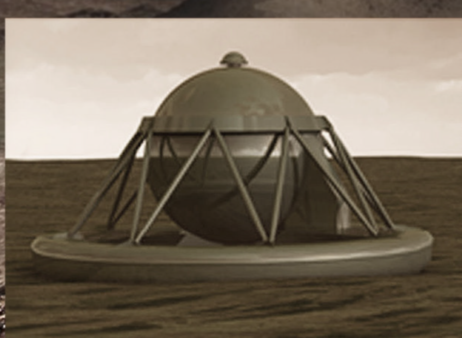
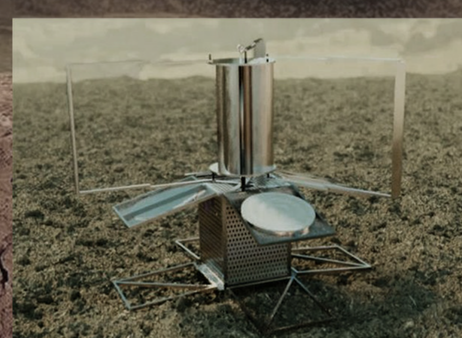
VENUS EXPLORATION
VEXAG
ADVISORY GROUP

VENUS STRATEGIC DOCUMENTS 2019





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Foreword and Acknowledgements
Venus Strategic Documents

Why Venus and why now? Venus plays a pivotal role in our understanding of the origin, evolution, and habitability of rocky planets in our solar system and throughout the galaxy. Venus has key characteristics of habitable planets: geologic activity, a substantial secondary atmosphere, past surface water, and possibly a past dynamo. Of all the numerous Earth-sized exoplanets thus far discovered, none is more similar to Earth and more accessible to us than Venus. Venus acts as a proxy for those exoplanets. NASA has visited all other major rocky bodies of the solar system in the last two decades, including several missions to both the Moon and Mars. The VEXAG **Goals, Objectives, and Investigations** document is a community consensus document that describes the scientific discoveries needed to fill the enormous gaps in comparative planetology that will advance our understanding of planet evolution and habitability.

A suite of missions is ready and actively being proposed to fill these gaps. The breadth of highly-rated mission proposals to NASA's Discovery and New Frontiers programs reflects the compelling nature of Venus and the science drive to understand its evolution from interior to surface to atmosphere. The high ratings, supported by funded Phase A studies of recent Venus mission proposals, demonstrate both technical feasibility and the value of Venus science in the coming decade. The U.S. is poised and primed with the advanced technologies, solid mission concepts, and talented, enthusiastic workforce necessary to resume international leadership of a Venus exploration program. Over the past 25 years, NASA has explored the expanse of the solar system, from the Sun itself to Kuiper Belt Objects, and from comets to giant planets. The VEXAG **Roadmap for Venus Exploration** delineates how we can return to our nearest neighbor.

The missions in the Roadmap are enabled by the technologies described in the VEXAG **Venus Technology Plan**, which performs a detailed assessment of the maturity of the technologies needed to conduct missions to Venus. It expands upon a series of earlier studies of small satellites[1], aerial platforms[2], and "Venus Bridge" small mission approaches[3] to Venus exploration. In addition to these overarching studies, NASA has made significant investments in developing enabling technologies, including the High Operating Temperature Technology (HOTTech), Long-Lived In-Situ Solar System Explorer (LLISSE), and Heatshield for Extreme Entry Environment Technology (HEEET). Many of scientifically important missions to the second planet can be implemented with existing technology, while some fundamental science questions can only be successfully answered with new mission paradigms.

Collectively, these three Venus Strategic Documents lay out the vision of the Venus Exploration Analysis Group (VEXAG) and the Venus community it represents. In addition to periods of weekly committee meetings, many opportunities for public input resulted in improvements in these documents:

- First draft versions were posted on the VEXAG site for public comment in December of 2018. A virtual town hall to discuss these drafts was held on February 7, 2019. Approximately 30-40 Venus community members participated.

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[1]NASA (2017) Planetary Science Deep Space SmallSat Studies (PSDS3) program, https://www.nasa.gov/feature/nasa-selects-cubesat-smallsat-mission-concept-studies.

[2]Cutts, J.A. and the Venus Aerial Platforms Study Team (2018) Aerial Platforms For the Scientific Exploration of Venus, Summary Report. JPL D-102569.

[3]Grimm, R., Gilmore, M.S., and the VEXAG Venus Bridge Study Team (2018) Venus VEXAG Bridge Study.

- Second drafts were posted by March 1, 2019, and an in-person Town Hall meeting was held on Sunday, March 17 in The Woodlands, Texas at the 50th Lunar and Planetary Science Conference to review those drafts with about 50 attendees.
- Third drafts were posted in the VEXAG site on May 24, 2019. A virtual town hall with about 25-30 participants to discuss these drafts was held on June 10, 2019.
- Final drafts were edited and posted on the VEXAG site in September of 2019, with a six-week period for final comments.

This iterative process ensured that the Venus community had ample time and opportunity to provide expert input to, and edit the documents. As a result, they represent a true consensus of Venus scientists and engineers.

This Plan owes much to the effort of the committee members who wrote them. We thank the GOI committee, led by Allan Treiman (LPI) and Joseph O'Rourke (ASU), which also included Giada Arney, Paul Byrne, Lynn Carter, Darby Dyar, James Head III, Candace Gray, Stephen Kane, Walter Kiefer, Kevin McGouldrick, Laurent Montesi, Chris Russell, and Suzanne Smrekar. The Roadmap committee was led by James Cutts (JPL) assisted by Michael Amato, Tibor Kremic, Candace Gray, Scott Hensley, Gary Hunter, Noam Izenberg, Walter Kiefer, Kevin McGouldrick, Joseph O'Rourke, and Suzanne Smrekar. The Technology Plan effort was led by Gary Hunter (GRC) supported by Jeffery Balcerski, Samuel Clegg, James Cutts, Candace Gray, Noam Izenberg, Natasha Johnson, Tibor Kremic, Larry Matthies, Joseph O'Rourke, and Ethiraj Venkatapathy. We are grateful to everyone who made this document possible.

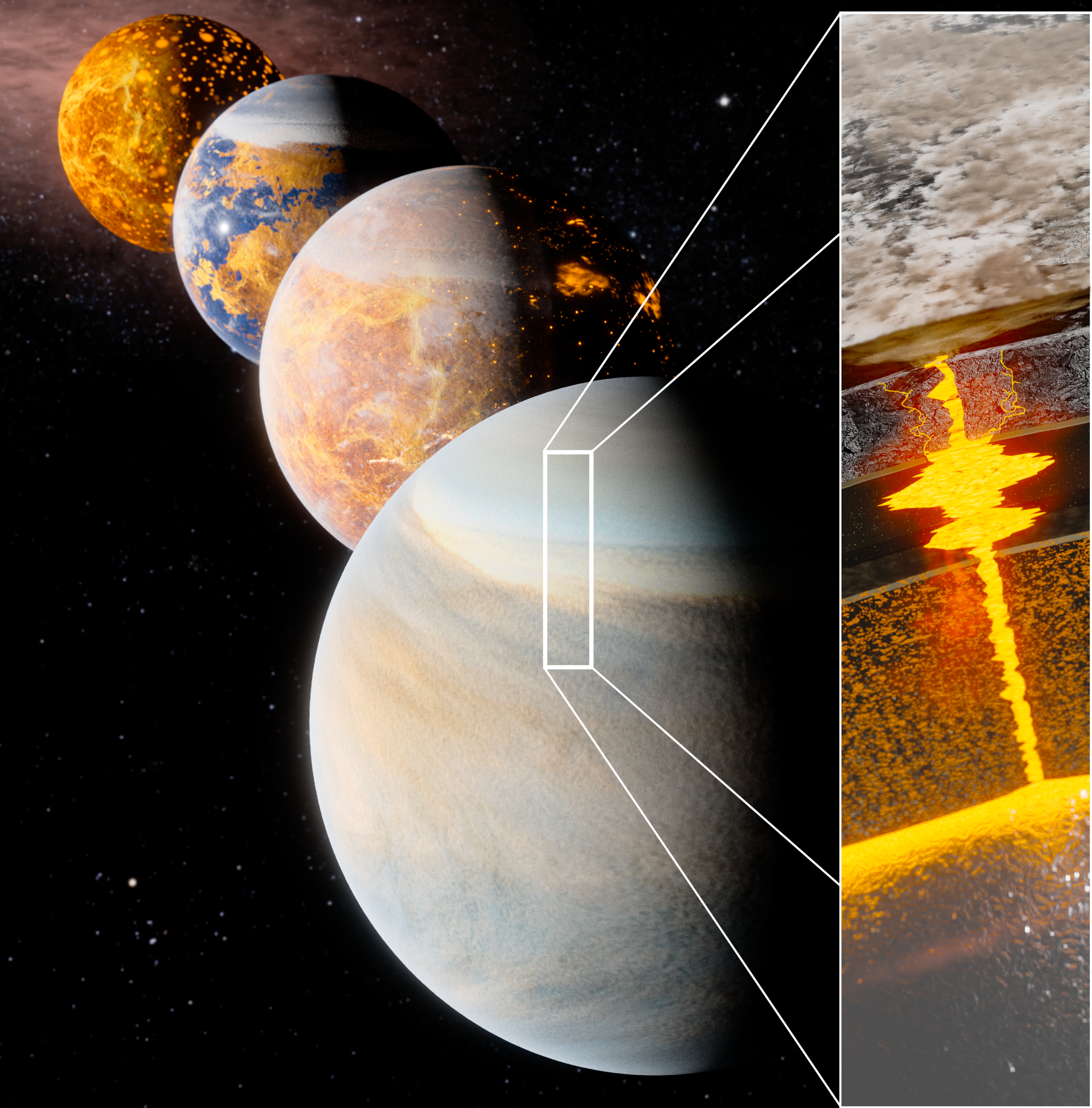
It is our hope that these Strategic Documents will pave the way for exploration of the least-studied terrestrial planet in our solar system, and launch a decade or more of Venus exploration. We stand ready as a community to go back to Venus!

M. Darby Dyar, Chair, Venus Exploration Analysis Group Steering Committee

Noam Izenberg, Deputy Chair, Venus Exploration Analysis Group Steering Committee

VENUS EXPLORATION
VEXAG
ANALYSIS GROUP
2019

VENUS GOALS, OBJECTIVES, AND INVESTIGATIONS



Cover image by John D. Wrbanek

At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major documents were selected to be updated: (1) the Goals, Objectives and Investigations for Venus Exploration: (GOI) document, providing scientific priorities for Venus, (2) the Roadmap for Venus Exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) the Technology Plan for future Venus missions. Here we present the 2019 version of the VEXAG Goals, Objectives and Investigations for Venus Exploration.

Prepared by the VEXAG GOI Focus Group: Joseph O'Rourke and Allan Treiman (Co-Chairs), Giada Arney, Paul Byrne, Lynn Carter, Darby Dyar, James Head III, Candace Gray, Stephen Kane, Walter Kiefer, Kevin McGouldrick, Laurent Montesi, Chris Russell, and Suzanne Smrekar.

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VEXAG Charter. The Venus Exploration Analysis Group (VEXAG) is NASA's community-based forum designed to provide scientific input and technology development plans for planning and prioritizing the exploration of Venus over the next several decades. VEXAG is chartered by NASA's Planetary Science Division (PSD) in the Science Mission Directorate (SMD) and reports its findings to NASA. Open to all interested scientists, VEXAG regularly evaluates Venus exploration goals, scientific objectives, investigations, and critical measurement requirements, including recommendations for the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

1.0 Executive Summary

Venus and Earth are often described as twins. Their sizes and densities are nearly identical, and they are much larger than the other terrestrial planetary bodies of our solar system. Yet past exploration missions reveal that Venus is hellishly hot, devoid of oceans, apparently lacking plate tectonics, and bathed in a thick, reactive atmosphere. A less Earth-like environment is hard to imagine. When and why did Venus and Earth's evolutionary paths diverge? Did Venus ever host habitable conditions? These fundamental and unresolved questions drive the need for vigorous new exploration of Venus. The answers are central to understanding Venus in the context of terrestrial planets and their evolutionary processes. Critically, Venus provides important clues to understanding our planet—does hot, dry Venus represent the once and future Earth? Current and future efforts to locate and characterize planetary systems beyond our Solar System (e.g., the Kepler mission and the Transiting Exoplanet Survey Satellite) are aimed at Earth-size planets in the "habitable zones" of their parent stars. Precisely because it may have begun so like Earth, yet evolved to be so different, Venus is the planet most likely to yield new insights into the conditions that determine whether a Venus-sized exoplanet can sustain long-lived habitability.

The planetary science community has consistently identified Venus as a high-priority destination for scientific exploration. In the latest Decadal Survey (*Visions and Voyages for Planetary Science in the Decade 2013–2022*, National Research Council, 2011), Venus was listed as an "important object of study" in all three crosscutting themes (building new worlds, planetary habitats, and workings of solar systems). The Decadal Survey recommended the Venus In Situ Explorer as one of seven candidate missions for New Frontiers 4 and 5 and the Venus Climate Mission as one of five candidate Flagship missions. The midterm review of NASA's progress towards implementing the Decadal Survey found that programmatic balance in selected missions is vital to achieving investigations of comparative planetology.

Exciting Venus research has been ongoing since 1994, the end of the last US mission to Venus, extending to the recent Venus Express (ESA) and Akatsuki (JAXA) missions. In particular, the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) instrument on Venus Express (VEX) provided tantalizing evidence that tesserae terrains are composed of felsic rock—suggesting that they formed in the presence of abundant liquid water. Laboratory simulations show that plume-induced subduction on Venus could serve as an analog for the initiation of plate tectonics on the early Earth. Akatsuki has revealed fascinating features in the atmosphere such as planetary-scale standing gravity waves at the cloud tops that are associated with specific topographic features and local times. Conditions similar to those that led to the emergence of life on Earth may have occurred on Venus, but the surface today is too hot for terrestrial life and the clouds are cooler but extremely acidic.

Through an extended process including input from the science community at three town hall meetings and a workshop at LPSC in 2019, the VEXAG community has developed this list of Scientific Goals, Objectives, and Investigations. They are intended to address the priorities of the *Visions and Voyages* (National Research Council, 2011) Decadal Survey for 2013-2022 and to motivate future efforts. In particular, NASA's future exploration of Venus should strive toward three non-prioritized Goals:

Goal #1. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-sized (exo)planets,

Goal #2. Understand atmospheric composition and dynamics on Venus, and

Goal #3. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

This document describes the six Objectives and 23 Investigations that support these goals. Every Investigation was judged to be technically and programmatically feasible and scientifically valuable. Collectively, they support a sustained program of Venus exploration would unveil the workings of Earth's nearest neighbor with broad scientific implications for our Solar System and beyond.

2.0 VEXAG Goals, Objectives, and Investigations (GOI)

Table 1 summarizes this entire report. Because understanding Venus as a planetary system requires progress in many scientific areas, Goals and Objectives are not prioritized. Investigations are typed as **Essential (1)**, **Important (2)**, or **Targeted (3)** based on their relationship to the corresponding Objective. Completion of all Essential Investigations fundamentally addresses their Objective. Important Investigations address many aspects of their Objective and provide valuable context for other Investigations. Targeted Investigations address particular aspects of an Objective that significantly contribute to our overall understanding of Venus. Investigations with the same ranking have the same level of priority. **All listed Investigations are deemed to be significant and worthy of programmatic consideration.**[1]

Potential Investigations that were judged as having less than high scientific value are omitted entirely from this report. Investigations that would have high merit but are not technically feasible within the timescale of the VEXAG "Roadmap for Venus Exploration" are not included in Table 1, although some of them are discussed in Appendix 1 of this report.

Investigations from the 2016 VEXAG GOI are included in the current version (Appendix 2). However, the 2016 Goals focused separately on 1) the atmosphere, 2) surface and interior processes, and 3) the atmosphere-surface interface. The 2019 VEXAG GOI blends Investigations of different focus areas to achieve overarching Goals and has been iterated with other VEXAG Focus Groups to serve as the foundation for the VEXAG Roadmap and Technology reports.

[1]Because this document is being written in anticipation of a new Decadal Survey for 2023 and beyond, it intentionally avoids specific linkages to the old *Visions and Voyages* document. However, Appendix B of this document relates our Goals to the Goals of the 2014 VEXAG GOI document, and such mappings can be found therein.

