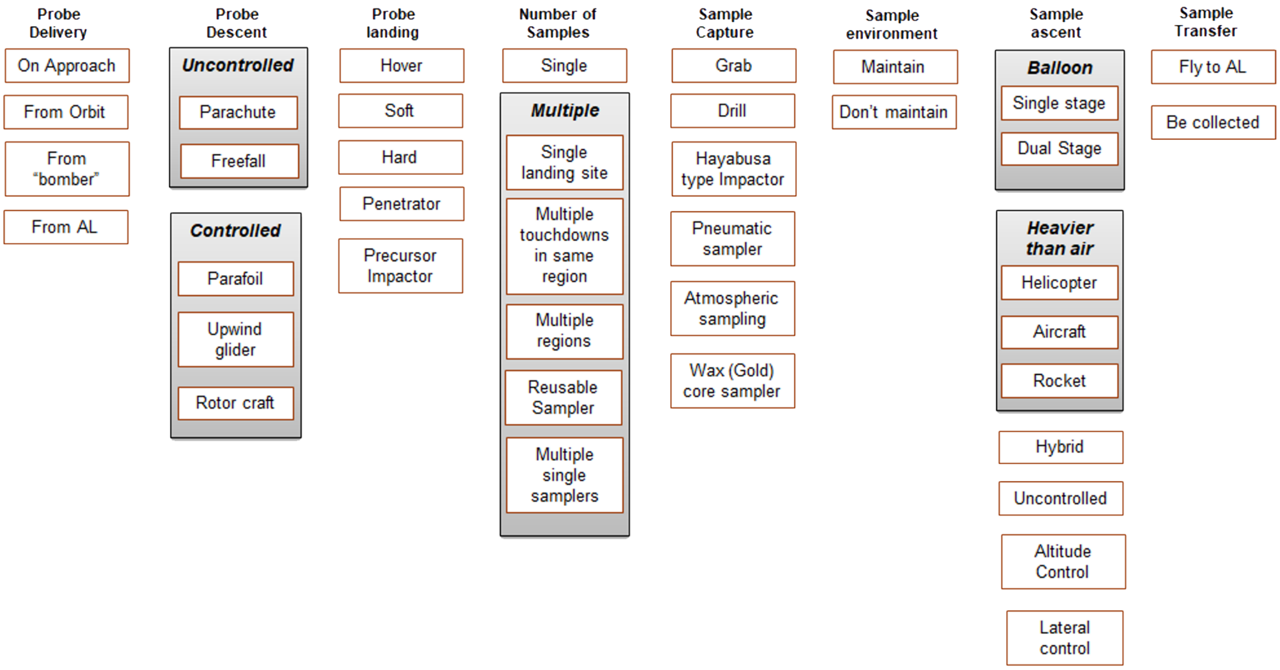


Figure A.1: Complete trade tree identified in KISS workshop.

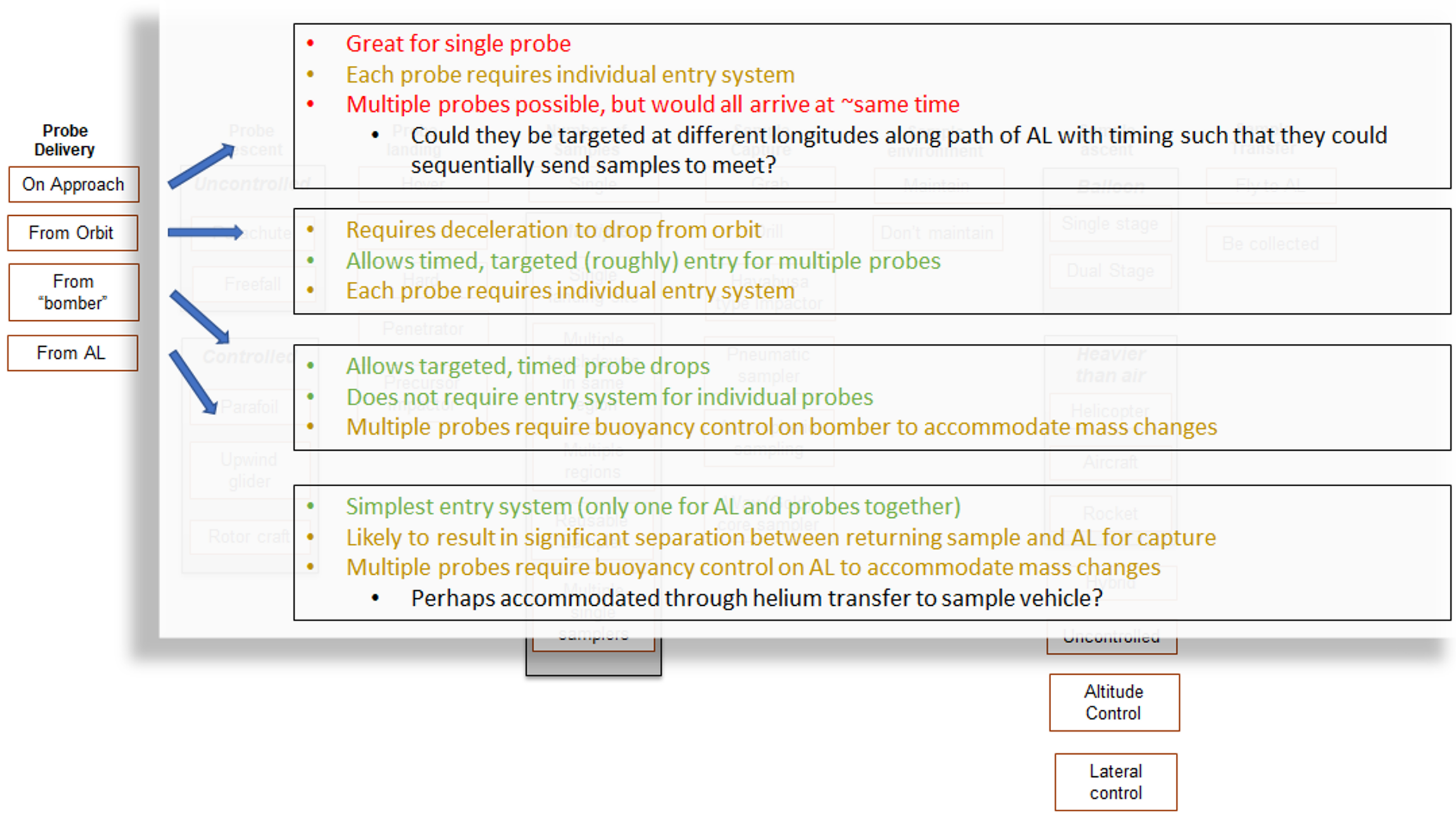


Figure A.2: Probe Delivery Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; red designates characteristics deemed unattractive for incorporation into VISTA, yellow are characteristics that present some challenges, green are characteristics deemed beneficial, and black are notes/open questions/items that were not identified as distinguishing characteristics.

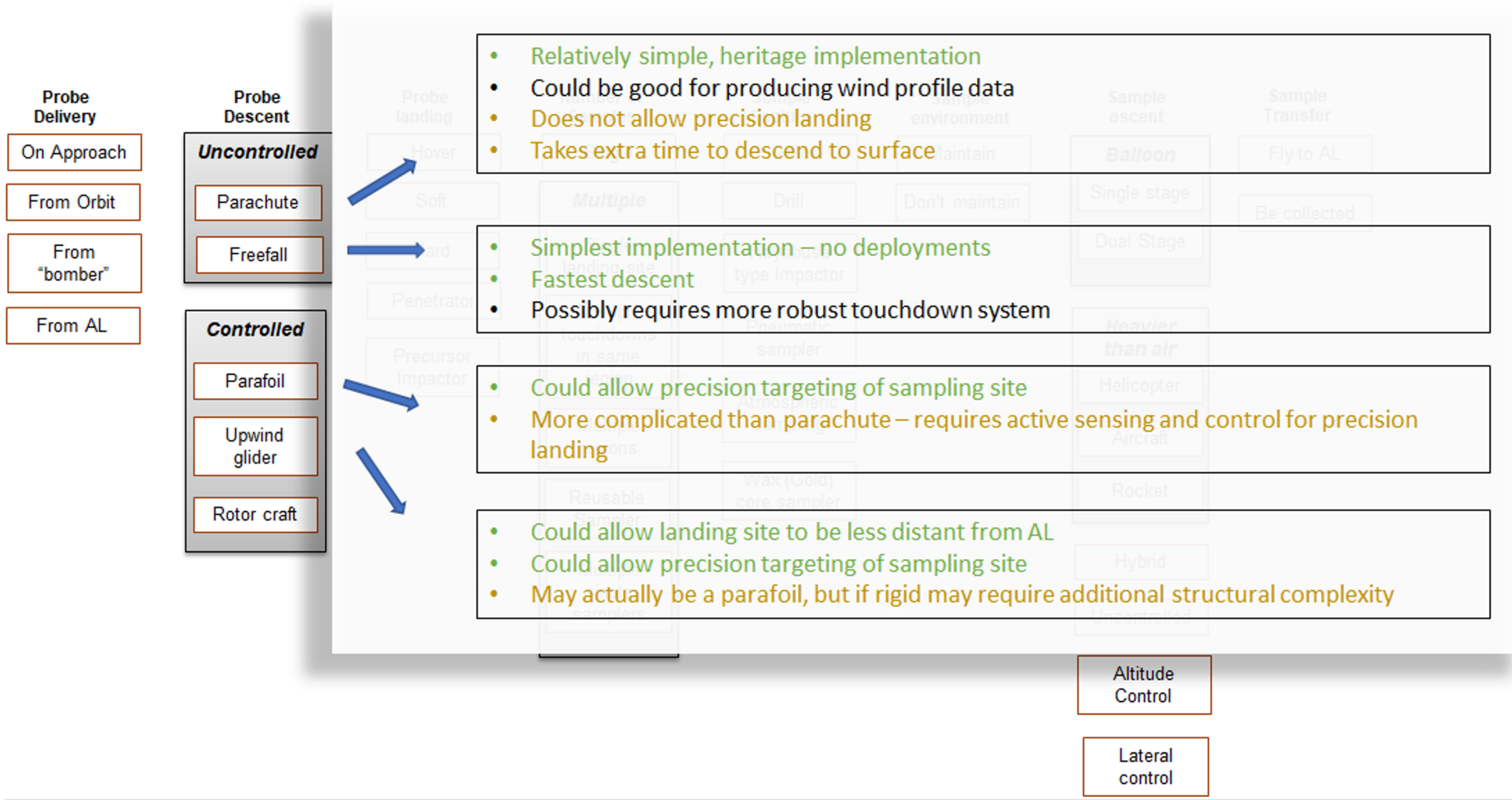


Figure A.3: Probe Descent Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; no characteristics were deemed unattractive for incorporation into VISTA; yellow are characteristics that present some challenges, green are characteristics deemed beneficial, and black are notes/open questions/items that were not identified as distinguishing characteristics.

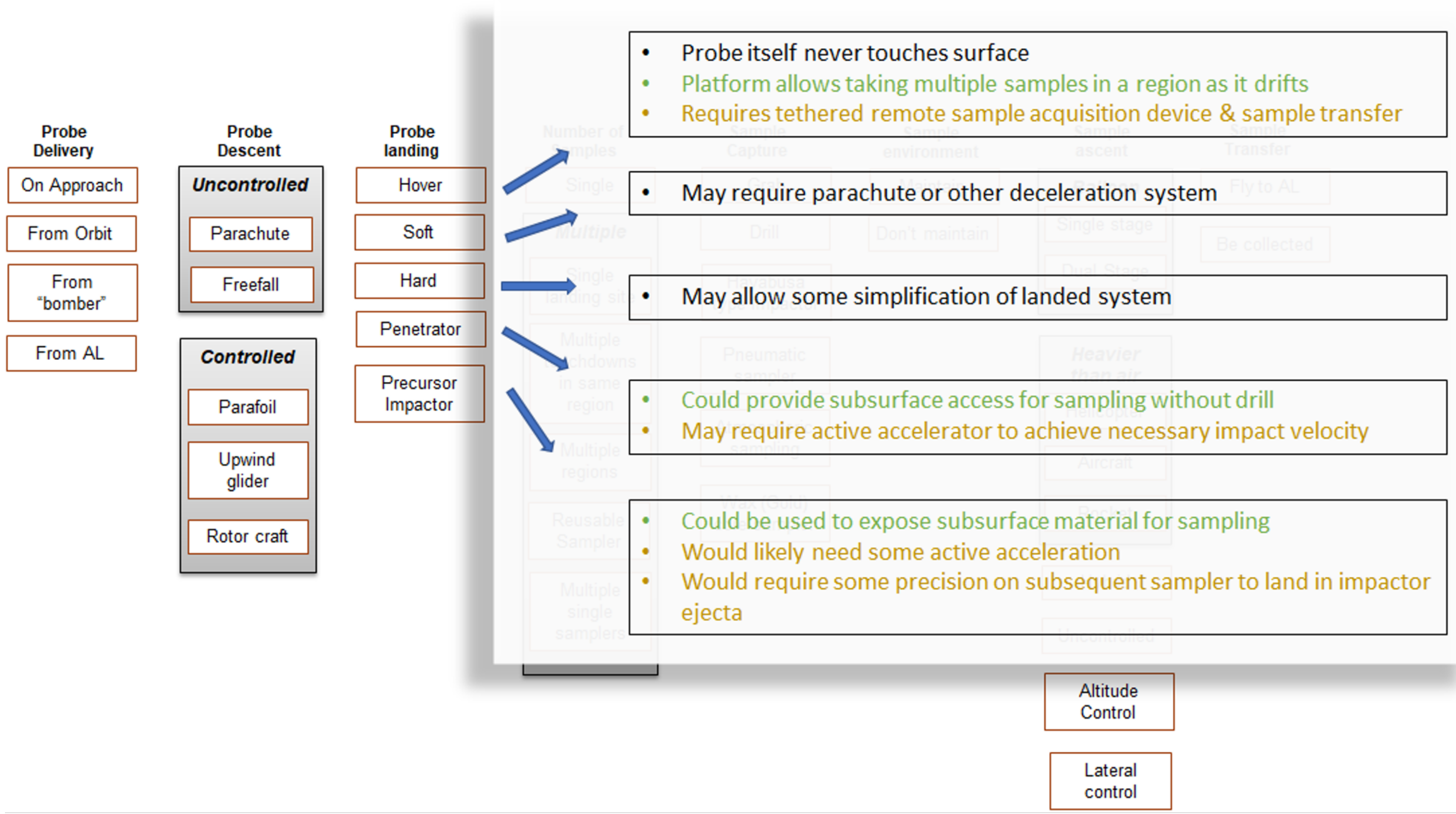


Figure A.4: Probe Landing Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; no characteristics were deemed unattractive for incorporation into VISTA; yellow are characteristics that present some challenges, green are characteristics deemed beneficial, and black are notes/open questions/items that were not identified as distinguishing characteristics.