Table 1. VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
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?	**HO. Hydrous Origins (1).** Determine whether Venus shows evidence for abundant silicic igneous rocks and/or ancient sedimentary rocks.
		RE. Recycling (1). Search for structural, geomorphic, and chemical evidence of crustal recycling on Venus.
		AL. Atmospheric Losses (2). Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons.
		MA. Magnetism (3). Characterize the distribution of any remanent magnetism in the crust of Venus.
	B. How does Venus elucidate possible pathways for planetary evolution in general?	**IS. Isotopes (1).** Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.
		LI. Lithosphere (1). Determine lithospheric parameters on Venus that are critical to rheology and potential geodynamic transitions, including: stress state, water content, physical structure, and elastic and mechanical thicknesses.
		HF. Heat flow (2). Determine the thermal structure of the lithosphere of Venus at present day and measure in situ heat flow.
		CO. Core (2). Measure the size of the core of Venus and determine whether it remains partially liquid.

Table 1 (continued, a). VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?	**DD. Deep Dynamics (1).** Characterize the dynamics of the lower atmosphere (below about 75km) of Venus, including: retrograde zonal super-rotation, meridional circulation, radiative balances, mountain waves, and transfer of angular momentum.
		UD. Upper Dynamics (1). In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
		MP. Mesoscale Processes (2). Determine the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus.
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	**RB. Radiative Balance (1).** Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.
		IN. Interactions (1). Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.
		AE. Aerosols (2). Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.
		UA. Unknown Absorber (2). Characterize the unknown short-wavelength absorber in the upper atmosphere of Venus and its influence on local and global processes.
		OG. Outgassing (3). Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition.

Table 1 (continued, b). VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
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?	**GH. Geologic History (1).** Develop a geologic history for Venus by characterizing the stratigraphy, modification state, and relative ages of surface units.
		GC. Geochemistry (1). Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units on Venus.
		GA. Geologic Activity (1). Characterize current volcanic, tectonic, and sedimentary activity that modifies geologic units and impact craters and ejecta on Venus.
		CR. Crust (2). Determine the structure of the crust of Venus in three dimensions and thickness across the surface.
	B. How do the atmosphere and surface of Venus interact?	**LW. Local Weathering (1).** Evaluate the mineralogy, oxidation state, and changes in chemistry of surface-weathered rock exteriors at localities representative of global geologic units on Venus.
		GW. Global Weathering (2). Determine the causes and spatial extents of global weathering regimes on Venus.
		CI. Chemical Interactions (3). Characterize atmospheric composition and chemical gradients from the surface to the cloud base both at key locations and globally.

3.0 Descriptions of the Goals, Objectives, and Investigations

3.1. Goal I: Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.

Like Earth, Venus may have hosted oceans of liquid water for billions of years (e.g., Way et al. 2016). Alternatively, these sister planets may have followed distinct evolutionary paths from the birth of the Solar System (e.g., Gillmann et al. 2009; Hamano et al. 2013). Because it may have begun so similar to Earth, yet evolved to be so different, Venus is the planet most likely to yield new insights into the conditions that determine whether a Venus-sized exoplanet can sustain long-lived habitability (e.g., Kane et al. 2018; Kane et al. 2014).

3.1.1. Objective I.A. | Did Venus have temperate surface conditions and liquid water at early times? The amount of water that Venus received during and after its accretion remains unknown. Standard models imply that Venus and Earth received similar amounts of water from comets and bodies that formed in the vicinity of Jupiter (e.g., Rubie et al. 2015). Temperate surface conditions would represent an important evolutionary path for Venus because of the implications for habitability of ancient Venus and Venus-sized exoplanets at present day.

<u>3.1.1.1. Investigation I.A.HO. Hydrous Origins (Essential):</u> Water is important to the geologic evolution and potential habitability of Venus. Although liquid surface water is now unstable, its presence may have been required to form many rock types on Venus, such as granitic rocks suggested for some tesserae (e.g., Gilmore et al. 2017; Gilmore et al. 2015; Mueller et al. 2009). Formation of Earth's large granitic continents required water in magmatic source regions in the crust and mantle (e.g., Campbell and Taylor 1983). Similarly, some sedimentary rocks cannot form without liquid water, such as those rich in sulfate and halide (e.g., evaporites), silica (e.g., in hot spring deposits and hardpans), or carbonates. Even deposits of clastic sediments can preserve physical signatures of transport by liquid water (e.g., delta deposits observed from orbit on Mars).

Remote sensing and in situ analyses may reveal signatures of hydrous origins. Granites have lower visible near-infrared (VNIR) emissivity than basalts. This can be measured through several spectral 'windows' (near 1 μm) in Venus' thick atmosphere (Gilmore et al., 2015; Hashimoto and Sugita, 2003). Similarly, low emissivity may reveal sediments rich in evaporites, silica, or carbonates. Emissivity could be measured from orbit, aerial, or surface platforms. Physical characteristics of clastic sedimentary systems may be discernable from orbital or aerial radar with high spatial resolution. Landers can provide detailed determinations of rock type and physical inter-relationships using high-resolution imagers and chemical analysis instruments (e.g., x-ray fluorescence, gamma ray spectrometry, or LIBS). Landers could potentially remove surface coatings caused by chemical weathering to determine the detailed mineralogy of a Venus rock.

<u>3.1.1.2. Investigation I.A.RE. Recycling (Essential):</u> Crustal recycling occurs when surface and near-surface materials are transferred by subduction and/or delamination to the interior, participating in melt production and chemical evolution of the lower crust and mantle. Identification of widespread ongoing or ancient crustal recycling on Venus would have profound implications for our understanding of thermal, chemical, geological, and atmospheric evolution on Venus and on terrestrial planets in general (e.g., Elkins-Tanton et al., 2007). Localized plume-induced subduction has been proposed to operate on Venus (Davaille et al., 2017), and there is evidence of substantial lateral mobility of some parts of the crust. Crustal recycling is predicted to result in lavas with distinctive geochemical

signatures, and numerous regions of tesserae on Venus have been hypothesized to be continental-like material formed during an earlier era of crustal recycling (e.g., Gilmore et al., 2017; Gilmore et al., 2015). Currently available gravity, radar image, and topographic data are insufficient to determine whether these processes operate more widely and/or took place in the geological past.

No single type of observation by itself can definitively establish crustal recycling on Venus. Global radar images, topography, and gravity data at high resolution could help search for geomorphological evidence of crustal recycling, especially if augmented by imagery and topography at higher resolutions at areas of interest. In situ measurements by a landed platform of lava flows could test for chemical evidence for recycling (enrichment or depletion of incompatible elements such as K, P, Zr, rare-earth elements, etc.). Similarly, direct chemical analyses of Si abundance of tessera terrain would test if that material corresponds to Earth-like continental crust. Finally, detections of seismic activity on Venus with orbital, aerial, or landed assets may help constrain models of recent or ongoing crustal recycling.

3.1.1.3. Investigation I.A.AL. Atmospheric Losses (Important): Atmospheric loss processes on Venus provide the upper boundary condition for the evolution of its atmosphere. The high D/H ratio in Venus' atmosphere (~100 times that of Earth's oceans) suggests it may once have held an ocean's worth of water that has since been mostly lost to space (e.g., Donahue et al. 1982). Because the H escape velocity is too high for thermal or photochemical processes to attain non-thermal escape driven by the solar wind is the most important process for atmospheric loss today (e.g., Airapetian and Usmanov 2016; Brain et al. 2016; Chassefière 1996; Shizgal and Arkos 1996). Intense solar wind disturbances, such as those generated by co-rotating interaction regions (CIRs) and interplanetary coronal mass ejections (ICMEs), are known to increase atmospheric escape. Observations of Venus' ion outflow during solar disturbances show that the escape flux can increase by orders of magnitude, especially during ICME events (Luhmann et al., 2008). Additionally, changes in the interplanetary magnetic field (such as those associated with CIRs) lead to magnetic reconnection on the Venusian dayside that further drives atmospheric loss. Atmospheric loss via ambipolar diffusion always occurs and is much more efficient at Venus than at any other terrestrial planet (e.g., Collinson et al. 2016).

Despite insights from Pioneer Venus Orbiter (PVO) and VEX, these loss processes have not been sufficiently characterized. Simultaneous observations of both the upstream solar wind and the Venusian thermosphere and ionosphere over the full range of local times and solar zenith angles would build a more complete picture of atmospheric erosion, especially if acquired during solar minimum and maximum. Relevant instruments for this Investigation include but are not limited to electron spectrometers, ion mass spectrometers, neutral particle detectors, UV and visible spectrographs and imagers, solar energetic particle (SEP) detectors, Langmuir probes, and magnetometers. Some of these measurements could be conducted with dedicated spacecraft or opportunistic flyby instruments (e.g., multiple SmallSats). For example, these could be used to image dayglow, aurora, and sample plasma conditions from ~150 km out to several Venus radii at the Sun-Venus L1 Lagrange point, as well as the upstream solar wind environment.

3.1.1.4. Investigation I.A.MA. Magnetism (Targeted): Venus has no intrinsic magnetism today but might have once hosted a dynamo. Its rotation is fast enough for the

Coriolis force to affect any convective fluid flows in the core (e.g., Stevenson 2010). Detection of crustal remanent magnetism would show that a dynamo existed in the past and that the surface has remained cooler than the blocking temperatures of magnetic minerals. For example, simulations predict that if the core of Venus was initially "Earth-like" (hot and chemically homogeneous), then a dynamo might have operated <750 ma (Gillmann and Tackley, 2014; O'Rourke et al., 2018). Common magnetic minerals such as magnetite and hematite may retain thermoremanent magnetization for billions of years at Venus surface temperatures (O'Rourke et al., 2019). Data from PVO and VEX rule out crustal magnetization that is both strong and has typical coherence wavelengths >150 km northwards of 50° South latitude only (e.g., Russell et al. 2007). Venera 4 measured magnetic fields down to ~25 km altitude above Eistla Regio and failed to detect any crustal remanence.

Orbiters could still detect fields produced by strong, large-scale crustal magnetization southward of 50° South latitude. Magnetization that is relatively weak and coherent over >150 km and/or strong and coherent over smaller scales could exist anywhere on Venus except at the Venera 4 landing site. Magnetometer measurements at low altitudes, such as from an aerial platform, would be needed because magnetic field power decreases rapidly (as distance cubed) at altitudes above the coherence wavelength of the source magnetization. While a non-detection would permit multiple scenarios (e.g., no dynamo and/or a hotter surface in the past), this Investigation is Targeted because any detection of crustal remanent magnetization would provide a unique constraint on atmospheric loss processes and recent climate history.

3.1.2. ***Objective I.B. | How does Venus elucidate possible pathways for planetary evolution in general?*** Only two Venus-sized planets made of rock and metal exist in our Solar System, but myriad examples of Venus-sized exoplanets are being discovered and characterized with new telescopes (e.g., Kane et al. 2014; Schaefer and Fegley 2011). Our general model for the long-term evolution of terrestrial exoplanets cannot rest on a foundation of fundamental ignorance about Earth and Venus. While Objective I.A. focused on a uniquely compelling evolutionary scenario, the following Investigations consider many possibilities (e.g., Glaze et al. 2018; Taylor et al. 2018).

3.1.2.1. Investigation I.B.IS. Isotopes (Essential): The isotopic composition of Venus' atmosphere should preserve significant clues to the accretion, differentiation, and early evolution of the planet (e.g., Chassefière et al. 2012). Interpretation of the D/H ratio has substantial uncertainties at present (e.g., Greenwood et al. 2018). Other atmospheric constituents such as N, C, Cl, and the heavy noble gases constrain the abundances, sources, and compositions of volatiles in Venus' early atmospheres. The isotopic compositions of these gases will help define the sources of Venus' volatiles (e.g., comets versus asteroids) and the extent to which they were affected by atmospheric loss processes, surface and interior outgassing, and (more speculatively) active biology. Xenon is critical to measure because the terrestrial planets appear to have tapped distinct sources (e.g., Pepin and Porcelli 2002). The same processes that produced the high D/H ratio on Venus may have depleted atmospheric Xe. In the mantle, radioactive decay of ^{40}K produces ^{40}Ar and decay of U and Th produces ^{4}He. Measurements of atmospheric ^{40}Ar and ^{4}He thus constrain the integrated amount of volcanic outgassing from the interior (e.g., Kaula 1999; Namiki and Solomon 1998). Oxygen isotopes could reveal whether Venus and Earth formed from the same reservoir of material. A finding of similar isotopic ratios for Earth and Venus versus

Mars would relax a key constraint on models of the origin of the Moon (e.g., Mastrobuono-Battisti et al. 2015).

Mass spectrometer measurements of atmospheric constituents are required to fulfill this Investigation. Analyses of material from deeper than the homopause, where the atmosphere is well-mixed, would be most useful (Chassefière et al., 2012). Any asset that enters the atmosphere—aerial platforms or atmospheric skimmers, probes and landers with heritage from Pioneer Venus or Venera/Venera Galley (VeGa), respectively—could potentially deploy a useful mass spectrometer.

3.1.2.2. Investigation I.B.LI. Lithosphere (Essential): Venus shows no evidence for the global regime of plate tectonics observed on Earth, implying that the lithosphere of Venus does not sustain localized deformation over long spatial and temporal scales. The current dynamical regime of Venus—whether it involves stagnant-lid convection, heat pipes, episodic overturns, or another mode of mantle convection—remains poorly understood (e.g., Smrekar et al. 2018). Determining key lithospheric parameters is considered an Essential Investigation because the lithosphere provides the upper boundary condition for mantle convection and links interior activity with surface observables.

High-resolution radar imagery and altimetry with global coverage would constrain lithospheric rheology through quantitative analyses of stress states, tectonic faulting, and volcanism. Electromagnetic sounding could determine whether the water content of the lithosphere is more or less than a few hundred parts per million (Grimm et al., 2012). These datasets would constrain models of processes that support topography. Elastic thicknesses would be retrieved by modeling admittance and/or flexural bending seen in topography. Mechanical thicknesses would then be derived and thus used to estimate the thermal gradient in the lithosphere that prevailed when elastic flexure first occurred. Existing estimates of elastic thickness from gravity data often have large uncertainties due to the limited accuracy and resolution of the present gravity field (e.g., Anderson and Smrekar 2006). Values from modeling topographic bending are currently limited to a small subset of volcanoes and coronae where flexure can be observed (e.g., Johnson and Sandwell 1994; O'Rourke and Smrekar 2018). Finally, seismology conducted from orbital, aerial, and/or landed platforms could determine the physical structure and deformation processes of the lithosphere (e.g., Cutts et al. 2018).

3.1.2.3. Investigation I.B.HF. Heat Flow (Important): Although models of mantle convection often predict that total heat flow through the lithosphere to the surface of Venus is roughly half of the measured value for Earth (Armann and Tackley, 2012; Driscoll and Bercovici, 2014; Gillmann and Tackley, 2014), these models remain unvalidated by direct observations. Measuring the lithospheric heat flow (e.g., thermal gradient times conductivity) would help evaluate models of interior convection. This Investigation is a benchmark for models of geodynamic evolution in synergy with other constraints.

In-situ measurements would provide the highest-quality heat flow measurements if the seasonal/daily temperature variation is quantified through coupled studies of surface brightness temperature. Selecting targeted locations that enable meaningful comparisons with models of mantle convection requires understanding the geologic history and relative ages of surface units. Electromagnetic sounding conducted from an aerial platform could determine lithospheric thermal gradients over larger areas (Grimm et al., 2012). Lightning-caused Schumann resonances are capable of penetrating to depths of ~50–100 km if the lithospheric water content is less than a few hundred parts per million. Retrieving thermal gradients in shallow regions is potentially tractable even if the lithosphere is relatively wet. Any measurement of present-day heat flow and thermal structure would complement constraints on past heat flow from elastic thickness measurements.

3.2.1.4. Investigation I.B.CO. Core (Important): The size and physical state of the core place key constraints on models of the thermal evolution of Venus. Energy from giant impacts (kinetic) and rapid accretion (gravitational) is expected to produce a completely molten core initially. The relative sizes of the silicate mantle and the metallic core constrain their compositions and the thermodynamic conditions of accretion through the abundance of light elements (e.g., silicon and oxygen) in the core (e.g., Rubie et al. 2015; Jacobson et al. 2017). Two basic measurements of Venus are lacking: its total moment of inertia and the radius of the core (e.g., Smrekar et al. 2018). Existing measurements of the tidal Love number also are arguably too imprecise to distinguish between a partially liquid core and one that has finished solidifying (Dumoulin et al., 2017).

Orbiters with modern radio tracking would provide improved measurements of the tidal Love number with the required precision. The moment of inertia of Venus may be constrained even without spacecraft missions. Simultaneous observations of radar echoes with the Goldstone Solar System Radar and the Green Bank Telescope allow measurement of the instantaneous spin orientation of Venus. Tracking the instantaneous spin orientation over years and decades enables a measurement of the moment of inertia. As planned for the NASA InSight mission on Mars, a single station with radio science may measure the radius of the core given a sufficient lifetime.

3.2. Goal II: Understand atmospheric dynamics and composition on Venus

The atmosphere of Venus is a planet-sized heat engine. Energy deposition and the efficiency with which that energy is distributed throughout the planet are key constraints on potential habitability. For Earth, a fleet of in situ and orbital platforms builds the complete, four-dimensional picture of atmospheric evolution. These Investigations divide the atmosphere of Venus into altitude-based areas, but these areas ultimately remain coupled in a planetary system.

3.1.1. Objective II.A. | What processes drive the global atmospheric dynamics of Venus?

Many fundamental atmospheric characteristics of Venus are poorly understood, including the global cloud cover and retrograde zonal super-rotation (RZS). Winds on Venus flow primarily from east to west at almost all altitudes below ~85 km. Wind speeds reach a peak in magnitude just above the cloud tops. Above ~75 km altitude, winds transition to a subsolar to antisolar (SSAS) flow, before transitioning back to RZS in the upper thermosphere (Sánchez-Lavega et al., 2017).

3.1.1.1. Investigation II.A.DD. Deep Dynamics (Essential): The super-rotation of Venus' atmosphere has been known from cloud top observations since the early 20th Century. Full understanding of the RZS structure and mechanisms for its maintenance remains elusive. Variability in the form of zonal jets has been inferred from Akatsuki observations. Global-scale waves observed by Akatsuki's Longwave Infrared camera are tied to the crests of continent-sized land masses and recur regularly at similar times-of-day (Fukuhara et al., 2017; Kouyama et al., 2017). Similar waves may have been seen by the VeGa balloons near the dawn terminator while flying over Aphrodite Terra (Blamont et al., 1986). These orographic waves demonstrate the importance of surface-atmosphere interactions for the dynamics of Venus and its atmosphere. Generation and dissipation of the orographic waves has been inferred to produce measurable changes in the rotation rate of the solid planet, and to affect solar-atmosphere interactions even in the deep atmosphere (Navarro et al., 2018). Understanding RZS will be a milestone advance for atmospheric sciences in general, and provide tests of exotic behavior in models of exoplanetary atmospheres.

The deep atmosphere of Venus is defined in this context to be the portion of the atmosphere that is beneath the cloud tops, i.e., below ~75 km altitude. This Investigation is Essential because a critical transition in atmospheric dynamics occurs here, according to measurements of wind speed and temperature. Almost nothing is known about atmospheric composition and dynamics very near the surface (below 22 km). Above ~75 km altitude, the primary means of data acquisition would most likely come from an orbital platform. Below this altitude, measurements should be possible from both in situ and remote platforms. Simultaneous observations of radar echoes with the Goldstone Solar System Radar and the Green Bank Telescope allow measurement of the instantaneous spin period of Venus, which was not achieved with either Magellan or Venus Express. Tracking the instantaneous length-of-day provides a time history of variations in atmospheric angular momentum that can be used to constrain global circulation models.

3.1.1.2. Investigation II.A.UD. Upper Dynamics (Essential): The RZS must also be understood at planetary scales. RZS flow loses strength in the upper mesosphere, so SSAS flow dominates near 100 km. However, RZS flow becomes prevalent again in the thermosphere for unknown reasons (e.g., Gérard et al. 2017). Flow dynamics in the thermosphere can be constrained through observations of nightglow and auroral emission. One of the brightest Venusian nightglow features is the 1.27 µm O_2 ($^1\Delta_g$) emission, which is strongest at ~99 km elevation near the antisolar point. VEX observations show that this nightglow follows the SSAS flow. However, simultaneous observations of O_2 ($^1\Delta_g$) and the NO UV bands (~115 km elevation) reveal that the NO bands are shifted three hours away from local midnight towards the dawn sector, indicating a recurrence of the RZS flow between those elevations (Gérard et al., 2009; Stiepen et al., 2013). Auroral OI emission (at 130.4 nm) is also offset towards the dawn sector (Phillips et al., 1986). Offsets are expected between the OI UV emission and the OI auroral emission that is present during solar storms, but no spatial mapping has been conducted.

Recent studies suggest that the ionosphere and neutral atmosphere are more intimately connected than previously believed (e.g., Futaana et al. 2017). Measurements are needed of auroral and other excited gas emissions driven by solar processes as well as by the solar wind in order to understand the connections between the solar wind and the Venusian atmosphere. Instruments needed to study the Venusian atmosphere and the solar wind via remote sensing and in-situ measurements include but are not limited to electron spectrometers, ion mass analyzers, ion and neutral mass spectrometers, energetic neutral atom detectors, UV and visible spectrographs and imagers, SEP detectors, Langmuir probes, and magnetometers.

3.1.1.3. Investigation II.A.MP. Mesoscale Processes (Important): The previous two Investigations target global scale processes and observations according to vertical spatial domain (above and below an altitude of ~75 km). Investigation of processes at smaller scales (mesoscale) is important because they drive planetary atmosphere dynamics at both larger and smaller scales. Adequate general circulation models of a planetary atmosphere must include reliable parameterizations of these "sub-grid-scale" processes, mandating new observational constraints from Venus.

Critical mesoscale processes include the behavior and evolution of convective cells, horizontal and vertical wave propagation, and other mesoscale structures. These processes can be observed from orbit, as demonstrated by the discovery of numerous mesoscale features in both Venus Express and Akatsuki data (Peralta et al., 2019, 2017). The rate and global distribution of lightning is a proxy for a certain rate of convective activity that is necessary to drive charge exchange (Takahashi et al., 2008). Direct in-situ measurement of the local dynamics of isolated convective structures and/or wave propagation would also contribute to this Investigation. However, degeneracies between spatial and temporal variations would remain—as are present in the meteorological data from the VeGa balloons—in the absence of simultaneous measurements from orbiters and aerial platforms.

3.1.2. Objective II.B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance? The atmosphere of Venus is a coupled chemical, radiative, and dynamical system. The composition and evolution of the atmospheric constituents are strongly regulated by chemical processes in the highly complicated, sulfur-based chemical networks. Yet, significant questions remain regarding the identities and/or the sources and sinks for many of these constituents.

3.1.2.1. Investigation II.B.RB. Radiative Balance (Essential): Gradients in the upwelling and downwelling radiative fluxes, in both incident solar and emitted planetary radiations, determine the heating/cooling rates that drive atmospheric dynamics. These gradients are determined by absorbers and scatterers of both shortwave and longwave radiation that are distributed throughout the atmosphere, which are involved in a variety of physical and chemical interactions. Although the local radiative balance has been measured many times to reasonable precision (e.g., Pioneer Venus, Venera, and VeGa missions), a mismatch remains between the measured radiative and dynamical parameters of the Venus atmosphere and those produced by models (Crisp, 1989; Limaye et al., 2018a). What is the magnitude of the influence of variability of the numerous radiatively active species, and cloud microphysics and opacity on the radiative balance of Venus? To what extent does this distribution of radiative sources and sinks drive the tropospheric dynamics?

Direct, in-situ measurement of spectrally resolved (or integrated) upwelling and downwelling radiances on both the nightside and dayside can support this Investigation. Probes, landers, and/or mobile aerial platforms could make relevant measurements. The utility of these measurements increases substantially with the number and lifetimes of platforms, and with global context. High spectral resolution, full spectrum measurements of emitted and reflected radiation would substantially contribute to this Investigation. Orbital assessments of radiative balance would benefit from improving the foundational models of atmospheric constituents.

3.2.2.2. Investigation II.B.IN. Interactions (Essential): Constituents of the atmosphere of Venus comprise a highly coupled system involving sulfur and carbon chemistry, aerosol microphysics, and possibly even biological activity. Agreement between chemical models of the Venus atmosphere and observed vertical profiles of multiple participating constituents is necessary for constraining models of radiative balance and atmospheric evolution. Examples of unresolved questions include the relative roles of OCS and SO_2 as sulfur donors to the sulfurohydrologic cycle of sulfuric acid generation, as well as the role of H_2O in that process (Marcq et al., 2018). Photochemistry and thermochemistry in Venus' atmosphere are quite dissimilar to those on Earth, and have not been fully explored in the lab. Finally, the chemistry of supercritical CO_2 in the deep atmosphere remains unexplored, though recent research suggests it may explain why the temperature profile measured by the VeGa probe is stable against convection in the lowermost atmosphere (Lebonnois and Schubert, 2017).

An orbiter capable of acquiring high spectral resolution measurements across a broad wavelength region and retrieving high precision vertical profiles of chemically relevant species could make substantial progress towards achieving this Investigation, especially when coupled with improved models of atmospheric chemistry in the Venus environment. In situ aerial platforms could make substantial progress on understanding the aqueous chemistry, as has been done for Earth. Lightning has been mapped on the nightside. Statistical assessments of the presence and distribution of lightning, mapped on the nightside by Pioneer Venus and at polar latitudes by Venus Express in the Venus atmosphere, would constrain the effects of lightning discharges on atmospheric constituents. Finally, landers and descent probes capable of simultaneously measuring meteorological parameters and the mixing ratio of CO_2 (and other species) in the lowest ~10 km could study supercritical CO_2.

3.2.2.3. Investigation II.B.AE. Aerosols (Important): This Investigation studies the impact of aerosols on the Venus greenhouse effect, as well as on its remotely observable properties. Aerosols are an integral part of the atmospheric chemical system as both active and passive constituents (Titov et al., 2018). Spherical particles of highly concentrated sulfuric acid with typical radii of 1 μm are the primary aerosol in the upper clouds, but the exact nature of Venusian aerosols is incompletely known. A submicron mode of particles is known to exist in and below the upper, middle, and lower clouds, but its size distribution at all altitudes remains poorly constrained. In the upper clouds, the composition of aerosol particles has been assumed but never proved to be sulfuric acid. In and below the lower and middle clouds, the composition of this submicron aerosol mode remains similarly unknown. Finally, particles with the largest inferred sizes remain controversial. Their night-side, near-infrared inhomogeneities are attributed largely to variations in the Mode 3 population, but their existence remains unconfirmed and their composition unknown (Barstow et al., 2012; Knollenberg and Hunten, 1980).

In-situ nephelometer and mass spectroscopy of cloud aerosols would reduce uncertainties in aerosol size distributions and compositions. Observations at altitudes throughout the cloud column are key because different populations of aerosols occur at different altitudes.

3.2.2.4. Investigation II.B.UA. Unknown Absorber (Important): Short-wavelength visible and near-ultraviolet light are unaccountably absorbed in Venus' upper atmosphere. The effects of this unknown absorber are strongest in the near-ultraviolet, but are apparent well into at least the wavelengths of visible light. The unknown absorber varies in strength over space and over a wide range of timescales. The unknown absorber is responsible for at least half of the deposition of solar insolation into the atmosphere (Crisp, 1986).

Numerous candidate absorbers have been proposed, including sulfur allotropes (S_x), iron chlorides ($FeCl_3$), and OSSO and its isomers. The unknown absorber might not be a single species because OSSO does not absorb enough near 400 nm to match observations. A biological origin for the unknown absorber in the "habitable zone" of the atmosphere has been suggested by comparison to the spectral properties of terrestrial acidophilic organisms (e.g., Limaye et al. 2018b).

Mass spectrometry of atmospheric material in the region of the unknown absorber is the measurement most likely to accomplish this Investigation. The platform most appropriate to carry this mass spectrometer is likely a descent probe, or aerial platform. In addition, high-resolution spectroscopy from orbit or from an aerial platform can contribute to the investigation. In general, synergistic measurements from multiple platforms are desired.

3.2.2.5. Investigation II.B.OG. Outgassing (Targeted): This Investigation will determine whether volcanic outgassing affects atmospheric composition, which might provide insights into crustal composition and internal structure and dynamics. Indirect observations hint that Venus is volcanically active today. Overall, the surface has a young average age of ~750 Myr and hosts myriad volcanic surface features (Smrekar et al., 2018). Transient and high concentrations of SO_2 in the atmosphere and thermal anomalies on the surface have also pointed to currently active volcanism (e.g., Esposito et al. 1988). Massive H_2SO_4/H_2O clouds are most likely the products of volcanic outgassing of SO_2 in the past ~10–50 Myr (Bullock and Grinspoon, 2001). The VIRTIS instrument on VEX measured near-IR surface emissivity anomalies interpreted as a lack of surface weathering at fresh volcanic flows on and near several massive shield volcanoes (Smrekar et al., 2010).

Direct imaging of hot spot volcanism and volcanic lakes at near-IR wavelengths and SAR interferometry from orbit would characterize the ongoing rate of volcanism on Venus. Direct monitoring of heat from volcanic activity remains a viable, low-risk method to detect the 'smoking gun' of active volcanism on Venus. Spectroscopic remote sensing of transient gases in a volcanic plume (SO_2, H_2O) has also been suggested as an indirect means of sensing volcanic activity and outgassing. Aerial platform measurements acquired from beneath the clouds could be used to confirm the nature of events detected from orbited in images with five orders of magnitude better spatial resolution. In situ chemical measurements, including light isotope abundances, could help constrain the composition of outgassed materials.

3.3. Goal III: Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

Unveiling the past requires understanding the present. Although previous missions provided the first glimpses of the Venusian surface, many first-order questions regarding their interpretation and implications await answers, which motivates collecting higher-resolution imagery, topography, and many other datasets that are available for other terrestrial planets.

3.3.1. Objective III.A. | What geologic processes have shaped the surface of Venus? Since the Magellan mission, models for the geologic history of the surface have been spread between catastrophic and uniformitarian end-member scenarios. Moving beyond this controversy requires answering many basic questions about the present-day surface, including its stratigraphic history, composition, and potential for ongoing geologic activity.

3.3.1.1. Investigation III.A.GH. Geologic History (Essential): Developing a stratigraphic history for the sequence of geological events on Venus is crucial to provide a framework for understanding the processes that shaped the coupled evolution of the surface, interior, and atmosphere (e.g., Guest and Stofan 1999; Hansen and Lopez 2010; Ivanov and Head 2013; Ivanov and Head 2011; McGill 2004; Strom et al. 1994). Volcanism and tectonism are ultimately driven by processes in the interior of Venus, and volcanism also contributes to development of the atmosphere. Similarly, the history of tectonic activity constrains the style and temporal evolution of convection in the mantle. In addition, a stratigraphic history for Venus would facilitate comparisons with other terrestrial planets.

Key data sets for this Investigation are high-resolution radar imagery and topography. Magellan provided near global radar imaging at ~120–300 m/pixel and altimetry at ~8–25 km/pixel. Ideally, a follow-up mission would provide order-of-magnitude improvement in resolution in both radar images and altimetry. Global imaging coverage is desired to fully picture Venus' geologic evolution. A targeted survey could focus on mapping at high spatial resolution highland regions with obvious tectonic or volcanic features plus a representative fraction of the regional plains. The signal-to-noise ratio should be sufficiently large to detect variability that may be present in the radar dark plains. Infrared imaging of selected regions at relatively high spatial resolution from a variable altitude aerial platform, deployed below the cloud deck, would be complementary to the greater spatial coverage possible from an orbiter.

3.3.1.2. Investigation III.A.GC. Geochemistry (Essential): The surface chemistry and mineralogy of Venus remain poorly characterized. Chemical analyses provided by the Venera and VeGa missions, although they were engineering and scientific triumphs, do not permit detailed interpretations like those from rover analyses on Mars (e.g., Treiman 2007). In particular, Soviet x-ray fluorescence (XRF) analyses of major elements did not return abundances of Na, and their data on Mg and Al are little more than detections at the ~2σ level. Data for K, U, and Th (by gamma rays) are imprecise, except for one (Venera 8) with extremely high K contents (~4% K_2O) and one (Venera 9) with a non-chondritic U/Th abundance ratio. The landers did not return data on other critical trace and minor elements, like Cr and Ni. In addition, the Venera and VeGa landers sampled only materials from the Venus lowlands. Given all these ambiguous results, rock types that may indicate igneous provenance cannot be identified (e.g., Grimm and Hess 1997; Treiman 2007). Similarly, no information is currently available to identify Venus mineralogy (Gilmore et al., 2017).