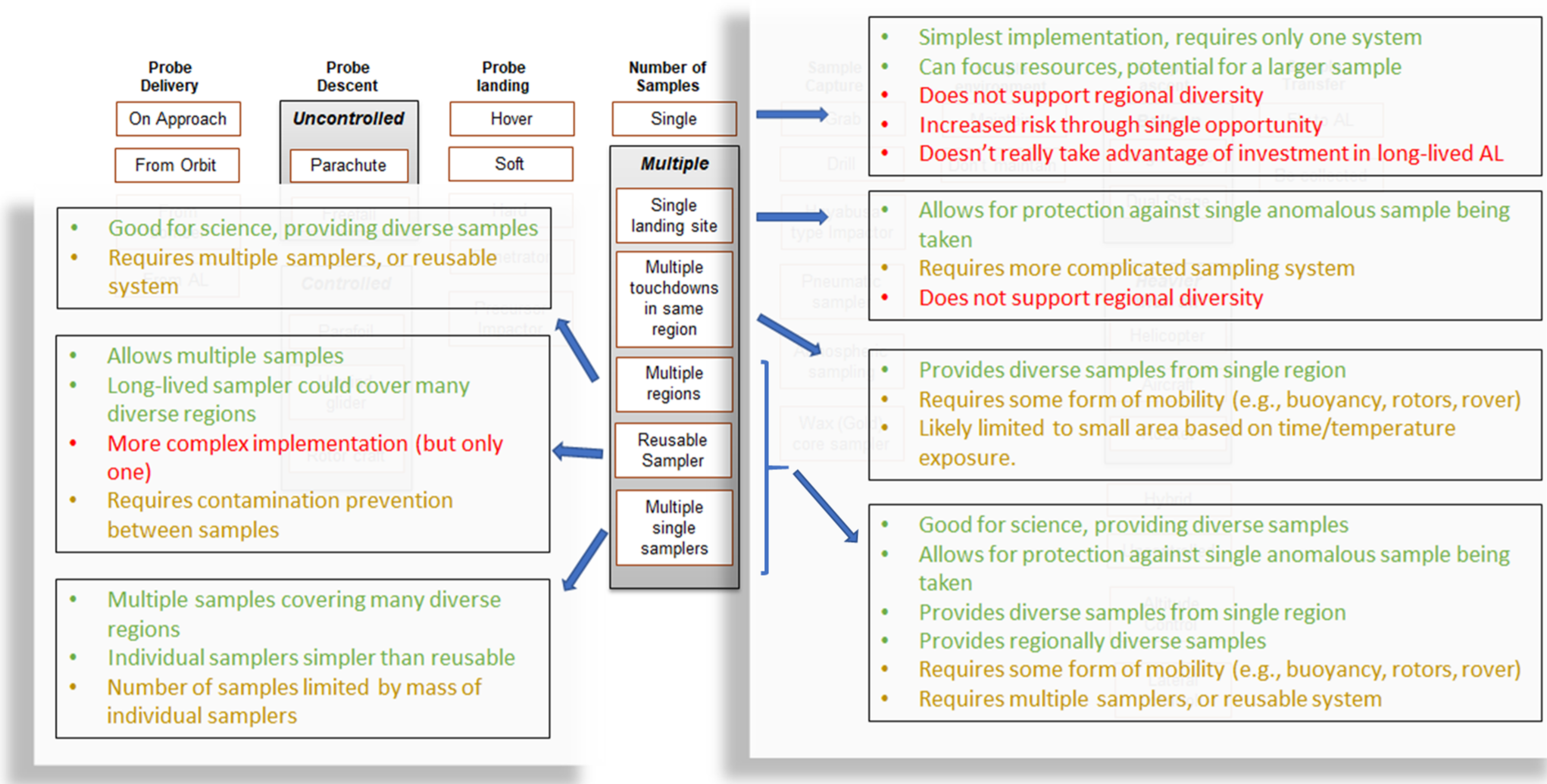


Figure A.5: Number of Sample Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; red designates characteristics deemed unattractive for incorporation into VISTA, yellow are characteristics that present some challenges, and green are characteristics deemed beneficial.

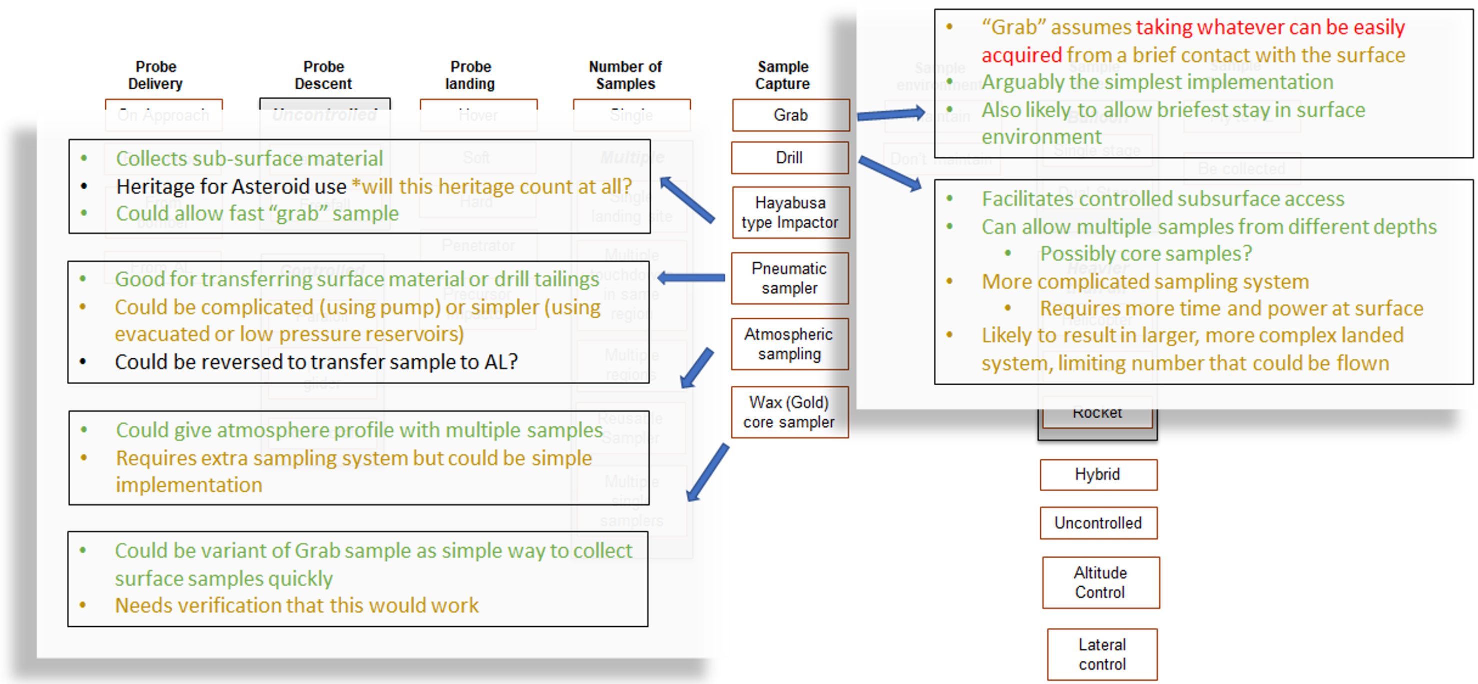


Figure A.6: Sample Capture Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; red designates characteristics deemed unattractive for incorporation into VISTA, yellow are characteristics that present some challenges, green are characteristics deemed beneficial, and black are notes/open questions/items that were not identified as distinguishing characteristics.

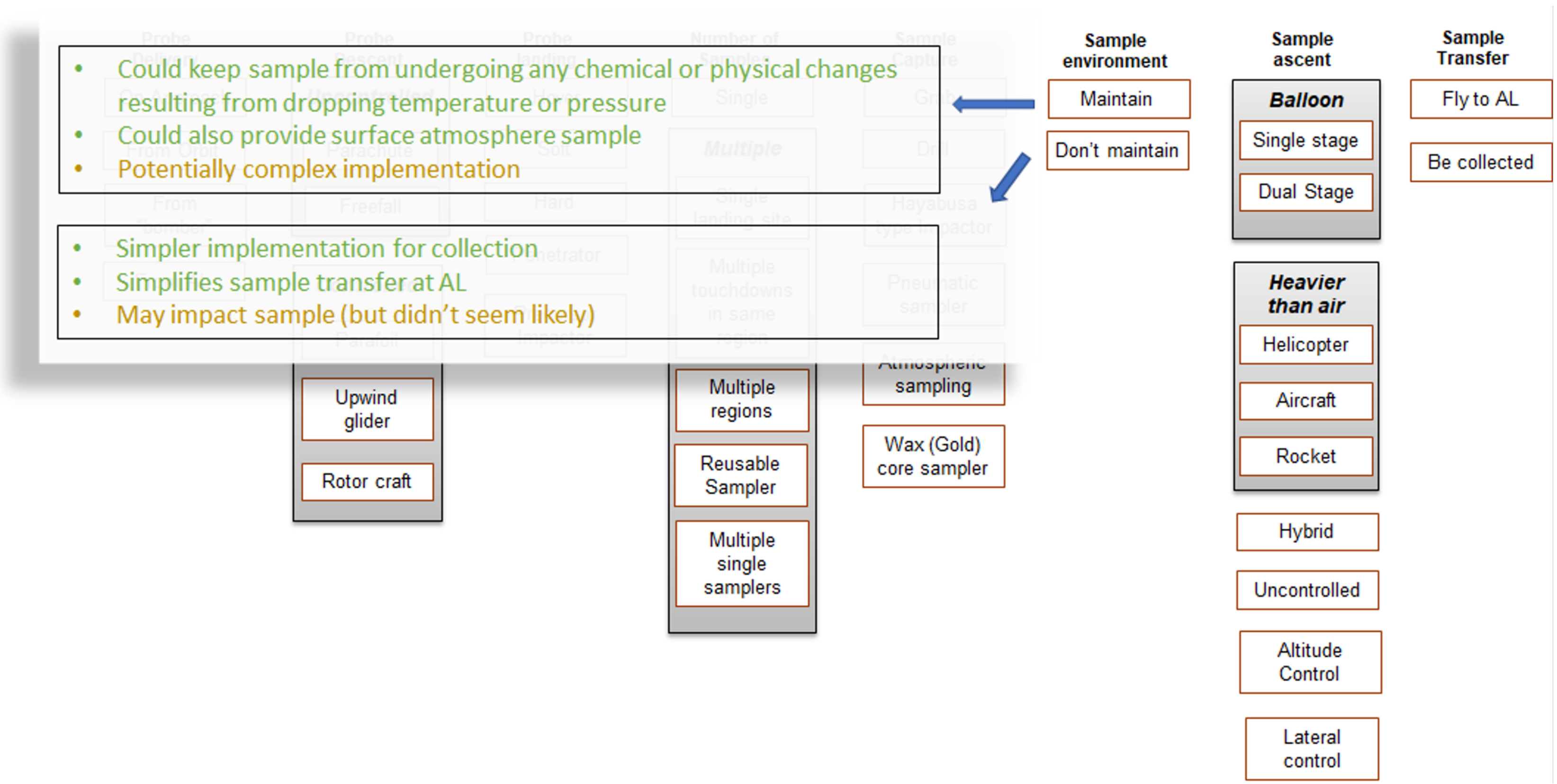


Figure A.7: Sample Environment Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; no characteristics were deemed unattractive for incorporation into VISTA; yellow are characteristics that present some challenges, and green are characteristics deemed beneficial.