3.3.1.3. Investigation III.A.GA. Geologic Activity (Essential): The relatively young surface age of Venus implies that Venus is geologically active. Key data sets are radar imaging and topography as well as seismic measurements (e.g., Smrekar et al. 2018). Comparison of radar imagery and altimetry from a future orbital mission with archival data from Magellan could detect surface changes over a period of several decades. Differential InSAR altimetry from a future orbiter could detect small topographic changes (≤10 cm vertically) due to active tectonism or volcanism that occur over the timescale of that orbiter mission. Seismic measurements via a long-lived lander of seismicity induced by active tectonism or volcanism would also be invaluable. Measurements by a single lander would be sufficient to detect such activity, but measurements by a network would enable more quantitative analysis of the activity. Because the rate of such activity is not known, this approach is enhanced by increasing the duration of seismic measurements. As demonstrated by Venus Express, fresh flows (i.e., with little chemical weathering) are observable with NIR spectroscopy from orbit (e.g., Shalygin et al. 2015; Smrekar et al. 2010). Experiments suggest these flows may be only years old.

Several types of supporting measurements also are possible. Coupling of surface motion into the thick Venus atmosphere can propagate pressure waves into the upper atmosphere that are detectable in high temporal resolution infrared images from orbit or by infrasound measurements from an aerial platform (e.g., Cutts et al. 2018; Stevenson et al. 2015). Volcanic flows temporarily raise the surface temperature, which could be measured by infrared or microwave radiometry. Observing this thermal signature is easiest for flows with high flux rates, which prevent the flow from crusting over. Outgassing associated with large explosive volcanic eruptions may temporarily create a disequilibrium in the atmospheric composition which could be measured by orbiters, atmospheric entry probes or sondes, and/or aerial platforms.

3.3.1.4. Investigation III.A.CR. Crust (Important): The crust of Venus has at least partially recorded the last billion years or so of tectonic and volcanic activity on the planet. Crustal thickness can constrain the total amount of magmatism, and variations related to location of more ancient materials like tessera or more recent units like rift zones can help quantify activity outside of the resurfacing event (e.g., Anderson and Smrekar 2006; James et al. 2013). Information about the structure of the crust, including the thickness of plains units and the penetration of faults at depth, are also crucial for reconstructing the history of geological activity on Venus and how it may have changed over time. Timing and volume of volcanic flows (e.g, Ivanov and Head 2013) and their interactions with impact craters (e.g., Herrick and Rumpf 2011; Strom et al. 1994) would constrain whether volatiles were released gradually or catastrophically from the interior.

Global radar images, topography, and gravity data collected by orbiters and/or aerial platforms at high precision and resolution would constrain the thickness and density structure of crustal units such as regional plains and volcanic flows. Improving the spatial resolution of global geological maps by one or more orders-of-magnitude would enable the delineation of individual lava flows, mapping individual fault blocks, and characterizing geologic contacts between volcanic and structural units, fundamentally transforming our understanding of volcanic and tectonic processes on Venus. Radar data in circular polarizations, as done by Arecibo and other planetary radars, would help quantify the thickness and grainsize of surface materials (e.g., volcanic deposits versus ejecta and/or regolith). Other geophysical techniques such as ground-penetrating radar (from orbital or aerial platforms) and seismology (from a surface instrument or detected in the atmosphere, which is strongly coupled to the ground) would provide strong constraints on the thickness and distribution of near-surface units on Venus.

3.2.3. Objective III.B. | How do the atmosphere and surface of Venus interact?

Temperatures of ~470°C and pressures ~90 bars near the surface ensure geologically rapid chemical reactions. Available data suggest that the deep atmosphere composition is not consistent with chemical equilibrium. However, significant uncertainties remain in the reactions that occur at the atmosphere-surface interface, the redox state of the atmosphere-surface boundary, and the concentrations and spatial variations of important trace gases near the surface.

3.2.3.1. Investigation III.B.LW. Local Weathering (Essential): The history of gas/fluid interactions between Venus' hot, dense CO_2-rich atmosphere and its surface materials is recorded in the minerals that have experienced such alteration. Laboratory and phase equilibria studies predict oxidation of primary igneous minerals to ferric oxides such as magnetite and hematite (e.g., Fegley et al. 1997; Zolotov 2018; Zolotov 2015). This investigation would search for the presence of anhydrous salt minerals such as anhydrite and possible presence of alteration phases from basaltic minerals. This would involve in situ instruments for mineralogy, including visible-mid-IR and Raman spectroscopies. Penetrating beneath surface alteration could provide valuable information on the depth of alteration and the underlying mineralogy.

3.2.3.2. Investigation III.B.GW. Global Weathering (Important): Among the most striking findings of the Magellan mission was the discovery of great differences in radar backscatter brightness with elevation (e.g., Pettengill et al. 1997): the highlands are significantly brighter than the lowlands. However, approaches to identifying candidate substances responsible for this dichotomy (e.g., Schaefer and Fegley 2004) depend on the assumed surface geochemistry and oxidation states, which are poorly known (e.g., Treiman 2007). Possible Investigations to resolve these questions are two-fold. Orbital spectroscopy utilizing the windows in the ~1 μm region may allow discrimination among key rock types (e.g., basalt vs. granite) and can distinguish among minerals responsible for radar backscatter variations with elevation, such as magnetite hematite, and pyrite (Gilmore et al., 2017). Surface mineralogy could also be measured using in situ visible-mid-IR spectroscopy, X-ray diffraction, and Raman Spectroscopy, while Mössbauer spectroscopy could measure oxidation state. Measurements of the near-surface atmosphere would also inform the state of surface-atmosphere equilibrium.

3.2.3.3. Investigation III.B.CI. Chemical Interactions (Targeted): It is important to determine the abundances of crucial species (e.g. CO, OCS, SO_2) in the lowest atmospheric scale height, where surface-atmosphere interactions occur (Gilmore et al., 2017; Zolotov, 2018). Inferences about their near-surface concentrations have previously been made through extrapolation of their observed higher elevation concentrations (e.g., Arney et al. 2014) and through model predictions (e.g., Fegley and Treiman 1992), which also suggest several possible atmospheric reaction products. Because the average Venus atmosphere is oxidized compared to basaltic rock, surface chemistry should produce reduced gas species, like CO from CO_2, and SO_2 or S_2 from SO_3. Oxygen fugacity (fO_2) is also directly linked to surface equilibrium chemistry through these variables and is poorly constrained for Venus. Data from Venera landing sites indicate that some Venusian surface materials may be enriched in S relative to Earth basalts, suggesting processes of sulfur-based basaltic weathering. SO_3 in the atmosphere may react with Ca-bearing silicates to form $CaSO_4$ (anhydrite) thus reducing the proportion of atmospheric sulfate (Barsukov et al., 1982). Atmospheric halogens could exchange with the surface, perhaps reducing the Cl/F ratio by formation of Cl-bearing phosphate phases. If Venus' volcanic rocks include hydroxy-bearing igneous minerals (such as amphibole or biotite), then their decomposition should release hydrogen (with D/H values of the interior) to the atmosphere.

In-situ direct measurements of the deep Venus atmosphere would provide clarity to questions of the concentrations and distributions of gases whose lowest scale height concentrations have only been inferred. This Investigation could be accomplished via landers or descent probes with suitably designed mass spectrometers. Determining gradients on a regional scale would be enabled by orbital or aerial platforms carrying high-spectral-resolution spectrometers. Interpretation of these deep atmosphere spectra would be improved by better laboratory and/or theoretical estimates of the effects of pressure broadening on the specific line widths and strengths relevant to the Venus lower atmosphere. Experiments at the relevant temperature and pressure of the Venusian surface could answer questions of which surface-atmosphere chemical reactions are plausible explanations for observed gas concentrations.

4.0. Conclusions

Many fundamental questions about the origin and evolution of Venus await answers. Venus could have maintained a habitable environment with liquid water oceans for billions of years, and detectable signatures of this ancient epoch could await discovery by new missions. The rapid rate of ongoing discoveries of Venus-sized exoplanets makes unveiling Venus especially pressing, given that many more exoplanets may soon be amenable to atmospheric characterization. After a year-long process featuring a plethora of forums for community feedback, VEXAG has prepared this report centered on three Goals, six Objectives, and 23 Investigations that could drive a sustained program of Venus exploration. Dramatic advances in our scientific understanding of Venus and other terrestrial planets are achievable within the next few decades if we can muster the collective will to explore Venus.

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Appendix A: Future Investigations

All Investigations in Table 1 were judged to have very high scientific merit along with feasibility in terms of technology and mission opportunities within the designated time period of these reports (i.e., within a few decades). Thus, this report does not include potential Investigations that may have very high scientific merit but relatively low feasibility. In particular, two Investigations were considered but judged to require resources substantially beyond the Flagship mission class and/or technology development outside the scope of these reports. We provide their descriptions as examples of the types of science that would be become achievable beyond the next decade after a program of Venus exploration has advanced:

Example Investigation III.A.AA. Absolute Ages

In the absolute sense, nothing is known about the surface age of rocks on Venus' surface. Although impact ages suggest the surface may be quite young (McKinnon et al., 1997), the possibility remains that some units might date from a time when Venus was habitable (Gilmore et al., 2017; Hansen and Lopez, 2010). Technology for in situ age dating is rapidly evolving, as evidenced by the success of the Sample Analyzer at Mars (SAM) instrument on Mars Science Laboratory. A long-term goal of the Venus Exploration Program is to obtain analogous in situ measurements of multiple locations on the surface. Current technology in development for this purpose includes SAM-like instruments and other solutions using high resolution Laser induced breakdown Spectroscopy (LIBS). The latter method measures the emission spectra of molecules and molecular ions, enabling identification of specific isotopes within the plasma plume. Because sample preparation is not needed, LIBS provides a viable solution for Venus exploration.

Example Investigation I.B.DS. Deep Structure

Decades of study have revealed heterogeneous structure within Earth such as mantle plumes, laterally varying depths of seismic velocity discontinuities associated with mantle phase transitions, large low shear velocity provinces, and ultra-low velocity zones in the mantle (e.g., French and Romanowicz 2015; Hernlund and McNamara 2015). Seismology has also revealed hints of slow layers at the top and bottom of the liquid, outer core (e.g., Adam and Romanowicz 2015; Garnero et al. 1993). This structure reflects thermal and/or compositional variations that constrain planetary accretion, differentiation, and ongoing processes. Considerable investment and technological development would be required to return Earth-quality seismic data from Venus. However, many signatures of important dynamical processes are likely buried in the deep interior. Excitingly, True Polar Wander (TPW) may occur quite rapidly on Venus relative to Earth and Mars because the equatorial bulge in the solid body is tiny and provides little obstacle to rotational realignment. Mantle convection (or, more detectable, large volcanic eruptions) could provide enough mass redistribution to provoke an episode of TPW.

Orbiter missions that conduct radar imaging with long temporal baseline could track the motion of surface features associated with TPW (e.g., at rates of ~1 m per year). Obtaining detailed constraints on plume structure, mantle seismic discontinuities, and chemical stratification in the lower mantle and core would require a global network of long-lived surface platforms.

Appendix B: Linking the 2019 and 2016 VEXAG GOI Documents

The following table illustrates the connections between the Investigations in this document and previous versions. Overall, items in the GOI have been reworded and reorganized but the overall scientific content remains mostly unchanged. Removing the relative prioritization of Objectives and Investigations is perhaps the most impactful difference between this document and previous versions. Because so many pressing questions about Venus await answers, it is accurate to describe multiple Investigations as having the highest level of scientific priority.

Table A2.1. Investigations in the 2019 and 2016 VEXAG GOI

Note that Objectives and Investigations were prioritized in the 2016 GOI. Investigations in the 2019 GOI are categorized but not prioritized within each category. For example, Investigations I.A.HO. and I.B.IS. have equal (highest) priority in this 2019 GOI.	
Investigation in 2019 GOI	**Related Investigation(s) in 2016 GOI**
I.A.HO. Hydrous Origins (1)	III.A.2. III.A.3.
I.A.RE. Recycling (1)	II.A.3.
I.A.AL. Atmospheric Losses (2)	I.A.2.
I.A.MA. Magnetism (3)	II.A.3.
I.B.IS. Isotopes (1)	I.A.1. I.A.2. II.A.2. III.A.1. III.B.1. III.B.4.
I.B.LI. Lithosphere (1)	II.A.3.
I.B.HF. Heat Flow (2)	
I.B.CO. Core (2)	II.B.4.
II.A.DD. Deep Dynamics (1)	I.B.1. I.B.3. I.C.1.
II.A.UD. Upper Dynamics (1)	I.B.1. I.B.3.
II.A.MP. Mesoscale Processes (2)	I.B.1. I.B.3. I.C.1.
II.B.RB. Radiative Balance (1)	I.B.2.
II.B.IN. Interactions (1)	I.C.1.
II.B.AE. Aerosols (2)	I.C.1. I.C.2. I.C.3.
II.B.UA. Unknown Absorber (2)	I.C.2. I.C.4.
II.B.OG. Outgassing (3)	III.B.4.
III.A.GH. Geologic History (1)	II.A.1. II.B.6.

III.A.GC. Geochemistry (1)	II.B.1. II.B.2. II.B.5.
III.A.GA. Geologic Activity (2)	II.A.4.
III.A.CR. Crust (2)	II.B.3. II.B.6.
III.B.LW. Local Weathering (1)	III.B.2.
III.B.GW. Global Weathering (2)	III.B.2.
III.B.CI. Chemical Interactions (3)	III.B.3.

Appendix C: Linking the 2019 VEXAG GOI and Roadmap

The VEXAG "Roadmap for Venus Exploration" describes a program of Venus exploration featuring twelve mission modalities. The following tables define each modality and indicate those that are potentially useful to each Investigation. Because the VEXAG GOI is not designed to prescribe particular missions, the omnibus table is only intended as a general guide.

Table C.1

Platform Type/ Subtype Time Frame	**Description of platform and primary scientific objectives**
ORBITER	**Supports Investigations from orbital vantage points optimized for the scientific objectives**
Surface/Interior Near-term	Single spacecraft in a circular, low altitude, near polar orbit optimized for most Investigations of the surface and interior including those involving radar imaging and topography, infrared mapping, and gravity.
Atmosphere/Ionosphere Near-term	Single spacecraft in an eccentric, long-period orbit optimized for atmospheric remote sensing (e.g., nadir and limb viewing) and in situ sensors of the ionosphere and induced magnetosphere.
SmallSat or CubeSat Near-term	Single or multiple spacecraft focused on highly targeted Investigations requiring tailored orbits. May also provide relay, navigation support, and synergistic science for surface and aerial platform(s).
ATMOSPHERIC ENTRY	**Supports experiments during a traverse or descent in the Venus atmosphere**
Skimmer Near-term	Skims the atmosphere, sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay.
Probe Near-term	Enters the atmosphere and descends to the surface but not designed to operate after impact. Would investigate atmospheric structure and compositions along a single profile as well as near-surface imaging.
Sonde Mid-term	Deploys from an aerial platform that is already at the operational altitude. Sonde relays data through the aerial platform as it descends. Advanced versions could target surface features.
SURFACE PLATFORM	**Supports experiments on the surface of Venus in the high temperature high pressure environments**
Short-Lived Near-term	Classic (e.g., Venera) lander capable of surviving on the surface for several hours. Various instruments could investigate elemental and mineral compositions of nearby rocks, including variations with depth.
Long-Lived, Pathfinder Mid-term	Designed to operate for at least one Venus solar day (≥117 Earth days) on the surface. Measurements include temperature, wind velocity, and chemistry of major species and possibly demonstration of a seismic sensor.
Long-Lived, Advanced Far-term	Capable of both short duration (one Earth day) Investigations of the surface and longer-term Investigations of the atmosphere, heat flow and seismicity of the planet through at least two Venus solar days.

AERIAL PLATFORM	**Supports extended duration experiments in and from the atmosphere including sonde deployment**
Fixed Altitude – Mid Cloud Near-term	Floats at a nominal altitude of ~55 km in day and/or night at temperature near 20 °C. Carried around the planet in six days by the RZS and conducting Investigations of the atmosphere and interior.
Variable Altitude – Mid Cloud Mid-term	Controls altitude in the range ~50–60 km enabling compositional and structural Investigations of different regions within the clouds enhancing the range of Investigations of the atmosphere and interior.
Variable Altitude – Cloud Base Far-term	Controls altitude in the range ~40–60 km using passive thermal control systems to enable use of conventional electronics. Sensors in exposed locations must tolerate temperatures up to 150 °C.
FLYBY OPPORTUNITIES	**Opportunistic leveraging of non-Venus missions for Venus science of multiple possible types, depending on the opportunity**

*In keeping with other Venus guidance documents, 'Near-term' here refers to the 2020-2022 timeframe, 'Mid-term' to 2023-2032, and 'Far-term' to 2033-2042.

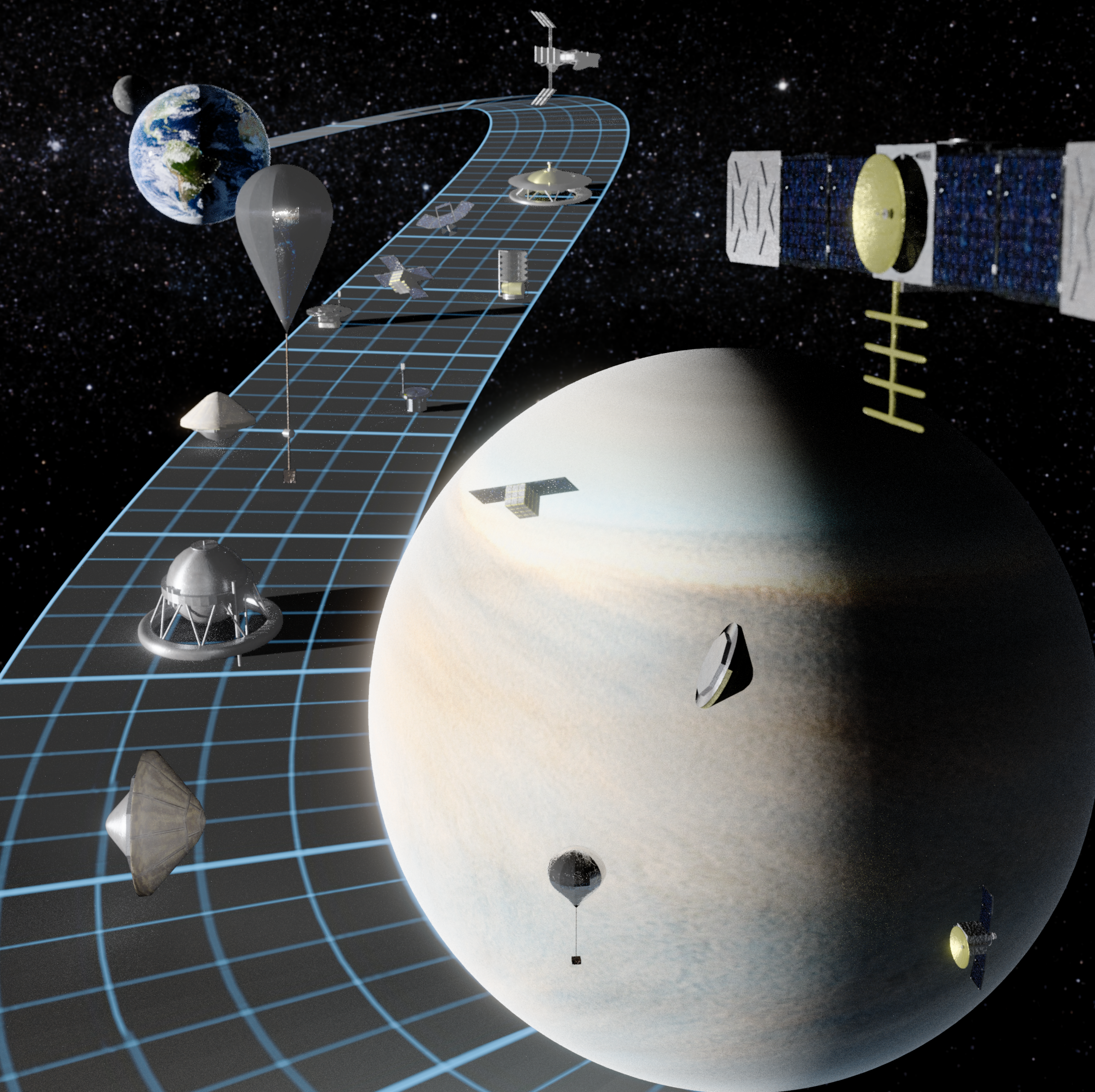
Table C.2 Mapping of GOI to Venus Roadmap

VEXAG GOI			Roadmap Mission Modalities											
Goal	Objective	Investigation	Orbiter	Orbiter	Orbiter	Atmospheric Entry			Surface Platform			Aerial Platform		
			Surface/ Interior	Atmosphere	SmallSat	Skimmer	Probe	Sonde	Short-lived	Long-lived (Pathfinder)	Long-lived (Advanced)	Fixed Altitude	Variable Altitude	Variable+ Altitude
			Near-term	Near-term	Near-term	Near-term	Near-term	Mid-term	Near-term	Mid-term	Far-term	Near-term	Mid-term	Far-term
I. Early evolution and potential habitability	Did Venus have liquid water?	I.A.HO. (1)	Vital	Supporting	Supporting				Vital		Vital			Vital
		I.A.RE. (1)	Vital						Vital		Vital	Supporting	Supporting	Supporting
		I.A.AL. (2)		Vital	Vital									
		I.A.MA. (3)		Supporting	Supporting				Supporting	Supporting	Supporting	Vital	Vital	Vital
	How does Venus inform pathways for planets?	I.B.IS. (1)				Vital	Vital	Vital	Vital		Vital	Vital	Vital	Vital
		I.B.LI. (1)	Vital	Supporting	Supporting					Supporting	Vital	Vital	Vital	Vital
		I.B.HF. (2)	Vital								Vital			
		I.B.CO. (2)	Vital		Supporting					Supporting	Vital			
II. Atmospheric dynamics and composition	What drives global dynamics?	II.A.DD. (1)		Vital	Vital		Supporting	Supporting		Vital	Vital	Supporting	Vital	Vital
		II.A.UD. (1)		Vital	Vital	Supporting								
		II.A.MP. (2)		Vital	Supporting		Supporting	Supporting				Supporting	Vital	Vital
	What governs composition and radiative balance?	II.B.RB. (1)		Vital	Vital		Supporting	Supporting	Supporting	Vital	Vital	Supporting	Vital	Vital
		II.B.IN. (1)		Vital	Supporting		Vital	Vital (light blue)		Supporting	Supporting	Supporting	Vital	Vital
		II.B.AE. (2)		Supporting	Supporting		Vital	Vital	Supporting	Supporting	Supporting	Vital	Vital	Vital
		II.B.UA. (2)		Vital	Vital		Supporting	Supporting				Supporting	Vital	Vital
		II.B.OG. (3)	Vital	Vital	Vital		Supporting	Supporting	Supporting	Supporting	Vital	Supporting	Vital	Vital
III. Geologic history and processes	What geologic processes shape the surface?	III.A.GH. (1)	Vital	Vital	Vital									Supporting
		III.A.GC. (1)	Supporting	Supporting	Supporting		Supporting	Supporting	Vital	Vital	Vital			Vital
		III.A.GA. (2)	Vital	Supporting	Supporting		Supporting	Supporting		Supporting	Vital	Supporting	Supporting	Supporting
		III.A.CR. (2)	Vital	Supporting	Supporting					Supporting	Vital	Vital	Vital	Vital
	Atmosphere and surface interactions?	III.B.LW. (1)	Supporting	Vital	Vital		Vital	Vital	Vital	Vital	Vital			Supporting
		III.B.GW. (2)	Vital	Vital	Vital				Supporting	Supporting	Supporting	Supporting	Supporting	Vital
		III.B.CI. (3)	Supporting	Supporting	Supporting		Vital	Vital	Vital	Vital	Vital	Supporting	Supporting	Vital

Color Code	Meaning
(blue)	**Vital:** Mission modality enables measurements that are vital (either alone or in combination) to completing the investigation.
(yellow)	**Supporting:** Mission modality enables measurements that substantially contribute to completing the investigation.

VENUS EXPLORATION
VEXAG
ANALYSIS GROUP
2019

ROADMAP FOR VENUS EXPLORATION



Cover image by John D. Wrbanek

At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major documents were selected to be updated: (1) the document prioritizing Goals, Objectives and Investigations for Venus Exploration: (GOI), (2) the Roadmap for Venus Exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) the Technology Plan for future Venus missions. Here we present the 2019 version of the VEXAG Venus Exploration Roadmap.

Prepared by the VEXAG Venus Exploration Roadmap Focus Group: James A. Cutts (chair), Michael Amato, Tibor Kremic, Candace Gray, Scott Hensley, Gary Hunter, Noam Izenberg, Walter Kiefer, Kevin McGouldrick, Joseph O'Rourke, and Suzanne Smrekar.

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VEXAG Charter. The Venus Exploration Analysis Group (VEXAG) is NASA's community-based forum designed to provide scientific input and technology development plans for planning and prioritizing the exploration of Venus over the next several decades. VEXAG is chartered by NASA's Planetary Science Division (PSD) in the Science Mission Directorate (SMD) and reports its findings to NASA. Open to all interested scientists, VEXAG regularly evaluates Venus exploration goals, scientific objectives, investigations, and critical measurement requirements, including recommendations for the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

1.0. Executive Summary

Venus is so similar to Earth in size, composition, and distance from the Sun that it is frequently referred to as "Earth's twin." Despite these similarities, Venus has gone down a different evolutionary path. Venus today is dominated by a greenhouse climate "gone wild" that resulted from a complex interplay of the same atmospheric, surface, and interior processes at work on Earth. There is strong evidence that Venus once had significant surface water over billions of years, and was thus habitable far longer than Mars. The demise of that habitable world and the reasons why Earth and Venus evolved so differently rank among the most important questions in planetary science. Overall, the study of Venus provides unique and important insights into planetary processes, the past and future of the terrestrial planets, and the likelihood of habitable planets in other planetary systems around other stars.

Exploration of Venus provides both major technical challenges and extraordinary scientific opportunities. This *Roadmap for Venus Exploration* lays out a framework for pursuing these, encompassing observations of the atmosphere, surface, and interior using a variety of mission modes ranging from orbiters, aerial platforms, long-duration landers, and probes, and opportunistic leveraging of events such as flybys of non-Venus missions. It was developed for the space science community by the Venus Exploration Analysis Group (VEXAG) to provide guidance to the Planetary Science Division and the Planetary Science Decadal Survey process, which is charged with framing a strategy for all of planetary exploration for the next decade and beyond. The process used to generate this NASA Roadmap is described in Appendix A.

Scientific guidance for this *Roadmap for Venus Exploration* (VEXAG, 2019b) is provided by the companion document *Scientific Goals, Objectives, and Investigations for Venus Exploration, or GOI* (VEXAG, 2019a), which establishes the foundation and priorities for future Venus exploration. To facilitate the identification of specific mission concepts, the *Roadmap for Venus Exploration* considers scientific contributions from different exploration platforms: orbiters, probes, surface platforms (landers), aerial platforms, and opportunistic flybys. New capabilities in Venus exploration depend on advancing technologies, and the *Venus Technology Plan* companion document (VEXAG, 2019c), details the technological advances have enabled multiple new mission modes to answer pressing Venus science questions. Collectively, these three documents describe a path forward from the prolonged hiatus in U.S.-led Venus exploration. Thus, the Venus science community is poised now with mature mission concepts, intellectual capital, and experience. These documents present the case for a Decade of Venus.

2.0. Venus Exploration in NASA's Science Program

This Section addresses the important Venus science that can be accomplished within multiple mission programs sponsored by different NASA Science Directorates. Because of the diversity of compelling Venus science questions, even highly focused measurements can yield breakthroughs. Thus, relatively low-cost missions and opportunistic observations (such as those from flybys to other objects) can make major contributions. Conversely, complex inter-relationships and variability among atmospheric, surface, and interior phenomena on Venus make it an ideal candidate for large, multi-disciplinary missions. This *Roadmap for Venus Exploration* envisions NASA missions funded through the established programmatic lines complemented by missions led by other space agencies. This section reviews each of the NASA programs that support Venus exploration and discusses the status of international collaborations. It connects these programs with the companion *Technology Plan* (VEXAG, 2019c).

2.1. Discovery Missions

The Discovery Program of Principal Investigator (PI)-led smaller missions provides opportunities for targeted investigations with relatively rapid flight, and is ideally suited for missions to Venus. Flight times to Venus are short, and power and communications bandwidth are plentiful for orbital missions. Its dense atmosphere can be used for aerobraking or aerocapture to reduce propellant requirements. Venus also provides an attractive and scientifically rich environment for probes or aerial platforms. Important surface compositional and topographic measurements, including change detection, can be made from orbit using radar, altimetry, and emissivity techniques already proven at Venus. Appendix B lists known past and current (as of this document's publication date) Discovery mission proposals to Venus.

Discovery missions can make critical steps toward understanding Venus and its scientific relationship to Earth, and also serve as pathfinders for more complex multi-disciplinary missions. More than 20 Venus missions of different types have been proposed to the Discovery opportunity since the program's inception, resulting in Category 1 concepts.

2.2. New Frontiers Missions

The New Frontiers Program consists of PI-led medium-class missions addressing specific strategic scientific investigations endorsed by the *Decadal Survey of 2011* (NRC, 2011). The Decadal Survey recommended a single Venus New Frontiers mission, the Venus In Situ Explorer (VISE). The New Frontiers NF-4 Announcement of Opportunity released in December 2016 included VISE as one of its mission themes, focused on examining the physics and chemistry of Venus' atmosphere and crust by characterizing variables that cannot be measured from orbit, including the detailed composition of the lower atmosphere, and the elemental and mineralogical composition of surface materials. Venus missions of different types have been proposed to almost every New Frontiers opportunity, resulting in several concepts evaluated as Category 1.

2.3. Flagship Mission Concepts

Flagship missions address high-priority investigations that cannot be achieved within the resources allocated to the Discovery and New Frontiers Programs. The 2011 Decadal Survey Inner Planets Group selected a single small Venus Flagship mission concept, the Venus Climate Mission (VCM), for the period 2013–2022. VCM would make synergistic observations from multiple platforms (orbiter, balloon, mini-probe, and dropsondes) to enable global three-dimensional characterization of the atmosphere. VCM was ranked fourth in priority, along with an Enceladus mission, behind Flagship missions to Mars, Europa and Ice Giants. Since 2014, NASA has also been exploring a role in Venera-D, a potential Russian-led Flagship-class mission (see section 2.5).

2.4. Small Missions and Missions of Opportunity

As the pressure on space science budgets grows more severe, NASA must consider alternative mission modes that contribute to Venus science at lower cost. In 2018, VEXAG completed the Venus Bridge study (Grimm and Gilmore, 2018), identifying multiple potential small missions and components with highly focused objectives. Some of these require further investment in technology while others are feasible now. Although scientific payoff of missions scales with mission size, small, focused missions have the potential to address specific Venus Science Investigations (Table 1, VEXAG, 2019a). Flyby opportunities of non-Venus missions provide more potential to benefit Venus science.

2.5. International Opportunities

The international community has demonstrated a strong interest in Venus, with the potential to enhance future exploration of Venus. The European Space Agency's (ESA) Venus Express mission, which ended in December 2014, and the ongoing Japanese Space Agency's (JAXA) Akatsuki, both had NASA Participating Scientists. Looking forward, the Indian Space Research Organization (ISRO) is planning a Venus mission Shukrayaan-1 (schedule 2023 launch). It includes an orbiter with a large payload focused on both atmospheric and surface objectives.

Since 2014, Russia's Roscosmos and Space Research Institute have collaborated with NASA's Planetary Science Division on Venera-D, a Flagship class mission with both landed and orbital elements. Although a Joint Science and Technology Definition Team (JSDT) report was completed (JSDT, 2019), Venera-D remains a pre-Phase A mission concept study. NASA is also collaborating in a Phase A study of the ESA Envision mission concept, one of three candidates for ESA's Medium Class M-5 mission. If selected for flight, EnVision would be launched in 2032.

Other than the ISRO mission, there are no approved plans from other space agencies for a Venus mission. NASA leadership in Venus exploration is a prerequisite for the success of the Decade of Venus.

2.6. Technology Developments

Extreme environments are among the key challenges facing future Venus missions. New technologies described in the companion Technology Plan (VEXAG, 2019c) must play a vital role in future Venus exploration. Some key developments and new capabilities that have influenced this current Roadmap include:

- Heatshields for Extreme Entry Environment Technology (HEEET), under development for the last five years, have reached TRL 6. This new capability makes entry into the Venus atmosphere more feasible and less restricted than before.
- Long-duration surface platforms enabled by the development of high-temperature electronics and power technologies under the HOTTech program (Mercer, 2018) will play an important role in future Venus exploration and feature prominently in the Roadmap.
- Variable altitude aerial platforms operating high in the Venus atmosphere where temperatures and pressures are close to those of the Earth at sea level show promise for investigating both the atmosphere and surface and interior (Venus Aerial Platform Study Team, 2018).
- Interplanetary Smallsats and CubeSats, following the flights of the CubeSats (MarCO1 and 2) in support of the InSight mission, have demonstrated that small low cost systems can be sufficiently robust to support missions to the inner planets. Their potential for Venus exploration is covered in the Technology Plan.