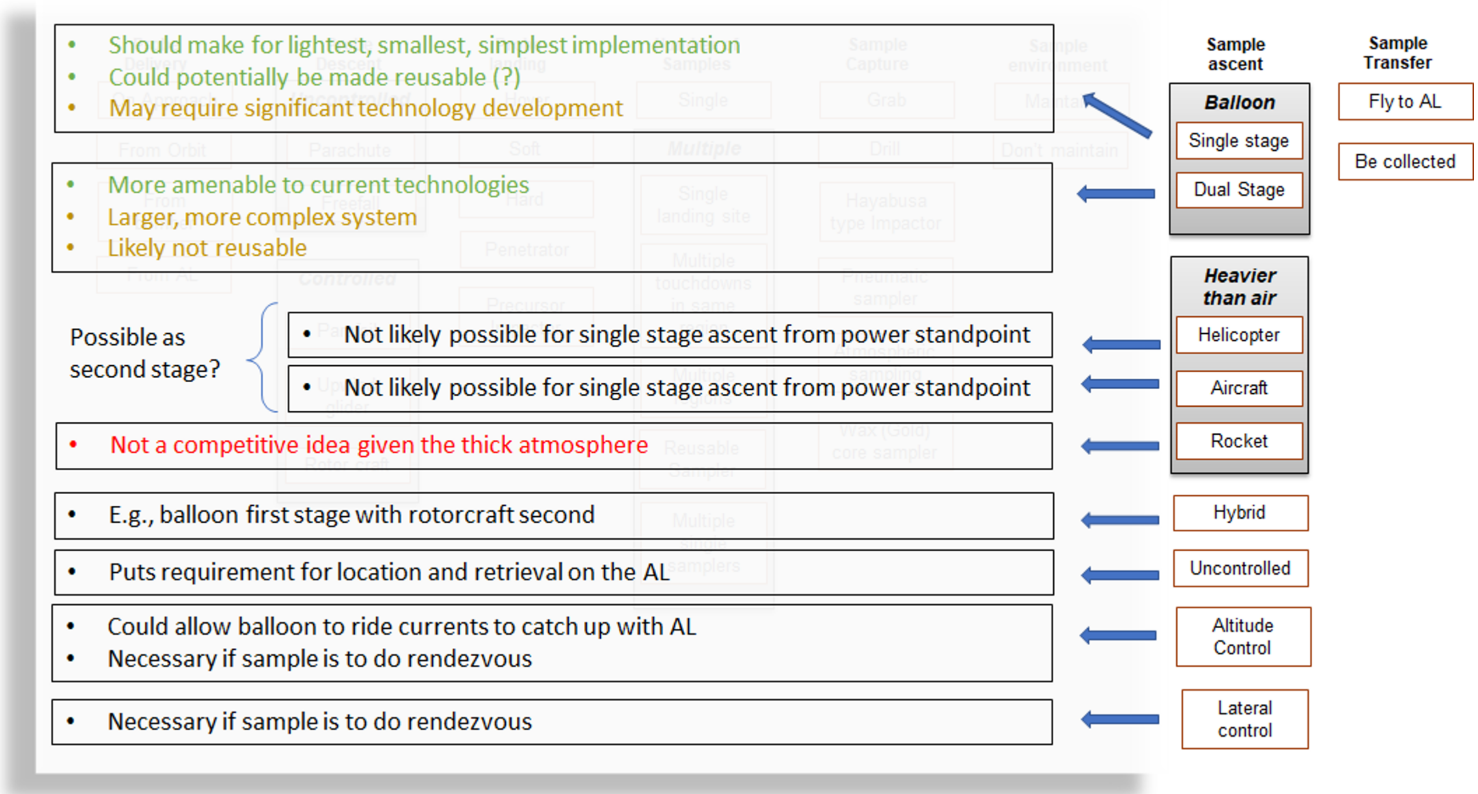


Figure A.8: Sample Ascent Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; red designates characteristics deemed unattractive for incorporation into VISTA, yellow are characteristics that present some challenges, green are characteristics deemed beneficial, and black are notes/open questions/items that were not identified as distinguishing characteristics.

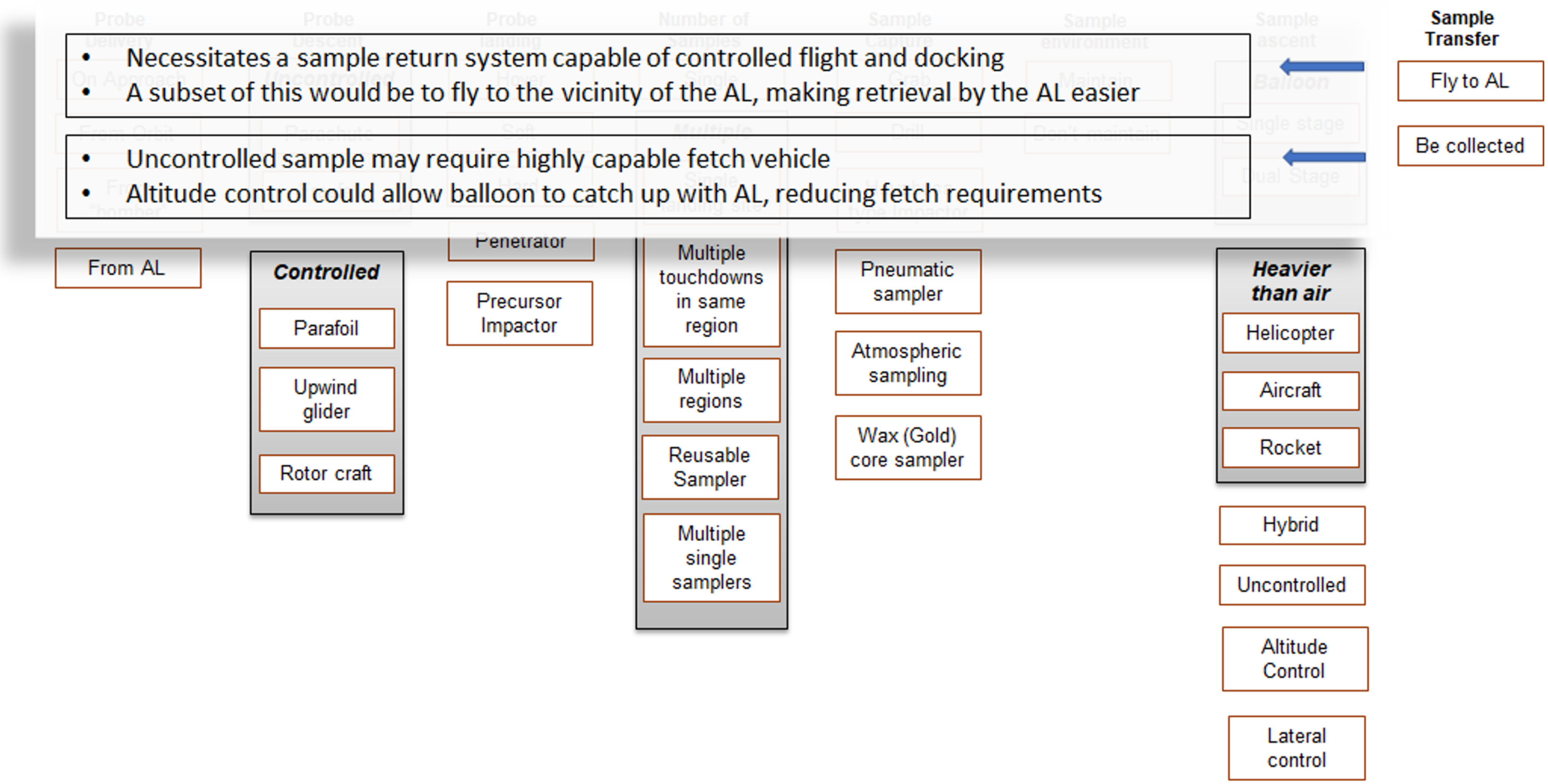
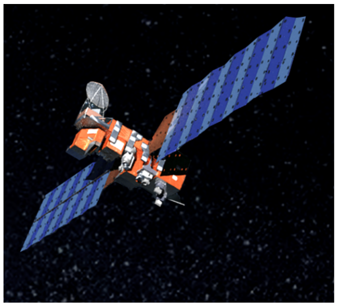


Figure A.9: Sample Transfer Options; color designations were used to help distinguish between different options with the information in hand at the time of the workshop; all identified characteristics were deemed as not distinguishing between the different options.

A.1 Elements and Trades Identified in Workshop

A.1.1 Orbiter (Asset 1)



The coordination of multiple assets is a challenge, and at least one orbiter is needed to achieve VISTA. In the event that an orbiter cannot be placed at Venus ahead of VISTA, an orbiter would be necessary to complement the in situ vehicles. The primary function of the orbiter is to provide positioning for the Aerial Lab and the Ascent Vehicle, as well as to manage communication links between Earth and the in situ aerial platforms during daylight hours. While not required, it would be beneficial for the orbiter to provide real-time wind vectors via cloud tracking in the altitude range of 52–62 km to support mission planning for rendezvous of the Ascent Vehicle and the Aerial Lab.

A.1.2 Aerial Laboratory (Asset 2)

The Aerial Lab is the primary, long-duration, heavy payload asset for the VISTA mission concept—a solar powered workhorse for both carrying instruments and a mobility system for bringing them to targeted locations in the atmosphere. Due to Venus' dominant zonal wind, the Aerial Lab is expected to drift eastward around the planet, circumnavigating once every 5–7 Earth-days. The working hypothesis for this study is that centralizing instruments on a long-duration asset in the clouds allows for a relaxed operational schedule with humans-in-the-loop—a Perseverance-style payload that may be reused for multiple samples from multiple sites. Several options for the Aerial Lab were discussed, but ultimately it was decided that a large buoyancy (balloon) system was the best candidate given ongoing Venus aerial platform investment work going on at JPL, expected to reach TRL5 in mid-2023. The platform includes two envelopes, a balloon-in-balloon architecture, consisting of (1) a metalized Teflon-Kapton bilaminate outer envelope to survive the intense solar and acidic environment of the Venus cloud layer and (2) an inner Vectran envelope that acts as a buoyancy reservoir for altitude control. Two sub-scale prototypes have been built to-date [Hall 2021, Izraelevitz 2022], with outdoor flight tests planned in mid-2022.

Figure A.10: Two sub-scale prototypes of a Venus variable-altitude aerial platform. Images reproduced with permission from Izraelevitz 2022.

Crucially, variable altitude control allows the Aerial Lab to exploit north-south wind shear over a 10-km wide altitude band. This enables the Aerial Lab to target overflying certain sampling sites and decrease rendezvous distance to ascending samples while it circumnavigates the planet. The possible inclusion of propeller actuation could further decrease rendezvous distance to ascending samples. A number of design points for Venus variable-altitude balloon-in-balloon platforms already exist [Hall, AIAA Aviation Paper 2021]. Scaling the carrying capacity of such systems from a 100-kg gondola to the expected ~1000 kg of this concept would require a 25-m diameter outer balloon and the associated increased testing and inspection costs.

Existing JPL materials are consistent with a 117-day (1 Venus Solar day) lifetime. Expanding beyond this would be a necessary technology development activity. Lifetimes of 300+ days were demonstrated on Earth for variable-altitude platforms [Loon 2020], and multiple-year flights have been performed on Earth of constant-altitude platforms. For Aerial Laboratory longevity, extreme durations of five years on Venus (a 15x improvement over existing capability) may be possible given future development. Some strategies to limit life limiting helium diffusion that could be investigated include:

1. Additional metalization layers (or thicker layers) in the envelope laminates
2. Biasing loitering altitude higher (i.e. colder) where helium diffuses slower. The temperature at 60 km is significantly cooler than 54 km.
3. Larger balloon sizes have more favorable volume-to-area ratios
4. Helium replenishment from a pressure vessel or buoyancy gas extraction from the atmosphere; such as O_2 generation from CO_2 as recently demonstrated on MOXIE
5. Improved packaging and inspection techniques to improve probability of a zero-pinhole envelope.
6. Limiting altitude range capability (i.e. smaller outer balloon)—allowing more envelope mass to be dedicated to gas retention properties, easing deployment, and storing more gas in the inner balloon where multiple envelopes must be traversed before gas is lost.

A.1.2.1 Aerial Laboratory Entry and Deployment

The entry system that houses the Aerial Lab and inflation system enters into the Venusian atmosphere directly from the hyperbolic trajectory at ~11 km/s. The peak deceleration load on the system needs to be lowered to meet the requirements of the science instruments. The previously flown entry probes to Venus, such as Pioneer Multiprobe, experienced g-loads in the range of 200 to 480 g's [Dutta 2012]. To reduce the g-loads, the ballistic coefficient of the entry system and the entry flight path angle needs to be lowered. The entry system design proposed in the 2020 Venus Flagship Mission Study [Beauchamp 2021] has a peak g-load of less than 50 g's, showing the feasibility of such a system. Because of the high g-loads expected upon entry, instruments will need to be ruggedized to survive the entry.