Table 1. Platforms included in the Venus Exploration Roadmap

Platform Type/Subtype ***Time Frame***	**Description of platform and primary scientific objectives**
ORBITER	Investigations from orbital vantage points optimized for the scientific objectives.
Surface/Interior *Near-term*	Single spacecraft in a circular, low altitude, near polar orbit optimized for most investigations of the surface and interior including those involving radar imaging and topography, infrared mapping, and gravity.
Atmosphere/Ionosphere *Near-term*	Single spacecraft in an eccentric, long-period orbit optimized for atmospheric remote sensing (e.g., nadir and limb viewing) and in situ sensors of the ionosphere and induced magnetosphere.
SmallSat or CubeSat *Near-term*	Single or multiple spacecraft focused on highly targeted investigations requiring tailored orbits. May also provide relay, navigation support, and synergistic science for surface and aerial platform(s).
ATMOSPHERIC ENTRY	Experiments during a traverse or descent in the Venus atmosphere.
Skimmer *Near-term*	Skims the atmosphere, sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay.
Probe *Near-term*	Enters the atmosphere and descends to the surface but is not designed to operate after impact. Would investigate atmospheric structure and compositions along a single profile as well as near-surface imaging.
Sonde *Mid-term*	Deploys from an aerial platform that is already at the operational altitude. Sonde relays data through the aerial platform as it descends. Advanced versions could target surface features.
SURFACE PLATFORM	Experiments on the surface of Venus in the high temperature high pressure environments
Short-Lived *Near-term*	Classic (e.g., Venera) lander capable of surviving on the surface for several hours. Various instruments could investigate elemental and mineral compositions of nearby rocks, including variations with depth into the surface
Long-Lived, Pathfinder *Mid-term*	Designed to operate for one Venus day (~116 Earth days) on the surface. Measurements include temperature, wind velocity, and chemistry of major species and possibly demonstration of a seismic sensor.
Long-Lived, Advanced *Far-term*	Capable of both short duration (one Earth day) investigations of the surface and longer-term investigations of the atmosphere, heat flow and seismicity of the planet through two Venus days.
AERIAL PLATFORM	Extended duration experiments in and from the atmosphere including sonde deployment.
Fixed Altitude – Mid Cloud *Near-term*	Floats at a nominal altitude of ~55 km in day and/or night at temperature near 20 °C. Carried around the planet in six days by the Retrograde Zonal Superrotation (RZS) and conducting investigations of the atmosphere and interior.
Variable Altitude – Mid Cloud *Mid-term*	Controls altitude in the range ~50–60 km enabling compositional and structural investigations of different regions within the clouds enhancing the range of investigations of the atmosphere and interior.
Variable Altitude-Cloud Base *Far-term*	Controls altitude in the range ~40–60 km using passive thermal control systems to enable use of conventional electronics. Sensors in exposed locations must tolerate temperatures up to 150°C.

3.0. Venus Exploration Platforms

This section addresses four categories of Venus Exploration Platforms for carrying out the science described in the Goals, Objectives, and Investigations VEXAG document: Orbiters, Atmospheric Probes, Surface Platforms and Aerial Platforms. Only those platforms deemed feasible between now and 2042 are included here. Additional details on the platforms appear in Appendix B. The systems needed to deliver the platforms to Venus and for orbital and/or atmospheric entry, descent and deployment, are detailed in the Technology Plan (VEXAG, 2019c). Venus Exploration Platforms are characterized by the vantage point (orbit, atmosphere, or surface), the nature of the platform, and the path or trajectory that the platform follows. A single platform launched to Venus can constitute a mission. However, multiple platforms launched on a single launch vehicle, as occurred with the Venera and VeGa missions, offer scientific and technical synergies as well as cost savings.

The earliest time-frame in which each of these platforms could be deployed at Venus is based on the following readiness factors:

- Technology Maturity: The maturity of the enabling and enhancing technologies required for each platform (VEXAG, 2019c).
- Complexity: The complexity of the platform systems including delivery, deployment and operation at Venus as well as the number of individual technologies required.
- Resource Needs: Estimates of the resources and time needed to advance technologies and demonstrate complex systems to ready them for flight.

Technical readiness of each type and subtype of platforms described in Table 1 is depicted as a color coded box in Figure 1, which also displays the earliest time period when the platforms could be deployed to Venus.

- Those platforms that are deemed to be of very high technical readiness can be proposed now with a high chance of success and are shown in the Pre-Decadal time-frame prior to 2023.
- Platforms with moderate to high technical readiness could be ready for missions in the Decadal time-frame 2023 to 2032.
- Platforms with low to moderate technical readiness have been assigned to the Post-Decadal time frame 2033 to 2042.

Platforms with low technical readiness have been deferred until after 2042. In particular, Venus Surface Sample Return (a multiplatform mission) and Mobile Surface or Near Surface exploration, which were featured in the 2014 Roadmap, have been deemed to be infeasible within the 25 year time frame of the this Roadmap.

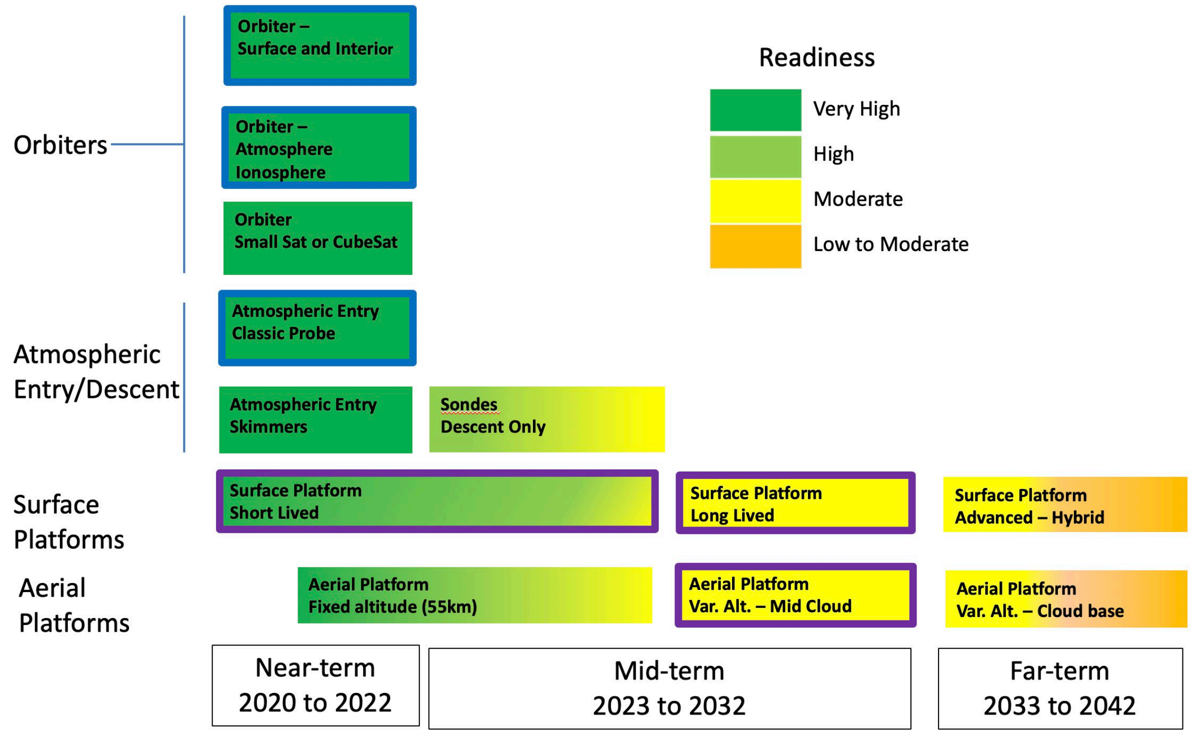

Figure 1. Time frames in which exploration platforms could be ready for deployment are ordered in based on their readiness. Readiness is a composite measure based on technology maturity, complexity and resource needs. Near-term Roadmap missions have very high and high readiness. Mid-term Roadmap missions have high and moderate readiness. Far-term Roadmap missions have moderate and low readiness.

4.0. Scientific Assessment of Venus Exploration Platforms

This section shows how the Venus Exploration Platforms described in Section 3.0 map to the Venus GOI (VEXAG, 2019a). Science contributions that can be made by each platform to address the investigations in the GOI are indicated in Table 2 with a color code as either **Vital** (blue) or **Supporting** (orange). This color coding is at a high level and thus does not specify how many of the suggested asset would be required to satisfy the objective. A more detailed exposition of these contributions, and potential for synergies between observations with different platforms are detailed in Appendix C. **Our overall assessment is that all these modalities are vital.**

4.1. Orbiters

Three orbiter subtypes will play complementary roles in the further exploration of Venus. As Section 3.0 indicates, orbiters are ready now, although advances in Smallsat and CubeSats in particular are needed to exploit their full potential.

4.1.1 Orbiter – Surface-Interior: This class of orbiter, focusing on the surface and interior can make major contributions to Goal I and Goal III. Although some of the investigations rely on observations by individual instruments/experiments, there are important synergies that arise from the acquisition of detailed radar topographic maps that are applied in the analysis of infrared imaging and gravity data.

Table 2. Assessment of Ability of Roadmap Platforms to address GOI Investigations

VEXAG Goals, Objectives and Investigations					Roadmap Mission Modalities													
					Class	Orbiter			Atmospheric Probes			Surface Platform - Life time			Aerial Platform - Alt control			
					Platform	Surf-Int	Atm-Ion	SmallSat	Skimmer	Probe	Sonde	Short	Long	Advanced	Fixed Mid-	Variable Mid-cloud	Variable Sub-cloud	
Goals	Objectives	Investigations	GOI Code	GOI Rating	Time Frame	Near	Near	Near	Near	Near	Mid	Near	Mid	Far	Near	Mid	Far	Overall Assessment
I. Early Evolution, and Potential Habitability	A. Did Venus have liquid water?	Hydrous Origins	I.A.HO	1		V	S	S				V		V			V	V
		Recycling	I.A.RE	1		V						V		V	S	S	S	V
		Atmospheric Losses	I.A.AL	2			V	V										V
		Magnetism	I.A.MA	3			S	S				S	S	S	V	V	V	V
	B. How does Venus inform pathways for planets?	Isotopes	I.B.IS	1					V	V	V	V		V	V	V	V	V
		Lithosphere	I.B.LI	1		V	S	S					S	V	V	V	V	V
		Heat Flow	I.B.HF	2		V							S	V				V
		Core	I.B.CO	2		V		S					S	V				V
II. Atmospheric Dynamics Composition	A. What drives global dynamics?	Deep Dynamics	II.A.DD	1			V	V		S	S		V	V	S	V	V	V
		Upper Dynamics	II.A.UD	1			V	V	S									V
		Mesoscale Processes	II.A.MP	2			V	S		S	S				S	V	V	V
	B. What governs compositions and radiative balance?	Radiative Balance	II.B.RB	1			V	V		S	S	S	V	V	S	V	V	V
		Interactions	II.B.IN	1			V	S		V	V		S	S	S	V	V	V
		Aerosols	II.B.AE	2			S	S		V	V	S	S	S	V	V	V	V
		Unknown UV Absorber	II.B.UA	2			V	V		S	S		S		S	V	V	V
		Outgassing	II.B.OG	3		V	V	V		S	S	S	S	V	S	V	V	V
III. Geologic History and Processes	A. What geological processes shape the surface?	Geologic History	III.A.GH	1		V											S	V
		Geochemistry	III.A.GC	1		S	S	S		S	S	V	S	V			V	V
		Geologic Activity	III.A.GA	2		V	S	S		S	S		S	V	S	S	S	V
		Crustal	III.A.CR	2		V	S	S				V	S	V	V	V	V	V
	B. How do the atmosphere and surface interact?	Local Weathering	III.B.LW	1		S	S	S		V	V	V	S	V			S	V
		Global Weathering	III.B.GW	2		V	V	V				S	S	S	S	S	V	V
		Chemical Interactions	III.B.CI	3		S	S	S		V	V	V	S	V	S	S	V	V

(V = blue, S = yellow)

Vital: Platform enables measurements that are vital alone or in combination to completing investigation

Supporting: Platform enables measurements that substantially contribute to completing investigation

4.1.2 Orbiter- Atmosphere-Ionosphere: This class of orbiter makes its vital contributions to Goal II and can play an important supporting role in both Goals I and III. Although most surface and interior investigations require the low-altitude observations, infrared high-altitude observations can be employed for surface mapping and for detection of seismic events using infrasound.

4.1.3 SmallSats and CubeSats: Whereas some investigations addressed by larger orbiters can be accomplished by a small spacecraft, many cannot because of the limitations in the size of the instrument payload and the telecommunications capability. Small spacecraft can play a unique role where synchronous in situ or remote observations from many orbital locations are required. SmallSats may also be an excellent option for relay, navigation and observational support to a surface or aerial platform.

4.2. Atmospheric Entry

All three of the atmospheric entry concepts, spend comparatively brief periods in the atmosphere but with very different flight paths:

4.2.1 Skimmer: The skimmer can only sample the atmosphere at ~110 km and higher and the investigations that it can address are limited. However, it can play a vital role in the measurement of stable isotopes (I.B.IS) and a supporting role in investigating the dynamics of the upper atmosphere (II.A.UD).

4.2.2 Entry Probes: The entry probe can sample the upper atmosphere once it becomes subsonic and continues taking data down to the surface during a period of about an hour. It can also address the stable isotope investigation in Goal I, make important contributions to Goal II, and provide information on the near surface environment.

4.2.3 Sondes: Sondes are released at selectable times from an aerial platform. Because sondes require no entry system, they can be much smaller than entry probes. There is also the potential for deploying multiple sondes at different times of day and locations on Venus. While in principle, sondes can carry payloads similar to those of entry probes and address similar science, they are likely to be focused on investigations where multiple sampling locations are important. Advanced sondes, with the capability of precisely targeting surface features, could be used to acquire high resolution visual imaging.

4.3. Surface Platforms

The Short-Lived and Long-Lived (Pathfinder) platforms considered are very different in their measurement capabilities. The Advanced (hybrid) platform combines features of both these concepts in a more advanced form.

4.3.1 Short-Lived: With the ability to make geochemical measurements during a short lifetime of a few hours, this type of platform builds upon the accomplishments of past Venera and VeGa surface missions with modern, highly capable instruments. Since this platform follows a flight path very similar to that of the entry probe in its trip to the surface, it can perform many of the measurements of the Entry Probe, provided it is equipped with the appropriate instruments to do so.

4.3.2 Long-Lived (Pathfinder) Platform: This platform will support experiments carried out on the surface for up to a Venus solar day (116 Earth days). However, for these long time frames, measurement possibilities would be limited to temperature, pressure, wind speed and direction and major species over a duration of up to one Venus solar day. These measurements can provide a vital contribution to understanding the circulation in the deep atmosphere (II.A.DD and II.B.RB)

4.3.3 Advanced (Hybrid) Platform: This vehicle can address a very broad range of investigations since it comprises sophisticated measurement systems that only survive for up to one Earth day and more restricted measurement capabilities that will operate for up to two Venus solar days. Significant technical advances are needed to accomplish this. If successful, the platform can make significant contributions to multiple investigations for all three goals.

4.4 Aerial Platforms

Aerial platforms can address all three goals in the GOI including those requiring compositional and structural measurements of the atmosphere, geophysical measurements exploiting contact with the atmosphere and proximity to the surface and surface imaging. These measurements would be made over a period of about 100 days as the aerial platform circles every five to six days in the Retrograde Zonal Superrotating (RZS) flow.

4.4.1 Aerial Platform – Fixed Altitude: This platform can make vital contributions to all three goals with the predominant contributions made to Goals I and II. Key measurements include measurements of the composition of atmospheric gases and cloud particles, meridional and zonal wind components as a function of latitude and time of day and measurements of electromagnetic waves, remanent magnetism, gravity and seismic sourced infrasound.

4.4.2 Aerial Platform – Variable Altitude, Mid-Cloud. The ability to vary altitude within the atmosphere enhances the contributions that are made to number of investigations within Goal II including characterizing mesoscale processes (II.A.MP), investigating the nature of the unknown UV absorber (II.B.UA) and investigating the products of outgassing II.B.OG).