A.1.3 Sampling Lander (Asset 3) Entry, Decent, and Landing

The Sampling Landers, which carry the Sample Collection Systems and the Ascent Vehicles, have three options to enter and descend through the atmosphere: (1) Direct hyperbolic entry, (2) Orbital entry, or (3) Drop from Aerial Lab. Table A1 shows a comparison of the different options considered in the workshop. The Sampling Lander is envisioned to be a smaller probe compared to the Aerial Lab entry system, more similar to the DAVINCI probe in size. The parameters that need to be considered for the Sampling Landers include g-loads, landing dispersion ellipse, landing footprint, and terminal velocity. The direct entry option leads to higher g-loads and heat rates compared to orbital entry. For architecture options where the Sampling Landers are dropped from the Aerial Laboratory, no special entry system is required. The landing dispersion ellipse increases for increasing entry velocity and decreasing flight path angle, which means that the ellipse size is largest for direct entry and smallest for dropping from the Aerial Lab. The terminal velocity is mostly a function of ballistic coefficient and thus is indifferent to the entry method itself. Typically the terminal velocity is about 10 m/s but can be decreased to 3–5 m/s as well by adding a drag plate and generally increasing the drag area as required.

Table A.1: Qualitative comparison of different delivery strategies for Sampling Lander

Pros	• Reduced complexity of SL deployment • Possibility of extending number of samplers • Likely the lowest mass option	• Enables phasing of AL and lander • Less requirements of gondola mass and lateral control on AL	• Flexibility wrt accessible landing sites • Single entry system • Lighter Sampling Lander system
Cons	• Limited range of latitudes are accessible • Multiple entry systems • Constrained timeline for entry of AL and SL	• Additional orbiter complexity and mass • Multiple entry systems	• AL experiences stress when SLs are dropped • More mass and maneuverability requirements on AL

In the terminal phase of delivery, the lander has the option of performing a ballistic (hard) landing or a controlled (soft) landing. The two options affect the Sampling Landers, Sample Collection Systems, and Aerial Vehicle differently and are discussed in Table A2 below.

A.1.3.1 Site Selection

Selection of sites involves identifying those that are safe to land, reliable for acquiring samples, and provide the scientific information that we are seeking. Since the VISTA mission

Table A.2: Comparison of how the landing method impacts different flight elements

System Affected	Controlled Landing	Ballistic Landing
Sample Collection System and Ascent Vehicle	Designs not constrained by the impact	Should survive the impact
Sampling Lander	More mass and complexity	Less mass and complexity
Hazard avoidance or picking a spot to land	Possibility of choosing a better sampling site	Possibility of landing in an area where grabbing a sample is difficult (depends on site and sample type)

involves multiple sampling sites, we will be seeking information on the diversity of potential landing sites which will enable us to define a set of sites that capture the global variability of Venus. Between now and the deployment of VISTA, there will be a remarkable increase in information about Venus which will play a key role in site selection. We can also anticipate deployment of vehicles during the mission which can further augment information about the potential sites.

Most of what is currently known about the surface of Venus is based on radar data from the Magellan mission which orbited Venus between 1989 and 1994. There were prior missions equipped with radar—NASA's Pioneer Venus Orbiter and the Soviet Venera 15 and 16, but the data quality of these missions were inferior to that obtained from Magellan. The data included synthetic aperture images, elevation data and radiometry data. There were also a number of Soviet Venera landed missions during the 1970s and early 1980s. Four of these missions acquired images after landing on the surface which have established what we know about the surface at meter to millimeter scales.

The Magellan mission provided characterization of the planet including a subdivision between the extensive volcanic plains and elevated plateaus and mountains including the tessera—features found on no other planet.

The three missions that have recently been approved—VERITAS, EnVision and DAVINCI—will all provide important new information about the surface of Venus. VERITAS, which will arrive at Venus first, will provide radar imaging of the entire planet at much higher resolution than Magellan (Figure A.11 and [Gilmore, PMCS]).

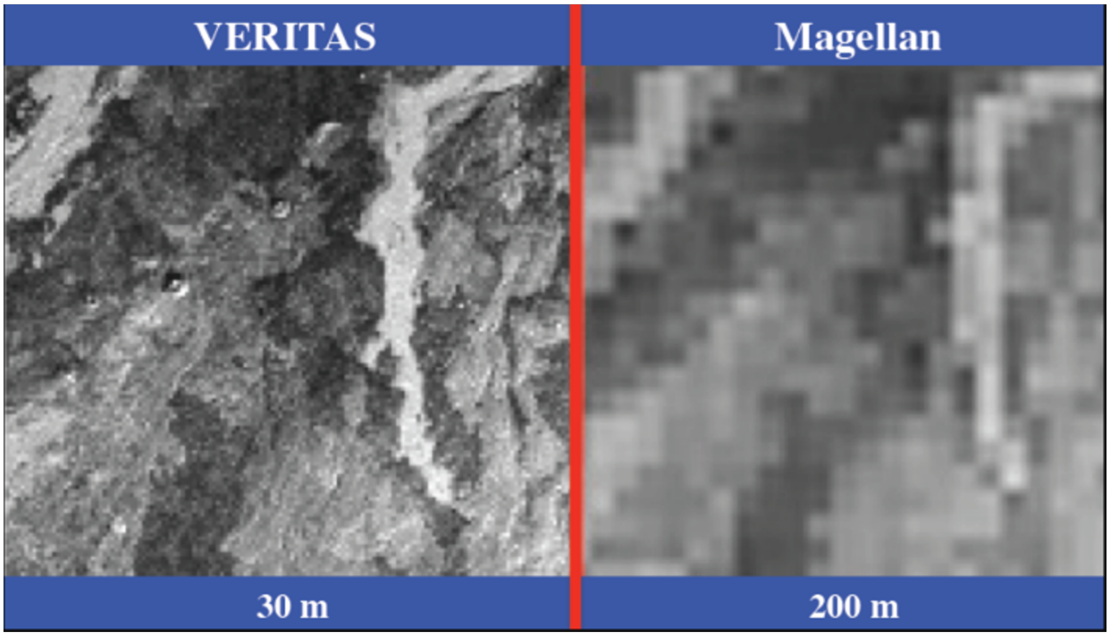


Figure A.11: Comparison of resolution of radar Imaging from VERITAS with that from the Magellan Mission.

VERITAS will also provide information on the topography of the planet at higher resolution than Magellan. Characterization of surface mineralogy, which is revolutionary but far more limited than what is envisioned for VISTA and what has been done at Mars, will be performed by the observations in the Near Infrared of thermal emission from the surface. Scattering in the clouds will limit resolution of this data to about 100 km. EnVision, also an orbiter, will obtain resolution of parts of the planet at even higher resolution than VERITAS and will also probe the subsurface with a radio sounder similar to those flown on Mars Express and MRO. The probe mission DAVINCI's objectives are mostly directed at the atmosphere but it will include a descent imaging system, never before flown on a Venus mission that will acquire images of Alpha Regio, a region of tessera. Because of scattering in the dense atmosphere during the daylight, clear imaging will only be practical below about 5 km and so the aerial coverage of these images will be limited but extremely high spatial resolution [Magellan VERITAS Comparison] [Garin, 2018] should be achieved during the last few minutes before impact with the surface.

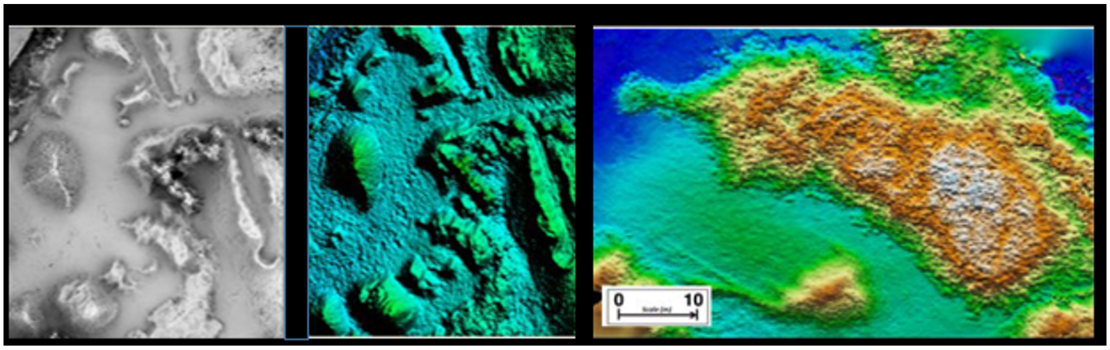


Figure A.12: Simulated Venus descent image at 30 cm/pixel (left and center) and 3cm/pixel right From Garvin et al., 2018.

We can anticipate that these missions will provide important information on the terrain and compositional diversity that will be useful in the selection of landing sites. Terrain roughness and topographic information from VERITAS and EnVision will be useful in ascertaining landing site safety. It is less likely that it will be useful in determining success in sample acquisition. The variability between different tesserae will limit the applicability of DAVINCI imaging data in landing site selection, but these images will provide an important first reference point for this type of terrain in a similar way as the Venera and Vega images from the plains.

Relevant questions for landing site analysis/selection:

- What is the expected surface composition (primarily surface morphology and physical characteristics, but also chemical composition and mineralogy) at the targeted sampling site? Is it possible to predict the percentage of rocks or fines for the sampling system?
- Is landing safe? What is the expected slope, rock distribution, and local topography at the landing site? What is the expected % chance of success of safe landing and successful sample acquisition at a given site?
    - See (J. Rabinovitch, K.M. Stack, "Characterizing landing site safety on Venus using Venera panoramas and Magellan radar properties," Icarus, Volume 363, 2021, 114429, ISSN 0019-1035, https://doi.org/10.1016/j.icarus.2021.114429) for sample landing site analysis which tried to determine the "safest" landing sites on Venus from an engineering design perspective. It is expected that this style of analysis will be updated in the future based on higher-resolution data sets and additional surface images to be provided by EnVision, VERITAS, and DAVINCI.
- What are the targeted sites that can be reached with the Aerial Lab and Sampling Landers architectures? The initial estimates put the Aerial Lab operating at a ± 60

degree latitude band around the equator, but this may change based on science and power requirements.

Landing site selection for the current mission will ultimately be determined by a combination of scientific interest and landing site safety assessment (and associated risk posture). Different sampling sites of interest will likely include features such as relatively fresh volcanic material, tessera, crater ejecta, volcanic plains and flows of different ages, and coronae (though the list of sampling locations will depend on the specific science goals of the final mission). Accessible landing sites will be constrained to areas where it will be possible for the surface sample to be delivered to the Aerial Lab via the Sample Retriever. Furthermore, for power and imaging considerations, all sampling operations (including retrieval) will be performed while the Aerial Lab is on the day side of Venus, giving the mission a ~72 hour window (rough estimate based on winds at 65km altitude) for sampling actions before waiting for the Aerial Lab to travel through the night side and return to the day side.

A.1.3.2 Possible precursor missions to VISTA to improve landing site selection

VISTA is not expected to be the next mission to Venus, and it is worth considering information that might be possible to acquire during the next decade that would provide further information on landing sites. These data could be acquired on a precursor mission to VISTA or by deployment of vehicles from the aerial platform prior to the beginning of the sample acquisition phase.

1. **Subcloud Imaging:** Observations from below the clouds can eliminate the cloud scattering that limits the spatial resolution of near infrared images that will be observed by the VEM instrument on VERITAS and EnVision. Imaging from below the clouds presents technical challenges. The temperature below the clouds at 47 km is in excess of 100°C and so most approaches that are being considered involve either platforms that descend below the clouds and then return to higher altitudes to cool or short lived platforms that end their mission when they are no longer able to tolerate the higher temperatures. In either case, data is relayed through the aerobot platform from which they are deployed. Very high data rates of 2Mbps or better are feasible because of the short ranges between the aerobot and the subcloud platform (generally less than 20 km).
   A platform operating below the clouds is swept around the planet in the super-rotating wind field at about 60 m/s. Depending on the implementation it will either lag behind or station keep with the aerobot from which it is deployed. In a period of a few hours, the subcloud platform can acquire stereo images of emitted radiation at a spatial resolution of about 10 m over a swathe of terrain about 30 km wide and 1000 km long. This would complement radar data from EnVision acquired at similar resolution with compositional information indicative of differences in both the parent rocks (basalt vs

granite), age constrained by weathering history and potentially continuing eruptive activity.

2. **Near Surface Daytime Imaging:** The DAVINCI probe will acquire images as it descents in a near vertical path towards the surface. Imaging coverage will resemble that acquired from the Range probes that crashed on the lunar surface which acquired nested images over limited areas with progressively increasing resolution. Data return is limited by the range to the flyby vehicle that deploys the probe which is typically thousands of kilometers. A concept that provides targeted coverage at high spatial resolution over much broader areas is a guided sonde [Cutts, 2014] that descends rapidly to below 5 km and then performs a shallow descent over a distance of up to 200 km while acquiring high resolution imaging data.
A decision on what precursor data is needed beyond that provided by the currently approved missions will hinge on the architectural choices for VISTA. Sampling concepts that are more robust to surface conditions and sites that are free from complex topography may obviate the need for some of the precursor data described above. Nonetheless, this information will remain a valuable addition to reducing risk to VISTA, at least until all of the trades are closed.

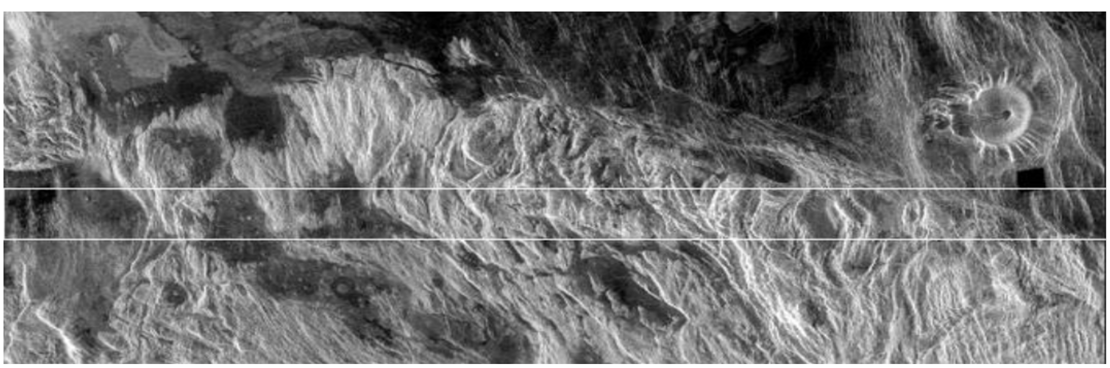


Figure A.13: Radar image of the northern part of a major tessera region Alpha Regio located near 20S and 15E. Tick volcano is the 30-km diameter crate at the upper right. The two parallel white lines illustrate the width of the imaging swath for an aerial platform operating below the clouds. The length is determined by the platform lifetime. Surface resolution will be about 10m and forward and backward looking cameras will enable quality stereo imaging (Reproduced from Fig 5 of [Cutts, DS White Papers].

A.1.4 Sample Collection System (Asset 3) and Surface and Atmospheric Sampling Strategies

Sampling from the atmosphere and sampling from the ground have extremely different options, but both are compatible with the VISTA mission. Discussions for both focused on options where the same instruments might be leveraged for analysis, as well as targeting

different science than selected for expected mission concepts. This resulted in a focus on atmospheric sampling strategies for the capture of aerosols. Not discussed in detail are options for continuous atmospheric monitoring at the Aerial Lab, nor the possibility of sealing pressurized atmospheric samples, either with the geological samples or independently during the descent-to-rendezvous process. These options are open trades, but were not discussed in detail during the workshop.

A.1.4.1 Collecting Aerosol Samples

Within the cloud and haze layers, where complex electronics and instruments can be operated for long times, instruments based upon those used to probe particles in Earth's atmosphere can be used for direct measurements of particles in the Venusian cloud and haze layers. Single particle nephelometers were deployed in the Pioneer Venus sounding probe to measure the size distribution of particles over the 1 to tens of microns size range, providing size distributions over the 66 to 31 km altitude range (Knollenberg and Hunten, 1980). High temperatures prevented measurements at lower altitudes. Instruments for atmospheric science experiments on Earth now perform measurements of both particle size and particle composition (Jayne, Worsnop, et al.), and such aerosol mass spectrometers are being developed for planetary science research (Baines et al., 2020). The capabilities of the Aerial Laboratory for analysis of geological samples will enable further analysis of particles collected at, or transported to, the laboratory. The presence of solid particles in the cloud layers was suggested in the original interpretation of the nephelometer data from the Pioneer sounding probe (Knollenberg and Hunten, 1980), but later studies suggest that the nephelometer signals could be explained as a large particle tail of the sulfuric acid droplet size distributions. Aerosol particles collected at the altitude of the laboratory may resolve this controversy.

On probe descent, inertial sampling methods could collect particles for return to the laboratory. Inertial methods rely on a balance between the aerodynamic drag acting upon particles and the particle inertia. For the smallest particles, viscous shear and normal stress (pressure) dominate the particle motion. Stokes' law predicts a drag force proportional to the velocity of the particle relative to the surrounding gas, and proportional to the particle diameter. The equations of motion for the particle in this limit lead to the definition of an aerodynamic relaxation time, ta. When a particle enters a region in which the flow changes direction or velocity, V, on a time scale $\tau_{\text{flow}} = L/V$ (where L is the length scale of flow change) that is small compared to τ_a for the particle, the particle inertia causes the particle to deviate from the gas streamlines, enabling particle separation from the gas, or collection. Drag forces on large particles will deviate from Stokes' law, but the separations can still be achieved, and the scaling still applies. The aerodynamic relaxation time, t_a, varies with altitude, particle size, and particle density, is the fundamental parameter that governs the sizes of particles that are collected, or separated from the gas flow. Inertial separations are possible when the ratio $St = \tau_a/\tau_{flow}$ is larger than a critical value (typically $\boldsymbol{O}(0.1)$ that depends on the specific geometry. Figure A.14 shows contours of t_a as a function of altitude for different particle diameters. A passive sampler that is exposed to the relative velocity between the probe and the surrounding (e.g., the terminal velocity of order textbf$O$(10 m/s)) thus describes the sizes of particles that can be collected; too small and they will not impact. For particles that are large compared to the mean-free-path of the gas molecules, the size dependence of τ_a is weak, but for smaller particles the size dependence increases. Based upon these scaling arguments, particles larger than a few tenths of a micrometer may be collected with a simple, passive sampler with little variation in the sampling efficiency with altitude below about 40 km altitude.

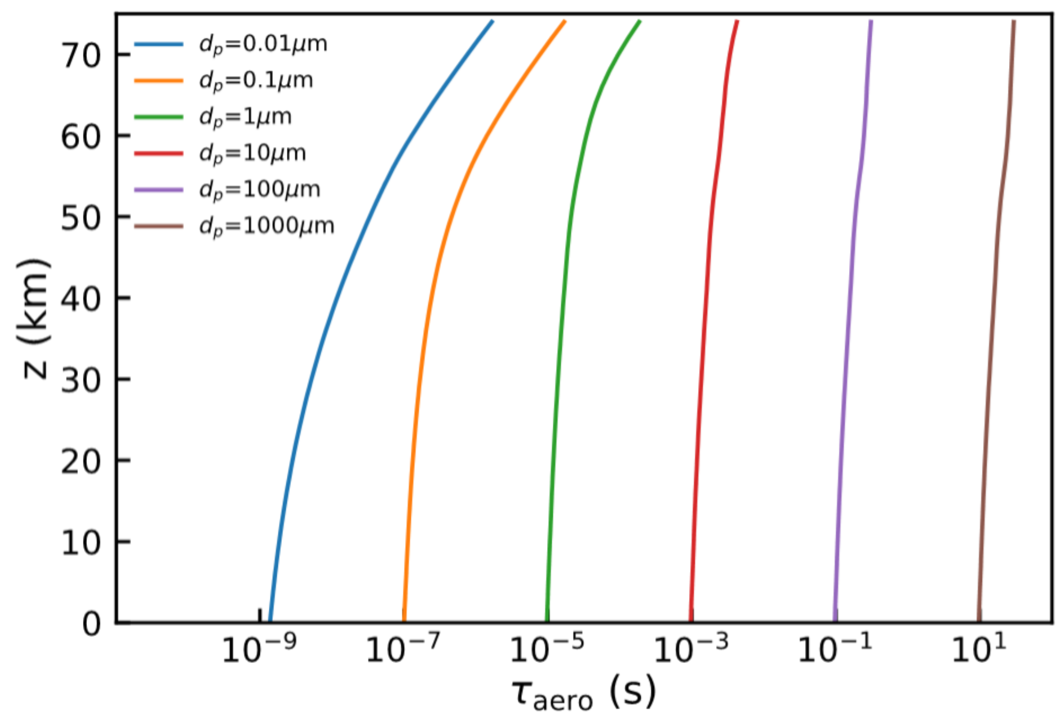


Figure A.14: Estimated aerodynamic relaxation time as a function of altitude in the lower atmosphere of Venus.

Two basic approaches are routinely employed for inertial sample collection: (i) impaction of particles onto the exterior surface of sampler body using the motion of the body to establish the impinging flow; and (ii) focusing an impinging gas flow onto an impaction substrate in an internal flow generated with pumps, followed by evaporation of the droplets and subsequent analysis with a chemical ionization mass spectrometer (Dhaniyala et al. (2003); Fahey et al., 2001). A version of the latter was developed for sampling polar stratospheric cloud droplets aboard the ER2. In that device, a tiny airfoil was moved by millimeters to shift collection between submicron interstitial aerosol particles and cloud particles tens of microns in size.

One approach to collecting aerosol particles is the particle trap impactor (Biswas and Flagan, 1986), in which the flow is directed into a cavity that prevents particles from bouncing out after initial impact. This system has been demonstrated for sampling particles from gasses at temperatures up to 500°C. Another version of the particle trap has been used to collect liquid aerosols in clouds and fogs (Jacob et al., 1984). The virtual impactor is a variant of this method that has been employed to separate large particles from small ones while maintaining the particles entrained in a gas flow.

Another approach for collecting aerosol particles is to embed impacting particles in a sticky substrate or loosely woven fabric. The benefit of this capture process is its simplicity. Collection on descent would require gold- or woven ceramic-coated cylinders attached to the collection vehicle. The cylinder with collected aerosols or particles on the "sticky" gold or woven ceramic would then be protected in an environment-tight container prior to landing on the Venusian surface. Only a handful of ceramics and metals are likely to survive Venusian surface conditions. These include Al_2O_3, SiO_2, SiC, AlN, Au, Ir, and perhaps 304 SS and Ti. [Lucko et al., 2018, 2020]. Of these, gold (Au) is promising as a "sticky" or deformable surface to which atmospheric droplets and particles could adhere. Alternatively, fibers of Al_2O_3 or sapphire could be architected into tailored weaves that would allow for sample capture of larger particles between fibers. Sampling could also be conducted on ascent, which would ensure that collected material would not be exposed to surface environmental conditions. This would require an orifice in the collection vehicle and an internal pump to facilitate the collection. Again, collected aerosols or particles would require encapsulation for transport to the Aerial Laboratory.

A.1.4.2 Collecting Geological Samples

To date, only three of six missions that sampled the surface of Venus have been successful: Venera 13 and 14 in 1981 and Vega 2 (Zacny et al., 2017). Drilling data from Venera 13 and 14 suggest that the rock is similar to weathered porous basalt or compacted ashy volcanic tuff-type. In addition, the cone penetrometer data from Venera 13 measured a surface strength of 260kPa–1000 kPa, analogous to heavy clays. In addition, the Venera-7 parachute failed but the lander survived. From the Doppler shift at impact, it was estimated that the surface was harder than sand but no harder than pumice. Even though these data points suggest the surface is relatively weak, we need to assume that there may be locations where we would encounter relatively hard, weathered igneous rock with a surface layer of particulates. As such, for the purpose of Venus drill development, Honeybee Robotics have been baselining 120 MPa Saddleback Basalt (Rehnmark 2017 and 2018).

Requirements for sampling tools are notional today, so the present focus is on robust methods for quickly acquiring geological samples. Video information about location would be valuable for guidance of the sampling process and would provide contextual information about sample sites. However, the sampling system needs to be robust to a range of surface conditions since the video information will not have the resolution of the order of the sampling system. The sampling system needs to be largely, or maybe entirely, autonomous in its operation because the sampling process must be fast (minutes, as opposed to hours or days that is typical of Mars and lunar missions). The target sample size is hundreds of milligrams to hundreds of grams. This section presents a number of concepts for devices that could achieve the notional requirements. While cores are often preferred for science, they tend to be unpredictable, so cores are not recommended for VISTA as it is envisioned at this time.

For over two decades, Honeybee Robotics and NASA JPL have been developing high temperature motors and drills for future missions to sample the surface of Venus, and a prototype is shown in Figure A.15 (Hall et al., 2022; Zacny et al., 2022). Successful end-to-end tests were conducted in the Large Venus Test Chamber (LVTC) at NASA JPL. These tests included drilling into 120 MPa Saddleback Basalt (basalt described in Peters et al., 2008) and pneumatic transfer to a receptacle. Additional tests were done at NASA Glenn GEER Venus chamber, which included more reactive trace gases found in the Venus atmosphere (tests at NASA JPL used CO_2). These tests were done to determine material compatibility for long duration Venus missions (Zacny et al., 2022)—testing under Venus-like conditions is extremely time consuming and significantly more difficult than testing for other planetary bodies where the ambient conditions are low temperatures and near vacuum. Related, but much smaller devices have been evaluated for rock drilling, coring, and impact breaking to shallow depths, but have not yet been evaluated at conditions of the Venusian surface (Zacny et al., 2015).

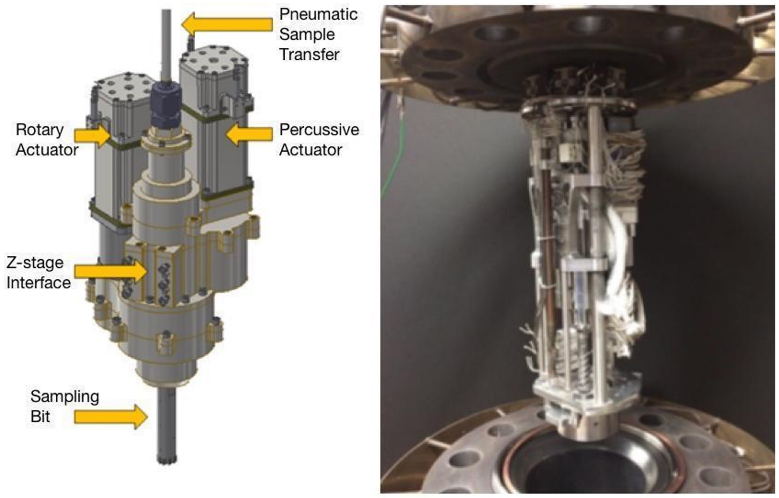


Figure A.15: Prototype drill consisting of high temperature BLDC motors, rotary-percussive drill with 5 cm drill bit, pneumatic transfer and provision for delivering a sample across an airlock.