4.4.3 Aerial Platform – Variable Altitude, Cloud-Base: This platform can address all of the investigations that are achievable with the other two platforms. In addition, it can extend the coverage of the atmosphere and make measurements of the surface at high resolution from the cloud base. The additional contributions arise from the ability to image the surface of Venus at high spatial resolution in the infrared (I.A.HO, III.A.GC, III.B.CI).

4.5. Measurement Platform Alternatives and Synergies

For the vast majority of investigations in GOI, there are multiple entries indicating that several platforms can, or are needed to, contribute to the investigation. In some cases, the same type of measurement can be made from a different type of platform. In other cases, the measurements are quite different but complementary to one another. Complementary measurements may need to be sequential or synchronous. We elaborate three examples below. A more complete discussion of measurement synergies appears in Appendix C.

4.5.1 Measurement Platform Alternatives: Some of the measurements needed to address GOI investigations can be conducted from more than one platform. For example, a surface platform descending through the Venus clouds can make the same observations as a descent probe executing a similar flight path. However, the ability of different platforms for addressing an investigation are not necessarily equivalent. For instance, the orbital infrared observations needed to address investigation I.A.HO are implemented most effectively by the near-circular orbiter because that class of orbiter can also generate the precise topographic maps needed to properly interpret the data whereas the highly eccentric orbiter optimized for atmospheric observations cannot.

4.5.2 Complementary Measurements – Sequential: Measurements with different platform types provide valuable complementary information. For example, for this same investigation I.A.HO, determining whether Venus shows evidence for abundant silicic igneous rocks and or ancient sedimentary rocks, orbital infrared observations provide the global classification of terrain types at a spatial resolution limited by atmospheric scattering. This sets the context for targeted infrared observations from an aerial platform at the cloud base at much higher spatial resolution. Definitive measurements of mineral types will require landed missions but the context provided by orbital and aerial measurements will be key to setting landed measurements in a global context. There is no particular benefit from making these orbital, aerial and surface measurements of the surface synchronous. In fact, if the orbital experiment is conducted first, it can contribute to targeting subsequent aerial observations and landing sites

4.5.3 Complementary Measurements – Synchronous: For investigations focused on the atmosphere, where temporal change is a major factor, multi-platform synchronous observations are desirable. For example, II.A.MP, determining the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus, synchronous observations with an orbiter and an aerial platform are mutually supportive in addressing the objective. Similarly, for II.A.DD characterizing the dynamics of the lower atmosphere measurements at the surface by a long-duration surface platform complements orbital observations. There will also be cases where measurements are made synchronously for operational convenience, the infrared and topographic observations of the surface discussed in Section 4.5.1 are an example.

5. Venus Exploration Roadmap

This Section addresses a programmatic framework dominated by the competitive missions in the Discovery and New Frontiers programs. Accordingly this Venus Roadmap lays out credible options to guide planning and technology investments and to address some of the consequences of different choices. In particular, this section considers how these platforms (Table 1 and Sections 4 and 5) fit with the existing NASA competitive opportunities, NASA Flagship missions, and international collaborations.

5.1. Near-term Proposal Opportunities – 2020 to 2022

Before the next Planetary Science Decadal Survey makes its recommendations, we assume that two Discovery calls, one New Frontiers opportunity, and smaller ride-along or other missions of opportunity may be solicited. Here, we adopt the following criteria for candidate missions associate with these opportunities:

- Scope should include single or multiple investigations in the GOI, proportional to mission class or scale.
- Technical readiness of exploration platform must be very high.
- Size and complexity of the mission must be compatible with the opportunity.

For example, using these criteria, platforms listed in Table 1 and Figure 1 could be candidates for Discovery opportunities:

- Orbiter – Surface and Interior
- Orbiter – Atmosphere and Ionosphere
- Atmospheric Entry – Probe

Although the Orbiter-SmallSat and the Probe-Skimmer have reached technical readiness (Section 4), the range of investigations that they would address is more limited. If there were an opportunity for a low-cost (e.g., ride-along) mission, then these concepts might be considered but they should not be viewed as alternatives to the Discovery candidates in our Roadmap. In addition to these missions, an aerial platform (fixed altitude) mission might be considered for the potential 2021 launch opportunity.

5.2. Mid-term Proposal Opportunities – 2023 to 2032

During this Planetary Decadal Survey period, up to four Discovery opportunities, at least two New Frontiers announcements, and up to two Flagship class new starts are anticipated. The larger class of missions enables more capable platforms, as well as multiple platform missions to be considered.

In addition to the platforms that would be available in the near-term, the following ones can be considered for this 2023-2032 timeframe:

- Surface Platform – Short-Lived
- Surface Platform – Long-lived
- Aerial Platform-Variable Altitude – Mid Cloud

New Frontiers and Flagship opportunities available in this time period would enable missions involving multiple exploration platforms. Deploying several platforms on a single launch rather than sequentially in separate launches could provide both operational and scientific synergy if deployed simultaneously at Venus. Three example concepts described below were chosen for presentation here based on the following criteria, *but this is not an exclusive list*:

- Science should represent a substantial gain over that feasible with a single Discovery mission.

- Missions must be technically ready in the time-frame of the next Planetary Science Decadal Survey (2022 – 2032).
- Missions could be more costly than Discovery (>$500M), include the New Frontiers category $1B, and extend to Flagship approximately $2B.

The three aspirational multi-platform concepts here resemble concepts previously studied by or proposed to NASA. However, there are significant differences reflecting recent scientific and technological advances (Figure 2).

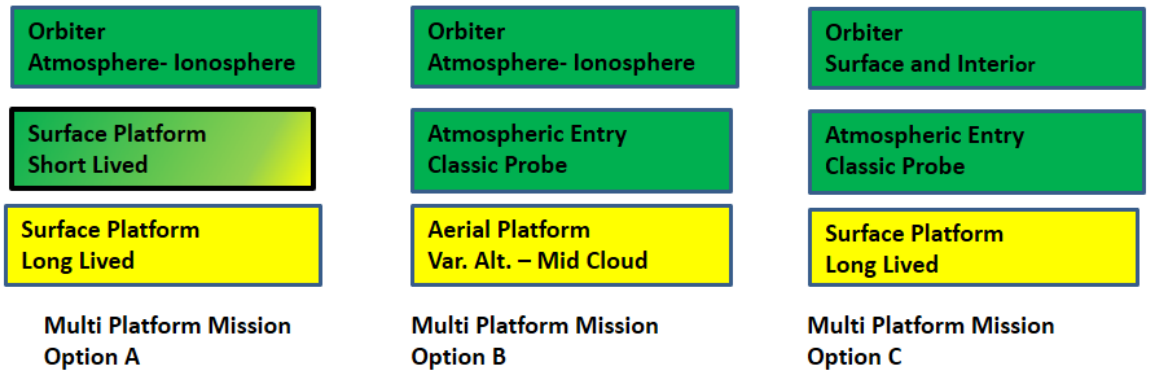

Figure 2. Options for Multi-Platform Missions for the Decadal Survey Period (2023 to 2032). Each mission includes three exploration platforms delivered to Venus with a single spacecraft. The in situ platforms (landers, probes and aerial platform) would be delivered into the atmosphere in a single aero shell. Color indicates current technical readiness (See Figure 1).

5.2.1 Multi-Platform Missions - Option A (MPM-A): This concept includes the Surface Platform – Short-Lived, the Surface Platform Long–Lived and the Orbiter–Atmosphere Ionosphere Science. The long-lived platform could be 1) attached to the short-lived platform taking advantage of the same descent and landing system, 2) deployed in the same aeroshell as the short-lived lander. or 3) deployed with an entirely separate entry descent and landing system. The orbiter would provide a communications relay capability for both short- and long-landers and would conduct observations that were synergistic with both. The science would emphasize in situ measurements of the surface and remote sensing measurements of the atmosphere. This mission resembles but is not identical to the Venera D mission studied by a Joint U.S. Russian Science team (Venera D Joint Science Definition Team, 2019).

5.2.2 Multi-Platform Missions - Option B (MPM-B): This concept includes the Aerial Platform Variable Altitude – Mid Cloud, an Orbiter Atmosphere and Ionosphere, an entry probe and multisondes. The last Planetary Science Decadal Survey recommended a Venus Climate Mission (VCM) that consisted of the following component platforms: an orbiter, a fixed altitude aerial platform, a descent probe and multiple sondes. The aerial platform, descent probe and sondes were packaged in the same aeroshell with the descent probe deployed immediately after entry and the sondes deployed some days or weeks later. Both descent probe and sondes would relay data through the aerial platform. The science would emphasize coordinated remote and in situ measurements of the surface and geophysical investigations of the interior.

5.2.3 Multi-Platform Missions - Option C (MPM-C): This concept includes a highly capable orbital platform for investigating the surface and interior of the planet with radar imaging, topography, repeat pass interferometry and near infrared spectroscopy. The concept would also include a descent probe for sampling the atmosphere from cloud levels down to the surface and for surface imaging and a long-lived lander. The science would emphasize in situ measurements of the atmosphere and remote sensing measurements of the Venus surface and interior.

Assessment of Multiplatform concepts: The ability to integrate multiple platforms in a single mission provides a number of scientific and technical advantages that are summarized in Table 3 below.

Table 3. Comparisons of the Multi Mission Platform candidates in terms of their scientific and engineering synergies

Roadmap Mission Two		Scientific Complementary and Synergy	Mission Synergy	Mission Synergy Guidance & Localization
Designation	**Platforms Included**			
MPM-A	Surface Platform - Short lived Surface Platform - Long lived Orbiter Atmosphere - Ionosphere	Compare diurnal measurements of surface temperature with orbital remote sensing	Orbital relay is essential for recovering data from long lived surface platforms	Enable refinement of entry and descent trajectory for the surface platforms
MPM-B	Aerial Platform – Variable Altitude Descent Probe Orbiter Atmosphere & Ionosphere	Compare orbital spectral signatures and cloud tracking with in situ observations	Orbital relay increases data return by 100X from the aerial platform relative to direct to Earth	Enables accurate localization of the position and velocity of the aerial platform as it is propelled by the RZS
MPM-C	Descent Probe Orbiter – Surface and Interior Surface Platform- Long lived	Radar imaging from orbit provides context for high resolution visual images from descent probe	May supplement data returned from the cruise stage deploying probe	May enable precise determination of point of entry and descent trajectory

The advantages of multi-platform missions include:

- Launching several platforms to Venus on a single platform is less costly than launching them separately.
- Inserting several in situ platforms (surface and aerial platforms and probe) into the atmosphere of Venus is less costly than for separate entry systems.
- For concepts with long duration operations in situ operation the presence of an orbiter may be required for returning data or enhance data return.
- For these same concepts the ability to acquire orbital context data will be valuable to the interpretation of the in situ data.
- Conversely, the in situ observations may provide validation of orbital measurements e.g. for wind velocity or surface temperature.
- Orbiters can provide a vital role in monitoring the position of an aerial platform particularly when the platform is on the far side of Venus relative to the Earth.
- Multiple platforms provide a more complete scientific investigation of interior, surface, and atmospheric interactions.

Developing an improved understanding of the trade space requires studies of multiplatform concepts incorporating the technical and scientific developments that have occurred in recent years. The Planetary Mission Concept Studies (PMCS) program, which was initiated by the Planetary Science Division with a ROSES call in the spring of 2019, provides an excellent opportunity to carry the recommendations of this Roadmap to the next level.

5.3. Long-term Proposal Opportunities – 2033 to 2042

This Roadmap cannot identify specific mission concepts for this time frame. However, there are candidates for single platform and multiple platforms that can be defined using a similar approach to that for the near-term decade 2023 to 2032.

The ability to carry out prolonged surface observations from a mobile platform operating on the surface or close to the surface would have enormous value to Venus science. Equally, the return of surface samples to Earth, where they can be examined with techniques that in variety and capability, cannot be equaled by in situ instruments remains an important long-range objective. Realistically, we need to learn from the experience of the Mars Program where it took a dedicated, funded program of multiple missions for three decades before being able to propose a sample return mission. Thus, these capabilities are currently well beyond the time frame of this Roadmap unless a substantial infusion of funds is allocated to Venus.

Even without surface sample return and near surface exploration mobile exploration, the rich variety of Venusian phenomena that will be accessible with the platforms and methods that we can deploy in this period will result in enormous progress in the understanding of our sister planet whose size and complexity approaches ours.

6.0. Summary

Today, the scientific strategy and the technology plan are in place for a systematic effort to address the questions posed by the Venus Science Community in the VEXAG GOI document. However, the mysteries of a planet as complex as Venus cannot be answered by one platform or even one mission, so the multi-mission strategy outlined in this Roadmap is required. Many of these platforms and missions are ready now; others will require technology investments. After a long hiatus, it is time to resume NASA's exploration of our sister planet. The coming decade can and should be the **Decade of Venus**.

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Appendix A. Roadmap Development Process

Three Focus Groups formed by VEXAG in May 2018 were assigned the task of revising VEXAG's guiding documents - the GOI, the Venus Exploration Roadmap, and Technology Plan. These VEXAG documents define scientific goals and the missions and technology needs needed to implement them. The process for updating the Venus Exploration Roadmap, is shown in Figure A.1, and is described in more detail below.

A.1. Initial Inputs

The starting point for the Roadmap Focus Group was the Venus Exploration Roadmap of 2014. The Roadmap Focus Group was briefed on subsequent mission and experimental concepts, which included developments in small satellites and CubeSats, aerial platforms, and high temperature electronics technologies enabling long duration *in situ* missions. There were also developments in instruments and experimental techniques including miniature instruments that could be deployed on SmallSats and CubeSats.

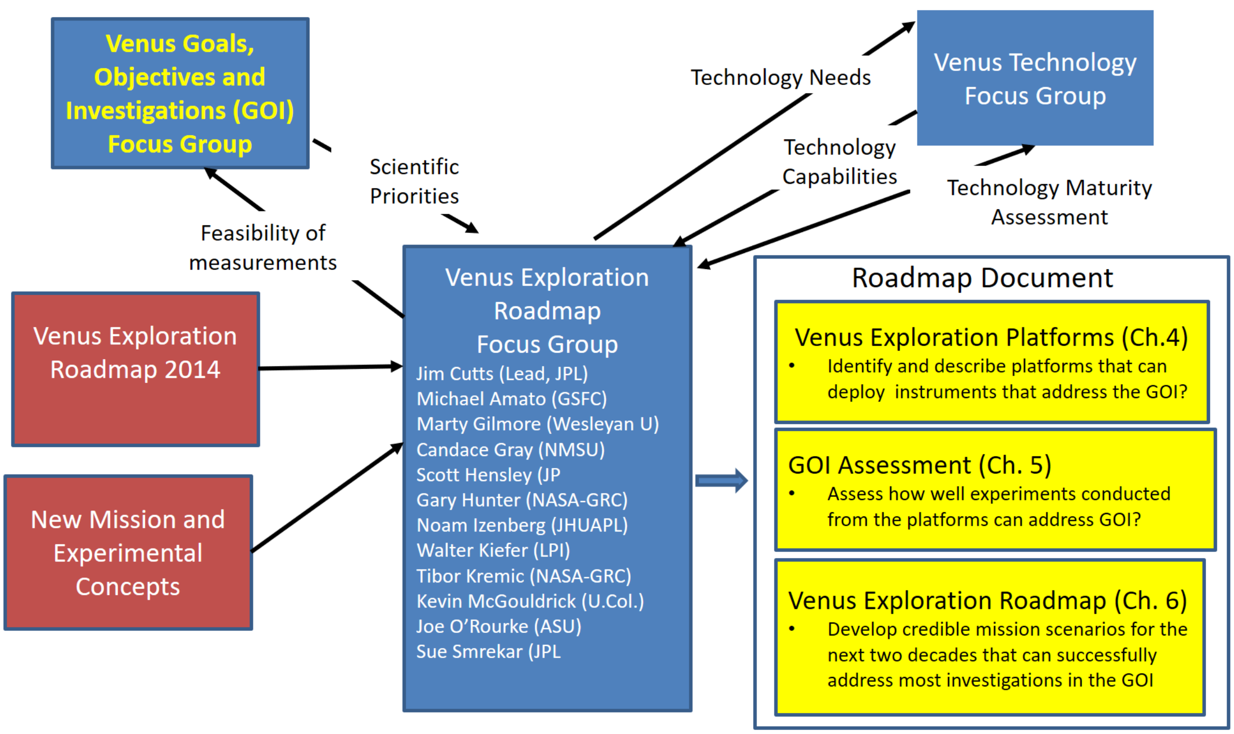

Figure A.1. Process for developing this VEXAG 2019 Roadmap.