Figure A.16 depicts a robust solution for collecting rock samples comprising a needle scaler / jackhammer and suction tube (Bar Cohen and Zacny, 2020). The jackhammer breaks rocks to powder and chips. The suction tube then transfers the sample to a container. An advantage of this system is that it should be able to collect samples from most surfaces. Figure A.16 is based on extensive development of powered percussion mechanisms. This system could, however, be designed to employ the high pressure atmosphere near the surface of Venus to obtain additional hammering power (i.e., a pneumatic impact forced by the differential pressure in a chamber and the ambient atmosphere), or the hammer tip could be fired by propellant.

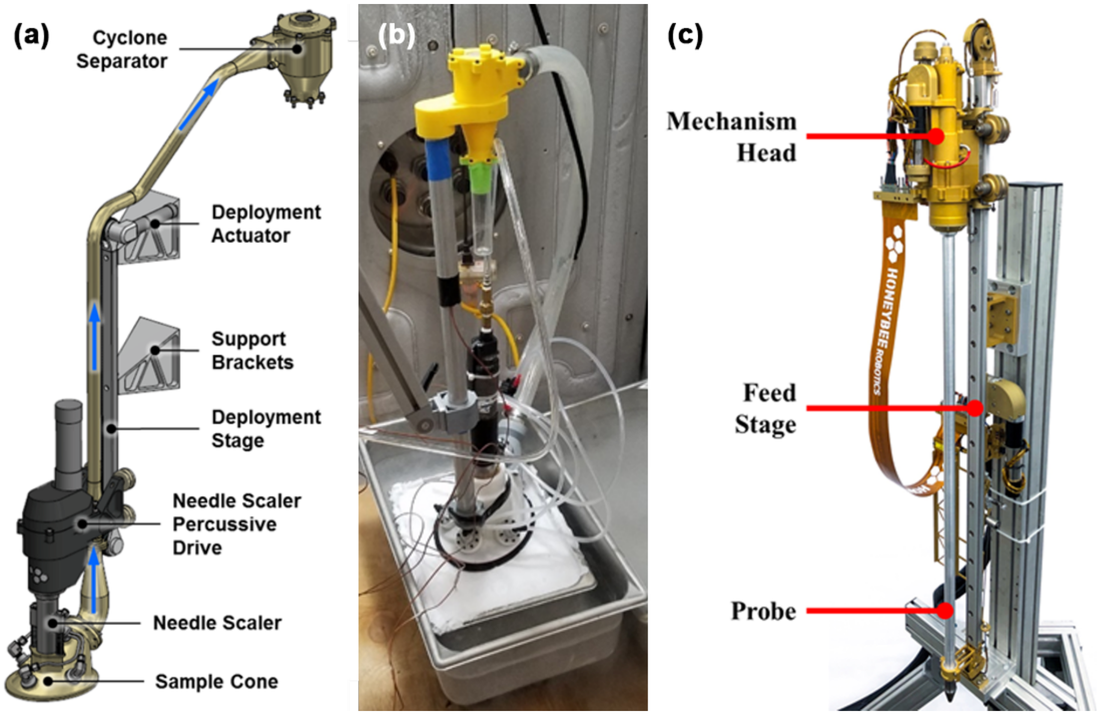


Figure A.16: A jackhammer sampler with some conceptual similarity to the percussive drill of Figure A.15.

As an alternative to mechanical methods, pneumatic methods can serve as vacuum cleaners to suck particles from the planetary surface into a transfer tube. This has already been demonstrated by Venera and Vega missions during a sample transfer step. The two options that would provide 'suction' include a dedicated blower (as in vacuum cleaners) or a vacuum tank that would fill up with Venus air during suction (this was done on Venera and Vega missions). A strength of this approach is that it is rapid and can work with particles with a range of sizes, however it requires the presence of loose material at the sampling site. Figure A.17 depicts three methods of particle handling, which could be used independently or in combination. These pneumatic methods could be used for sampling loose regolith, but could also be a component of a sampling system with mechanical tools to make chips or powders of rock (Zacny et al., 2015).

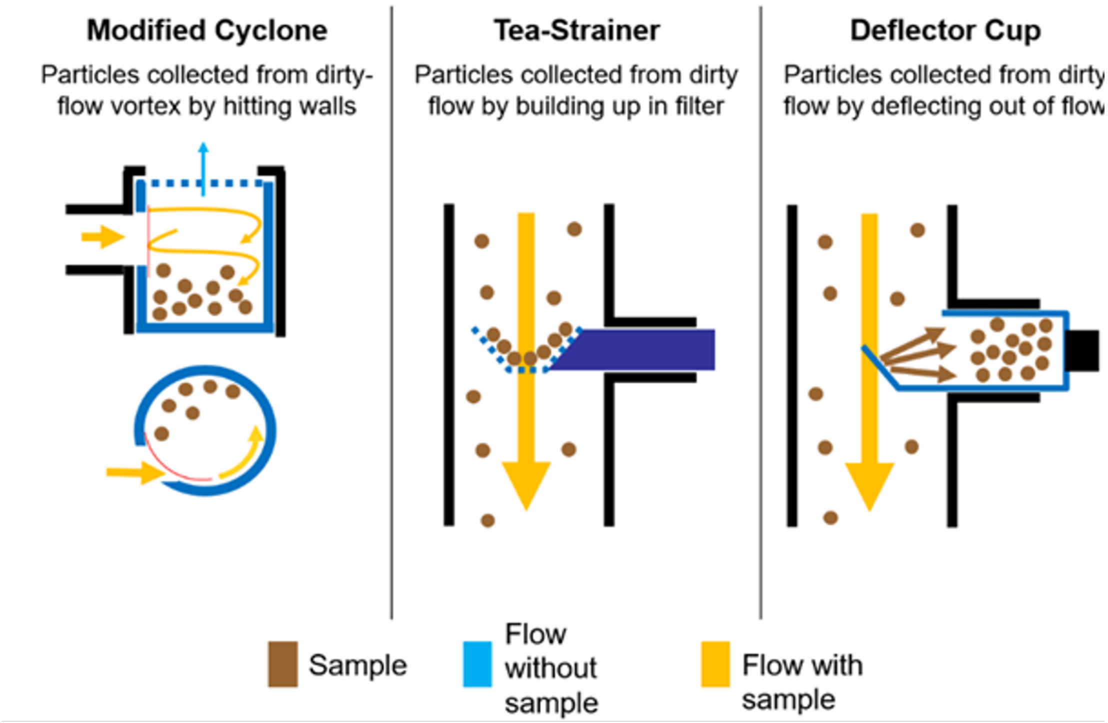


Figure A.17: Three approaches for capturing particulate samples: Modified Cyclone, Deflector Plate, and Tea Strainer.

Another option for particulate collection is a sticky pad which could collect powders or small rocks from the surface. One interesting option for this would be to use a gold metal pad, which is soft (but not liquid) at the elevated temperature of the Venus surface. These pads would be deployed onto the Venusian surface directly after landing or after surface rocks were chipped, then be retracted and stored. If samples must be removed from the pad for analysis, this could add complexity, but some analytical techniques may be tolerant to a sample partially embedded (and mounted) on a gold pad.

For the VISTA Sampling Landers, one challenge is the sample collection and transfer mechanisms. Of the multiple types of sample collection mechanisms available and described above, maturation of these systems is needed. This development could include methods to decrease power consumption, intelligent sample selection/processing, and optimization of autonomous operation of the system. Once the sample is secured, automated and reliable sample transfer mechanisms to each flight element need to be optimized. This includes testing in a representative ground test environment (GEER) to ensure functionality. Effects of the environmental conditions on mechanism operation and maintaining the integrity of the sample for delivery to the Aerial Laboratory should also be tested.

A.1.5 Ascent Vehicle (Asset 4)

The Ascent Vehicle is carried on the Sampling Lander along with the Sample Collection System. A variety of ascent vehicles were explored as possible options for departing the Venusian surface to reach the cruising altitude of the Aerial Lab. These were broken down into heavier-than-air and lighter-than-air vehicles, with options of altitude and lateral control. Heavier-than-air vehicles such as aircraft and rockets offer advantages over more passive systems, including precise altitude and lateral control. Their power and control would better overcome the uncertainty in wind, and could eliminate the need for a fetch vehicle (see Rendezvous section). There is less flight legacy for heavier-than-air vehicles, but this will improve with Ingenuity and upcoming missions such as Dragonfly. The main challenges for heavier-than-air systems are primarily their complexity, demand for high power, and the possible lack of loitering ability for gradual approach to the low-airspeed Aerial Lab.

Advantages of lighter-than-air vehicles such as balloons include flight legacy, simplicity, low power requirements, and fewer material constraints. Lighter-than-air ascent vehicles could be augmented with propulsion for lateral control, reducing the risk of unpredictable wind conditions for rendezvous with the Aerial Lab. Of course, this capability comes at the expense of increased power requirements, and complexity, raising some of the issues of the heavier-than-air ascent vehicles.

The harsh Venusian surface presents challenges for the operation and survival of ascent vehicles from high temperatures, pressures, and corrosive chemicals. Rockets were deemed not viable due to the density of the surface atmosphere. A helicopter or plane would also experience high drag near the surface. Significant technology development would be required to design a heavier-than-air vehicle that could operate both near the planet surface and at high altitudes, creating efficiency losses over a 60$\times$ atmospheric density range. A second-stage heavier-than- air ascent vehicle may still be a viable option, however.

A metallic balloon for a first stage of ascent can perform in temperatures near the Venusian surface. Balloons with expanding metallic bellows (Figure A.18, [Kerzhanovich et al., 2005]) have been designed to lift payloads to several tens of kilometers. Balloons made with typical metal alloys can reach altitudes of 15–20 km. An option was explored to have a single-stage metallic beryllium ascent balloon that could reach the Aerial Lab cruising altitude. This is a compelling option due to the simplicity of a single stage lift, and the possibility of reusability. However, it requires beryllium handling and tooling, which would require significant technology development owing to the toxicity and brittleness of beryllium.

A two-stage balloon emerged as the most feasible method for ascending from the Venusian surface at this time, leveraging initial architecture work performed in [Kerzhanovich & Hall 2005]. Crucially, the two-stage balloon approach allows for the use of lightweight polymeric materials for the upper atmosphere, and heavier metallic materials where the temperature is too hot for other options. The system consists of helium (or hydrogen [Bugga, 2022]) tanks, avionics to take the sample from the surface, sample tether, metal balloon, Kapton-Teflon laminate cloud-level balloon, and insulation box with phase change material that contains the cloud-level balloon. After the capsule has acquired the sample on the planet surface, the gas (He or H_2) acts as buoyancy gas and water as the phase-change material. The tanks are left on the surface, the first-stage metal bellows balloon releases at 15–20 km, and the second-stage balloon equilibrates at an altitude of about 62 km.

Figure A.18: 0.35-m diameter metal bellows at (a) ΔP = -84 mB, (b) ΔP = 114 mB, (c) ΔP 630 mB after exposure to +460°C.

Compared to the 1-balloon ascent system, advantages include having a smaller balloon at float altitude, better thermal characteristics at altitude (optimized alpha/epsilon), and the option of making the balloon either a super-pressure (i.e. survives the night, but at a mass cost) or a vented balloon (terminates at night). The second balloon also adds some complications. These include the transfer of lifting gas from the lower to the upper balloons, the addition of a thermal insulation system to safeguard the second-stage balloon, and a scaling of the balloon size with the time on the surface. Thermal protection at the surface may be required for a radio system in the ascent vehicle anyways, so this challenge may be common to other subsystems.

First, the spherical upper balloon (modeled as a sphere) was sized to be neutrally buoyant at 55 km, assuming a 0.5-kg payload. Neglecting the aerodynamic forces (drag force) because we are assuming a low vertical velocity, the sum of the buoyancy force, weight force of the balloon, and the weight force of the payload has to be equal to zero. Solving for the balloon's radius, a radius of 0.78 meters and a mass of 1.34 kg was calculated. Next, the thermal solution was sized to keep this balloon envelope below the damage threshold. A phase-change material was selected that melts at temperatures below Vectran and Kapton damage thresholds, like Lithium Trinitrate, which melts at 30°C (296 kJ/kg capacity). Assuming 1-hr ground-time, 0.5-hr descent, and 1-hr ascent, which is roughly equivalent to 1.75 hrs on the surface (includes half of ascent/descent), the insulation (Zircal-18) and phase change material were sized to meet the heat load, resulting in an estimation of 4.4 kg of PCM and 2.3 kg of insulation (7-cm thickness). Finally, the metal balloon was sized for carrying the entire balloon, thermal system, and payload (~10kg) to a crossover altitude of 20 km. Assuming stainless steel bellows that are ~100 microns thick with L/D equal to 3, the first-stage bellows balloon has a diameter of 0.72 m and a mass of 1.62 kg, for a total mass of the system of about 12 kg.

Figure A.19 shows how each mass, and the total mass, vary with increasing the payload mass, while Figure A.20 shows how the first- and second-stage balloon volumes increase with the payload mass.

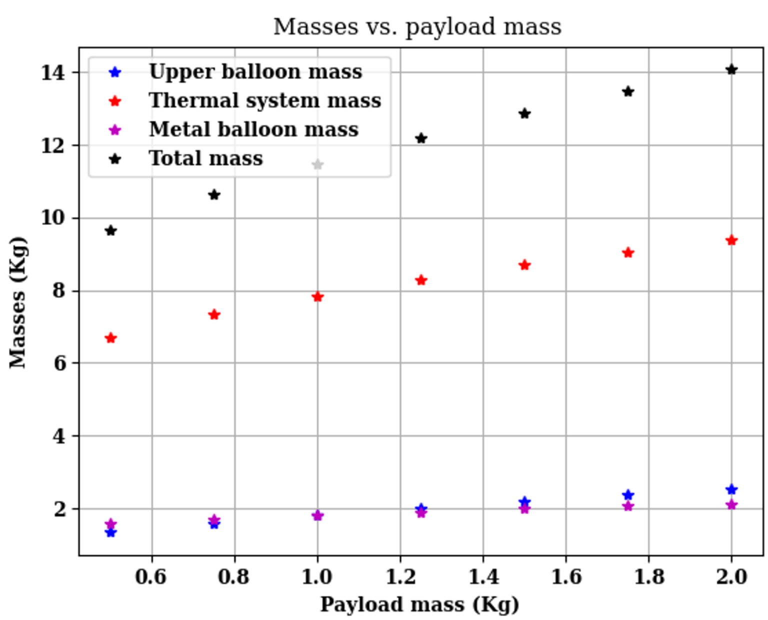


Figure A.19: System masses, varying payload mass.

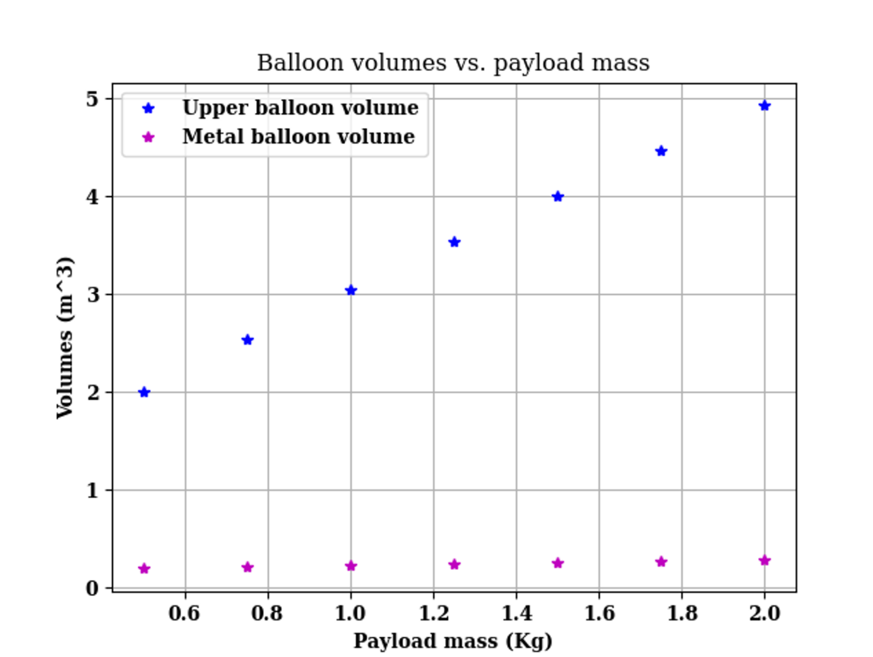


Figure A.20: Balloon volumes, varying payload mass.

A.1.6 Sample Retriever (Asset 5) and Rendezvous

In the likely absence of reliably, highly-maneuverable Aerial Lab and Ascent Vehicles, retrieval of the surface sample from the Ascent Vehicle will require a Sample Retriever, (i.e. a "fetch" vehicle) capable of launching from the Aerial Lab, traversing the separation distance to the Ascent Vehicle, and returning the sample to the Aerial Lab for analysis. High-level key capabilities needed to accomplish this final portion of the sample retrieval include the ability to accurately localize all three aerial assets at long and short range, some level of autonomous control of the trajectories of the Ascent Vehicle and Aerial Lab to limit the separation distance to less than the range of the Sample Retriever, high level autonomous control of the Sample Retriever, and the autonomous and/or automated ability to perform docking maneuvers with the fetch vehicle to transfer the surface sample package.

Several possible Sample Retriever configurations were considered to accomplish this mission, including lighter-than-air vehicles, e.g., blimps, and heavier-than-air platforms e.g., multirotor and fixed wing drones. Blimp-type platforms provide low-speed flight for docking maneuvers, but are susceptible to atmospheric turbulence. Furthermore, efficient flight speeds of blimps is only a fraction of speeds achieved by drones, which would increase the Sample Retriever operational duration by almost an order of magnitude, from several hours to tens of hours. Fixed-wing drones achieve high flight efficiency at much higher cruise speeds, but lack the ability to dock at low speed. Multirotor drones offer the maneuverability and low speed needed for docking, but are highly inefficient during cruise. The Sample Retriever must have the ability to efficiently fly a long-range flight between the Aerial Lab and the Ascent Vehicle, while also being able to perform an accurate and low-speed docking maneuver to collect and transfer the surface sample package. These combined flight requirements point to the use of a fixed-wing aircraft designed for long range and very low-speed flight and hover, e.g., vertical flight.

A promising system concept has already been developed and demonstrated under prior work for a similar Venus application using a novel annular wing design for fixed-wing flight and a quadcopter propeller arrangement for agile control in fixed-wing flight (Figure A.21). This design is highly applicable to the VISTA mission concept.

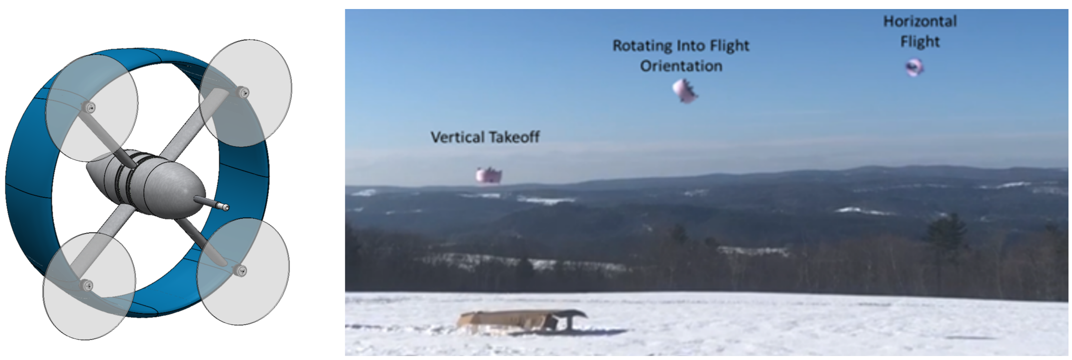


Figure A.21: A VTOL Ring-Wing Drone Based on a Quadcopter Configuration developed at Creare LLC. (a) VTOL Ring-Wing Drone Concept (2 to 10 kg and 0.9-meter-diameter ring wing). (b) Ring-Wing VTOL to Horizontal Flight Demonstration (video: `https://youtu.be/82-coC-vaNE`)

The current drone design can be readily scaled to carry the desired sample package size and mass. A 1 kg sample package will require an ~10-kg drone that has a total range of approximately 100 km. Refinements to this design could extend the range further if needed. For example, recharging the drone on the ascent vehicle or adding additional battery mass by increasing the total mass of the platform.

Many aspects of this system have already been demonstrated by Creare and collaborators under prior work for applications on Venus and Titan, including: (1) demonstration of terrestrial flights of the drone with vertical takeoff, fixed-wing flight, and vertical landing (video links: `https://youtu.be/KeGgT9Y2ev0;https://youtu.be/FH-YdBEn7nc`) and

(2) highly accurate control of drones with millimeter stability using a vision-based system under prior work for the National Institutes of Health, showing operation in a closed lab with little or no wind (video link: `https://youtu.be/nigFQFP48ys`). Evaluation of drone performance in a more realistic environment will be an important test of maneuvering feasibility.

Sample Retriever Control and Autonomy. Flight control software is readily available both as commercial products and in open source repositories for an array of both fixed wing drones, hovering multirotor drones, and combined fixed wing and hovering drones. Capabilities of this software include high-rate flight attitude controllers, autonomous path planning and flight trajectory management controllers, as well as user interfaces for flight systems managers to define and initiate missions remotely through a ground station with varying degrees of autonomy. Creare and its partners have leveraged existing flight control software and also developed customized software needed to accomplish key aspects of the proposed fetch mission. These include the ability to transition from efficient fixed-wing flight and vertical/hovering flight, and the ability to accurately dock a drone with another platform. A key difference between existing flight controllers used on Earth and one that would be used on Venus are the sensors used for localization. For terrestrial applications, Inertial Measurement Units (IMUs) are most commonly used as a key part of the high-rate attitude controller, while GPS is used for longer range path planning and flight trajectory management. On Venus, IMUs will still play a key role, but localization sensors other than GPS will be required. Highly reliable, assured autonomy of all rendezvousing components of the architecture over long distances (i.e., tens of vertical, and hundreds of lateral km) and multiple instances (e.g., repeat sorties of the fetch vehicles) is a critical enabling development for the VISTA concept.

Long Range Localization. The sensing modality and the required localization accuracy for the three aerial platforms varies with the localization range. At long range, i.e., beyond visual line of sight, radio signals from the orbiter provide data for global position and trajectory estimation of the platforms. Additionally, the Sample Retriever could utilize an array of patch antennae to detect radio beacons from the Ascent Vehicle and the Aerial Lab and determine relative range and pseudo-range using a well-established signal reduction methodology. [Mohammadi, 2018]These long-range localization strategies provide accurate global position and relative range and bearing for each platform in two dimensions. For determination of altitude, each platform will measure and report absolute atmospheric pressure, among other atmospheric measurements such as wind and temperature used in long range path planning.

Long Range Path Planning. The long-range path planning strategy incorporates stochastic atmospheric models, vehicle dynamics and near real-time wind measurements in the atmosphere to inform control of the ascent vehicle and aerial lab to minimize separation distance for rendezvous. The long-range path planning model determines the optimal altitude for the aerial platforms to achieve the most favorable closing trajectories based on the current and probable wind vectors. One option to estimate rendezvous locations for long term planning goals leverages a Monte Carlo simulation of the ascent vehicle trajectory, informed by stochastic wind vector models. Path planning computations are intended to be performed using onboard resources versus via communication with a ground station on Earth to allow for the greatest degree of flexibility. Besides direct atmospheric wind measurements from the three platforms, the path planning model may benefit from additional low-cost sondes dropped from the Aerial Lab to provide a more complete map of the winds from high altitude down to the surface. The path planning model ensures that the Ascent Vehicle and the Aerial Lab achieve a minimum approach distance within the range of the Sample Retriever. As the Ascent Vehicle and the Aerial Lab reach minimum separation distance, the platforms will also approach the same altitude to minimize the descent and climb requirements for the Sample Retriever, minimizing climb energy requirements and maximizing range.

Short Range Localization. Once the Sample Retriever is both within line-of-sight of the target platform and resolvable by its own tracking instuments, optical localization becomes possible. Upon initial visual contact, the fetch vehicle can accurately determine relative direction and range by imaging a flashing optical beacon on the target platform. At very close range, the Sample Retriever performs a docking maneuver to transfer the surface sample package and requires centimeter-accurate relative position and pose with the package. This level of accuracy can be accomplished using a camera on the Sample Retriever and well-defined optical or infrared targets on the package. A simple implementation and computationally-efficient approach could use infrared reflective targets based on ArUco markers. Visually transparent films with high reflectivity are available commercially for this application [Snyder, J., Howard, J., Potts, T., Hansen, K. and Dunn, D., "'Invisible' 2D Bar Code to Enable Machine Readability of Road Signs–Material and Software Solutions," In 2018 ITS America Annual Meeting Detroit. ITSWC, Jun 2018].

Under prior work, Creare has already developed a drone platform capable of achieving millimeter-accurate flight control under quiescent lab conditions as shown in the prior work for the National Institutes of Health. Additional development would be required to implement and characterize the performance of a drone performing a docking maneuver in an atmosphere similar to Venus while using a short-range vision based localization system. Understanding the performance of the drone under these conditions would provide key performance requirements needed for the docking mechanism and the required tolerances needed to capture the drone.

Sample Docking Mechanism. The drone docking mechanism must be capable of guiding the drone into a catch mechanism and then hold the drone to the Aerial Lab for sample transfer. The docking mechanism is a convenient connection to provide charging to the drone's internal batteries, and may also be used to transfer the stored sensor data to the Aerial Lab (but this may also be achieved via a short-range radio or optical link). Proper design of the docking mechanism can compensate for the achievable flight tolerances and control stability of the platform by guiding the drone into the catch mechanism. For example, Figure A.22 shows a proof-of-concept prototype designed and developed for this purpose. The cone shape of the dock receiver guides the tip of a sting, to be installed on the drone, into the latch mechanism to physically capture the drone. A more sophisticated version of this design could include electrically conductive sting elements to charge the drone.

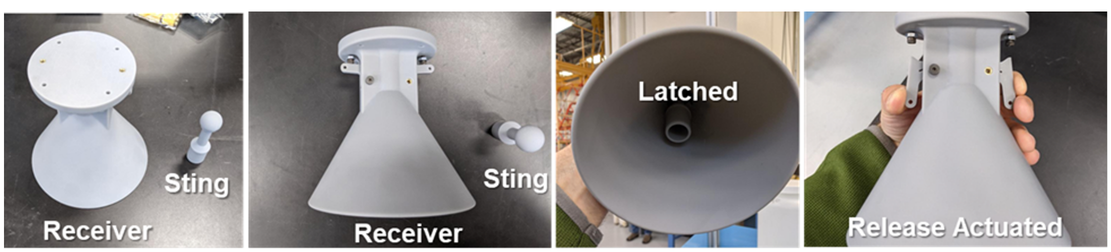


Figure A.22: Fabricated and Assembled Terrestrial Drone Docking Mechanism

Specific Sample Retriever design mitigations include drag reduction, increased motor efficiency, and additional or higher-efficiency energy storage devices. Current and future research in energy storage technologies could enable additional capacity to be added to the Sample Retriever without increases in vehicle size and mass.

Several rendezvous operational risk mitigations are also possible and are focused on obtaining in situ information on atmosphere and wind conditions. These include:

- An orbital asset could be used to obtain initial atmospheric and weather data prior to deployment of the Aerial Lab and possibly during mission operations.
- Once deployed, the Aerial Lab could also be utilized to capture in situ weather data prior to deployment of Sampling Landers or the Sample Retriever.
- Finally, low-cost disposable sondes deployed from the Aerial Lab could be deployed prior to Sampling Lander release. Data from the sondes could be used to make a final go/no decision for deployment of the Sampling Landers.

For the VISTA Sample Retrievers, a key risk in docking and sample transfer is the effect of unknown turbulence in the atmosphere. Potential effects are the inability to successfully dock or transfer the sample due to turbulence induced oscillations in the Ascent Vehicle, Sample Retriever, and the Aerial Lab. Other effects could be damage to vehicle and/or sample capture hardware or loss of the sample container. Earth-based flight tests utilizing a terrestrial Sample Retriever would be utilized for risk reduction. Actual flight sample transfer mechanisms would be utilized and the transfer procedure demonstrated. Test facilities should enable simulation of predicted wind and gust environment as well as conditions higher than predicted utilizing Monte Carlo Analysis. Development of adaptive flight control laws could also be developed to improve fetch vehicle controllability and counter the effects of unpredicted turbulence.

A.2 Science Implementation

The Aerial Lab and Sampling Landers will need instruments and sensors to make measurements for both the purpose of data collection and navigation. These include temperature, pressure, and wind speed measurements on both the Sampling Landers and Aerial Lab, as well as basic imaging capacity on the lander to characterize the sampling site. The Science objectives outlined in the STM call for an array of instruments on the Aerial Lab (Table A3), and to a lesser extent, on the Landers as well. Many of the objectives require that the sample be an intact rock, although a subset of the objectives can be achieved on fines/powders.

A.2.1 Example Sample Chain

One possible workflow would include capture of a rock sample on the Venusian surface into a primary container, which would be vented on the way to the Aerial Lab (taking advantage of the naturally lower pressure in the atmosphere compared to the surface). The atmosphere could be sampled (directly from the Venusian surface or possibly from the primary container) into a secondary gas-tight container and aerosol collected using one of the many methods described earlier.

Once docked into the Aerial Lab, the rock sample(s) container will be loaded into an airlock transfer chamber, and flushed with N2 (or some other inert gas) before exposure to the Aerial Lab interior envelope. Care must be taken in overall design to ensure that the Aerial Lab interior environment is maintained to protect all equipment from the corrosive Venus clouds. Once the sample is inside the Aerial Lab, an image of the entire sample will be taken, and sent to Earth for evaluation. If multiple rock samples have been obtained in the one container, material will be selected for analysis. Any remaining sample can be stored for later additional analyses, or even transferred to a long term storage capsule for possible return to Earth.

The rock sample selected will first be analyzed using techniques that require no sample modification, such as IR spectroscopy and microscopic imaging, or laser ablation. The necessary tools can be arranged strategically around a single sample location so the sample can remain in place for all analyses to be completed. Alternatively, the sample can be placed in a cup with an adjustable sample height that would be moved from one instrument to the next. These initial analyses would provide first-order information on composition. The sample could then move to a secondary stage of analysis involving sample preparation steps, most importantly, creation of a flat surface (through either breaking, cutting, grinding, or polishing). This would benefit techniques such as Mossbauer, IR, Raman, XRF, and laser ablation methods.

Flat surfaces could be prepared by mechanical abrasion, or cut with a saw (mechanical or chemical). A subscale version of a Rock Abrasion Tool, similar to that used on the Mars Exploration Rovers, located at a fixed position on the carousel could be used to grind a flat surface on the rock. These methods may also allow sectioning through the depth of the sample, a way to study reactions of the rocks with the Venusian atmosphere. Unfortunately, the mechanical methods will generate particulates. If loose, these powders present some danger to the other samples and perhaps to the operations inside the aerial lab. Chemical sawing usually employs strong inorganic acids, and the hazards they pose need to be considered. Mitigation of these risks may be possible by sealing the tools for sample preparation inside an isolated box, and washing down the box after preparing the sample. The liquid waste could be then filtered or discarded. Some development of tools for sample preparation may be necessary before setting requirements of flat surfaces for analysis.

The gas sample, in a dedicated container, would also be loaded into the Aerial Lab via the same airlock, and the gas-tight connections directed into the necessary purification lines connected to the relevant instruments (e.g., mass spectrometer). Impacted aerosol samples could be handled similarly to the rock samples, and make use of much of the same sample chain described above.

A.3 Opportunistic Science

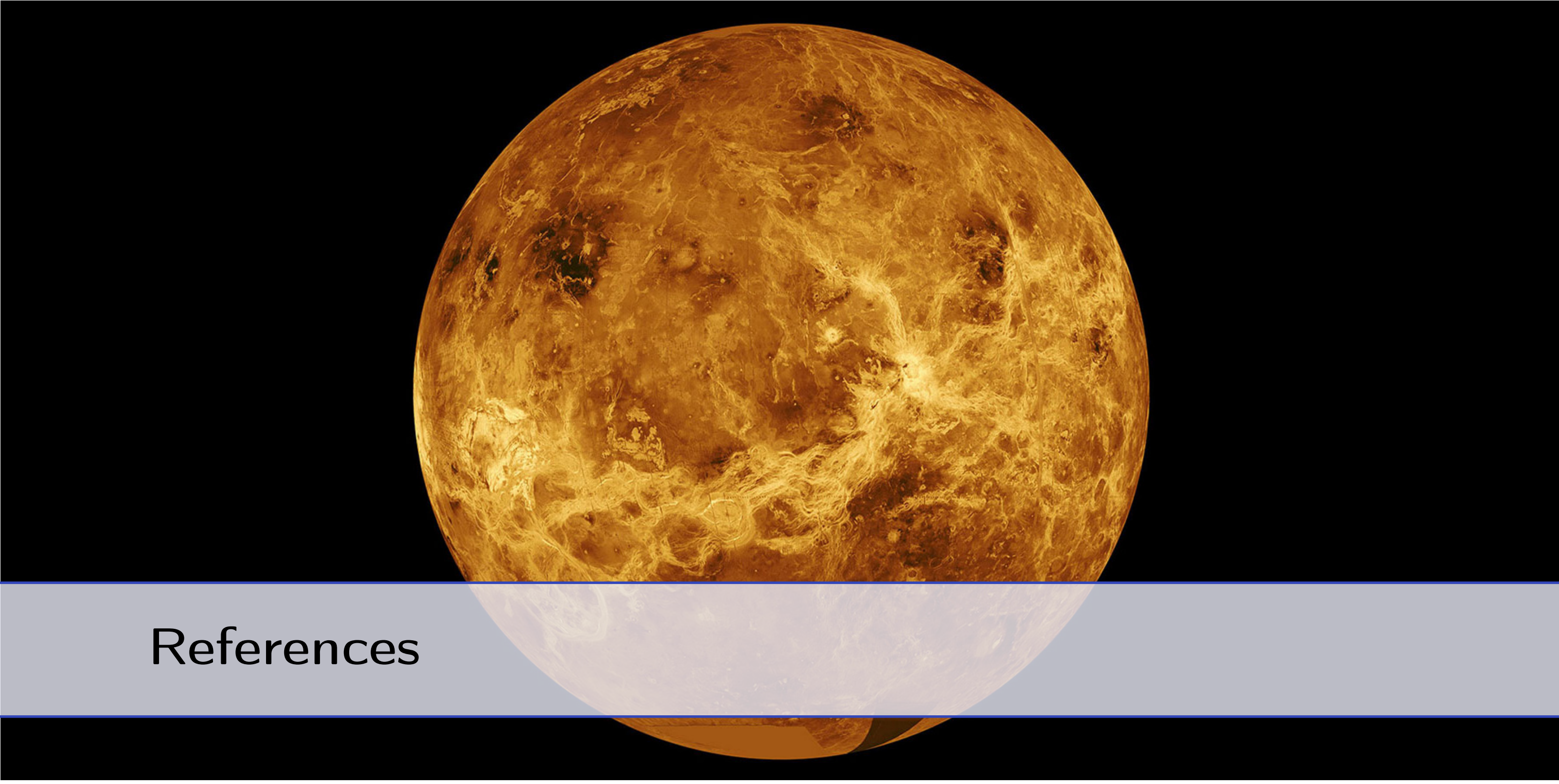
The VISTA mission concept requires certain data types via engineering sensors to be collected in order to allow for the synergistic operation of different mission assets. Some of this data is not fundamental to addressing the questions put forth in the mission STM, but is valuable scientific data for understanding Venus. Examples of this type of measurement include atmospheric condition measurements from the Aerial Laboratory (pressure, temperature, and wind speed), which would be used to help navigate and track the Aerial Laboratory over the course of the mission. Also, an extended duration atmospheric monitoring campaign would provide information on the atmospheric conditions at that layer and would be relevant to atmospheric modeling and chemical cycling. The Sample Retriever may also acquire similar information for guidance purposes, and this would provide information on additional layers of the atmosphere due to their increased travel range. Any dropsonde probes through the atmosphere used in advance of sample retriever deployment also provide atmospheric depth profiles that could be used in atmospheric dynamics modeling. Another example is context photos taken by the Sampling Lander assets. These photos, taken at a range of elevations as the asset drops to the surface (and if possible on the surface) are critical to properly interpret rock samples. Additional details in the images may be useful to understanding other geologic questions about Venus, for example, those relating to sediment budgets, geomorphology, or structural geology.

Beyond exploitation of engineering sensors needed to accomplish a multi-asset mission, there are opportunities for science not specified in the VISTA STM. Additional instruments to conduct science of opportunity could also be added to this concept, depending on the final design and budget. For example, if the sample retrieval rovers are leaving mass on the surface, that mass could contain simple long-lived weather station sensors, as in the LLISSE concept, to provide long duration environmental condition information at the sampling sites. The Aerial Laboratory could be outfitted with a pressure sensor to monitor infrasound evidence of earthquakes. An orbital communication asset could track atmospheric conditions or monitor for dayglow evidence of seismic activity. With multiple assets comes multiple opportunities to expand on the science, however cost will ultimately dictate this.

The chemical and mineralogical information returned by this mission will also provide important data that can be used in laboratory studies relevant to Venus. For example, the field of experimental petrology has provided revolutionary insights when applied to understanding all other rocky bodies in our solar system, but has been rarely applied to Venus only because we lack the relevant chemical and mineralogical data needed to determine how to conduct these experiments. Being able to explore the Venus mantle with these techniques will provide enhanced understanding of the planet and also increase our ability to understand the findings of the mission.

Table A.3: Possible instruments to be included on the Aerial Laboratory to achieve the Science Objectives in the STM.

Physical Parameter	Method	Heritage instrument	Sample form requirement
Available technology			
Grain-scale and bulk rock chemistry	XRF	PIXL	Rock, face with sufficient flatness (or on-instrument focus); powder for bulk chem only
	LIBS	SuperCam	
Mineralogy	Raman	SuperCam, SHERLOC	Rock face preferred for textural resolution of mineralogy (petrology)
	IR	Ma_MISS, micrOmega, MLPS	
	XRD	CheMin	Powder required for CheMin
	Mossbauer	MER/MB	Flat surface preferred
Textural analysis	Microscopic imaging	MAHLI	Rock face preferred
Noble gas isotopes	QITMS+heating (noble gas purification line)	Avice et al (2019)	
C, O isotopes	TLS, QMS	SAM/TLS, MOMA	
H, S isotopes			
Organics	UV fluorescence	SHERLOC	
Composition	GC/MS	SAM, MOMA	
Environmental control	Filter, vacuum pumps, small gas tanks (e.g., N_2)		
Magnetic field	Magnetometer		
Needing Development			
pH, mineral abundance (e.g., Mg and Na cations or Cl, Br, $(SO_4)^{2-}$, conductivity, redox potential	Wet chemistry	Phoenix/MECA	Powder
Pb isotopes	LA-TOF-MS	(Riedo et al., 2013)	Flat surface preferred
Sr isotopes	LA+TLS+RIMS	(Anderson et al., 2015, 2020)	Flat surface preferred
To develop from scratch			
Nd isotopes			
Trace elements (100 ppm–1 ppb)	Possibly LA-ICP-MS		



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