A.2. Interactions with the GOI Focus Group

Roadmap Focus Group provided feedback on the first Goals, Objectives and Investigations document in October, 2018, benefiting from the cross-cutting membership of the two groups. The Groups worked together to link the Roadmap missions with investigations in the GOI. A key issue was assuring that investigations in the GOI were defined with sufficient information to identify a platform and experimental approach for each. A number of iterations took place with the GOI Focus Group. Investigations that were enabled by either new experimental techniques or new platform technologies were communicated to the GOI Focus Group and incorporated in that document.

A.3. Interactions with the Technology Focus Group

These interactions spanned the topics of technology needs, technology capabilities and technology maturity assessment, also benefiting from the cross-cutting membership of the Roadmap and Technology Focus Groups. The technology needs for each of the Roadmap missions were communicated to the Technology Focus Group. A key factor in identifying the sequence of the Roadmap missions was the determination of the technology maturity of the missions in the Roadmap. This drew on assessments of both subsystem and system level technology maturity that were conducted by the Technology Focus Group. It also involved assessments of cost and risk tolerance that were provided by the Roadmap Focus Group.

A.4. Key Products of the Roadmap Group

Figure A.1 describes the three sections of the report.

A.4.1. Venus Exploration Platforms (Section 3): This section describes the platforms that deploy the instruments carrying out the measurements addressing the Goals Objectives and Investigations. The platforms included orbiters, probes, landers and aerial platforms. Only platforms that are technically mature today or feasible within the timeframe of this Roadmap are considered.

A.4.2. GOI Assessment (Section 4): This section describes how measurements made from these platforms can address the investigations in the GOI. For some investigations, measurements from a single platform can provide a complete or comprehensive response to the intent of the investigation. In other cases, measurements from multiple platform either synchronously or sequentially are required. An understanding of where multiple platforms investigations are important is key to mission definition.

A.4.3. Venus Exploration Roadmap (Section 5): This section synthesizes information from the GOI assessment with information on the technology maturity of each of the platform types to frame the content of the Venus Exploration Roadmap. Potential mission sequences are constructed that involve multiple platforms where required and provide the feedforward needed to effectively and efficiently addresses the Goals, Objectives and Investigations. The Roadmap considers missions in three time periods phased with respect to the next Planetary Science Decadal Survey (PSDS).

Near-Term or Pre-Decadal refers to the period of four years (2019-2022) before the implementation period for next PSDS begins.

Mid-Term or Decadal refers to the period of ten years (2023-2032), which is the period for which the PSDS will make its primary recommendations.

Far-Term or Post-Decadal refers to the subsequent decade (2033 to 2042).

In addition, the Roadmap addresses some objectives that are scientifically important but are considered not feasible until after 2042.

Appendix B. Venus Exploration Platforms

The purpose of the Venus Exploration Roadmap is to define the opportunities for advancing scientific knowledge of Venus by missions that can carry out the investigations described in the companion GOI document (VEXAG, 2019a). These missions are implemented with different types of instrument platforms, orbiters, probes, surface platforms (landers) and aerial platforms. In this Appendix, details on the capabilities of the platforms are given, expanding on descriptions of exploration platforms in Table 1 in the main body of the text.

B.1. Orbiters

Three orbiter subtypes play complementary roles in the further exploration of Venus Orbiters are technically ready now, although advances in Smallsat and CubeSats in particular are needed to exploit their full potential.

B.1.1. Orbiters: Surface and Interior: Despite the dense atmosphere and thick cloud cover of Venus, which present unique challenges for orbital investigations of the surface and the interior, much can be learned about the surface and interior of Venus from orbit.

- Radar imaging at an order of magnitude better than Magellan would provide an opportunity to observe entirely new processes.
- Improved topography using radar interferometry and stereo imaging two orders of magnitude better than available from Magellan would be critical to addressing many geophysical science objectives.
- Iron mineralogy and oxidation state, as well as thermal variations, can be obtained by observation in infrared windows at a scale of ~50 km to determine rock types, characterize weathering reactions, and search for recent and active volcanism.
- Global scale gravity field with sufficient spatial resolution would determine elastic thickness.
- Radio sounders would probe the shallow (~100m) subsurface stratigraphy.

The next step in orbital surface exploration should be a global mapping mission to improve resolution of radar images by an order of magnitude over Magellan and the spatial resolution of topographic maps by an even larger amount. The technology for such a mission is ready today as reflected in the Category 1 rating of the VOX missions in the recent New Frontiers (NF-4) competition. It is a candidate for upcoming Discovery and New Frontiers calls.

A second mission that would logically follow the global mapper would aim for still higher spatial resolution at areas targeted based on global mapping results. This mission would also include a radio sounder for probing the subsurface to look for buried structure indicative of recent sedimentary and volcanic processes. It would utilize precise global topography maps to remove surface clutter. The Envision Mission, which is now being considered for the ESA's M5 call, meets these criteria. The earliest it could by launched under current ESA plans is 2032.

Both of these missions involve orbiters that carry out most of their scientific missions from a near-polar and circular or near-circular orbit with a period of ~90 minutes. Because of the slow rotation of Venus, it is possible to obtain images of the same surface locations to detect any temporal changes during several successive orbits.

Global reconnaissance by orbital mission supports landed missions by identifying high priority and high science value venues for detailed examination. NASA has advocated mission sequences that first conduct reconnaissance, then conduct in situ measurements, followed by mobile exploration. The Mars Program has been highly successful in implementing this approach.

B.1.2. Orbiters: Atmosphere and Space Environment: The dense atmosphere and thick clouds of Venus are accessible to investigation with a variety of remote sensing and some in situ techniques. Prior missions to Venus, including the ESA Venus Express mission and the ongoing JAXA Akatsuki mission, have contributed to the most current knowledge of the Venusian atmosphere. Addressing the broad set of GOI objectives will require a comprehensive payload including spectroscopy, hyperspectral imaging, solar/stellar/radio occultations and particles and fields measurements. A highly eccentric and high inclination orbit is needed to support both nadir viewing and limb scanning observations. However, low inclination and low eccentricity orbits can also be well-suited for investigations focused on atmospheric dynamics and composition, as demonstrated on Earth by the synergy of geostationary platforms such as GOES and Himawari, and Low Earth Orbit platforms such as the A-Train.

B.1.3. Orbiters: SmallSats and CubeSats: The successful MarCO flights supporting Mars InSight landing in 2018 demonstrated the feasibility of interplanetary flight with very small spacecraft. The VEXAG-led Venus Bridge study (Grimm and Gilmore, 2018) studied the use of SmallSats with ~100 kg mass and CubeSats with ~10 kg mass for Venus exploration. Although the science payloads of such missions are much more constrained, orbits may be tailored to specific objectives to obtain targeted science such as for a mission to detect the airglow modulated by seismic events for which a high circular orbit is optimal (Sutin et al 2018). CubeSats may also enable missions with multiple platforms sampling different parts of the space environment contemporaneously or performing mutual radio occultations to dramatically increased spatial and temporal sampling of the atmosphere.

Beyond the traditional form of radio occultation technique implemented on Venus Express and Akatsuki (where the radio signal from the spacecraft is observed by a single ground-based antenna or conversely), CubeSats and SmallSats may also perform mutual occultations. This can vastly increase the number of locations where the atmosphere is probed over what is possible with a single spacecraft and, in addition, does not require costly ground bases antennas.

B.2. Atmospheric Probes

Atmospheric probes provide short duration observations. Three types of probe are considered here, distinguished by the manner in which they enter the atmosphere and consequently by the types of flight path they offer. They differ in terms of technology, complexity and cost and hence provide multiple opportunities for integrating them with other platforms into mission concepts.

B.2.1. Skimmers: A skimmer is a vehicle that passes through the upper reaches of the Venus atmosphere, acquires a gas sample, and then analyzes it after emerging from the atmosphere. A skimmer concept, the Sample Collection for Investigation of Mars (SCIM) mission (Leshin, 2002), proposed to the Mars Scout program. SCIM would have captured intact dust grain samples in aerogel for return to Earth. For Venus, the primary interest is *in situ* measurement of noble gases and their isotopes. The Cupid's Arrow skimmer concept was studied in NASA's Planetary Science Deep Space SmallSat Studies (PSDS3) (Sotin et al. 2018). Similar concepts have appeared under other names as part of Discovery and New Frontiers proposals.

The skimmer concept samples only the higher reaches of the atmosphere. The issue of whether the atmosphere at the sampled altitude is representative of the bulk composition and whether the hypervelocity sampling process induces fractionation is the subject of an ongoing investigation. Strengths of the technique include the limited heating experienced at this altitude, which greatly simplifies thermal protection relative to a deep probe. Skimmers can be implemented with modest amounts of thermal protection on the forebody and little or none on the backshell. The ability to perform analysis and data relay after the vehicle exits the atmosphere may be useful in mass spectrometric analysis, improving counting statistics during months when the skimmer is in solar orbit after exiting the Venus atmosphere; this could enable measurement of isotopes present in trace amounts.

B.2.2. Entry Probes: Atmospheric probes that descend through the Venus atmosphere and reach the surface were used in the 1970s by the Venera and Pioneer Venus missions. Implementation of a deep probe mission with greatly improved instrumentation including descent imaging is now possible. These differ from skimmer probes because all of the energy of the probe as it enters the atmosphere must be removed. Development of the High Energy Entry Environment Technology (HEEET) for tolerating the severe conditions of Venus entry not only makes an entry mission possible again (the TPS material used on Pioneer Venus probe is no longer manufactured) but also allows greater flexibility in entry conditions including shallower entry angles.

In addition to measuring the chemistry and cloud properties during descent, probes can also observe solar and thermal radiation environment as a function of altitude. Tracking of the probe from Earth or from an orbiter can determine wind velocity. The surface can also be imaged during the terminal stages of descent below 5 km, when degradation of contrast by atmosphere scattering drops to acceptable levels.

B.2.3. Sondes: The advent of Aerial Platforms enables a class of atmospheric probe that can be delivered to Venus without a separate entry and descent system. These sondes can be of smaller and much lower cost than conventional entry probes. Because they typically operate at less than a few tens of kilometers from the aerial platform, data can be relayed through the aerial platform and transmitted at high data return rates directly to Earth or via an orbiter or flyby spacecraft. Sondes were an integral part of the Venus Climate Mission (VCM) study conducted for the 2013 Planetary Science Decadal Survey. VCM included a large sonde released immediately after entry of the aerial platform and a smaller sonde carried by the aerial platform and released at a later time. Sondes can capitalize on technologies developed for CubeSats. Missions with multiple sondes, released at different times and probing only the upper atmosphere, have been considered. Missions with deep sondes that descend to the surface and use guidance for targeting surface features identified in high-resolution radar imagers are considered for the second (Planetary Decadal Survey, 2033 to 2042) time period in this Roadmap. The proximity of the aerial platform relay station, would enable much larger volumes or imaging data that can be retrieved for a sonde than an entry probe.

B.3. Surface Platforms

Vehicles that descend to the surface and then conduct investigations on the surface of Venus constitute a key element of this Roadmap. NASA's Planetary Science Division has initiated a Venus Surface Platforms study (Amato and Kremic, 2019) that is currently in progress. It includes consideration of platforms that can survive and carry out science measurements for periods of a few hours, similar to the Venera-VeGa landers, as well as long-lived platforms that are capable of months of operation that are being enabled by NASA's technology development programs.

B.3.1. Short Duration Landers: A short duration lander is a vehicle that relies on conventional electronics and sensors maintained in their operational temperature range by means of passive thermal control. The latter implies a combination of thermal insulation and the use of phase change materials. These approaches mitigate the temperature rise resulting from heat leaking into the payload compartment and generated by power dissipation by the payload. The typical lifetime of these landed missions is presently hours (not days).

A series of Venera and VeGa lander missions was carried out by the Soviet Union in the 1970s and 1980s, forming the primary basis for what is known about the elemental composition of the Venus surface. No lander mission has been conducted since. The last two Planetary Science Decadal Surveys have called for a Venus In Situ Explorer (VISE) and a VISE mission theme has been included in three New Frontiers proposal calls. However, a NF VISE mission has not been selected for flight yet. In addition, Russia has been studying the Venera D mission concept that includes a landed mission with a clear heritage to the Venera-VeGa landers of the 1970s and 1980s.

Three recent mission concepts, with platforms in this category, are described below:

- The Venus In Situ Atmospheric and Geochemical Explorer (VISAGE), proposed for NF-4, would descend to the surface and samples would be brought on board for analysis by infrared and X-ray spectroscopy.
- The Venus In Situ Composition Investigation (VICI), selected for technology development of a Venus Element and Mineralogy Camera under NF-4, uses lasers on the lander to measure the mineralogy and elemental composition of rocks and soils.
- Venera D is still in a Russian Pre-Phase A study. The January 2019 report of the NASA-Russia JSDT (2019) calls for samples to be brought inside the lander and elemental analysis to be conducted remotely using a gamma ray spectrometer.

B.3.2. Long-Lived Duration Landers: Long-lived platforms can operate on the Venus surface for up to one solar day using systems and components that can survive and function at Venus surface temperatures and in the high-pressure sulfurous environment. The model for this concept is the Long-Lived In Situ Surface Explorer (LLISSE) developed at Glenn Research Center. LLISSE could be deployed either as a self-contained payload attached to a short duration lander or in a vehicle with its own entry descent and landing system. The technical hurdles that LLISSE must overcome are described in detail the companion technology plan (VEXAG, 2019c). Only a limited number of instruments available now or project during the next decade can operate at Venus surface temperatures, but they can provide measurements of temperature, pressure, wind speed and atmospheric chemistry over a period up to or including a complete Venus day. This would represent a major advance. A technology demonstration of a seismic experiment including measurements of the seismic background in the Venus surface environment is also possible.

B.3.3. Surface Platforms: Advanced Landers: Advances in technology described in the companion technology plan will have a dramatic impact on the capabilities of surface platforms. An advanced lander concept, which is at low to moderate maturity now, can be brought to maturity in the Far Term of post decadal period (2033 to 2042) with technology development including:

- Landing Guidance: Improving the precision of landing or the ability to avoid hazards on landing.
- Robust landing. Mitigating the risks of landing in regions of complex topography.
- Extended surface lifetime: Extending lifetime significantly beyond 3 hours.

- Autonomy: Increasing the sophistication of surface operations.
- Instrument Performance: Increasing the speed at which chemical analyses are performed.

Concepts for conducting a surface seismology investigation were considered in the Venus Surface Platforms study (Amato and Kremic, 2019). A surface seismology experiment would require major development of a seismometer that can operate for months or even years in the Venus surface environment. It would complement and build upon seismic observations acquired from orbit and from aerial platforms using technologies that are much closer at hand. Precursor technology demonstrations on prior surface missions will be key to understanding the surface backgrounds. Key issues to be considered are:

- Feasibility and affordability of single station (like InSight/SEIS) and multi-station (network) concepts, and
- Seismic sources – Venus quakes, landslides, bolide impacts, atmospheric excitation.

The Advanced Lander envisaged here would integrate the evolving capabilities of short-lived and long-lived platforms. In particular it would include:

- Entry descent and landing capability enhanced with Terrain Relative Navigations to safe areas of scientific interest identified in orbital radar images.
- Enhanced surface lifetime through improved insulation, phase changed materials and reduced power consumption (target one Earth day).
- Analysis of samples brought into the lander thermally controlled volume and remotely using LIBS-Raman or XRD/XRF methods.
- A long-lived seismometer experiment that would be deployed to the surface by the spacecraft arm prior to carrying out its sampling function.
- A long-lived heat flow experiment implemented in a sampling drill hole.

B.4. Aerial Platforms

Aerial platforms make measurements from a vantage point within the Venus atmosphere, providing in situ verification of analyses based on orbital data. Aerial platforms can also be used to deploy sondes and capture their data for relay to an orbiter or return to Earth. The assessment given here draws on recent study conducted for the Planetary Science Division (Venus Aerial Platform Study Team, 2018). Five types of measurements that can made from aerial platforms and sondes are:

- **Atmospheric Gas:** Measuring the composition of noble gases and their isotopes as well as the active chemical species.
- **Cloud and haze particles**: Measuring the size and scattering properties of these particles as well as their chemical and potentially biological nature.
- **Atmospheric Structure**: Measuring temperature, pressure and upward- and downward-welling radiation as a function of altitude as well as all three components of velocity including turbulence.
- **Planetary Interior:** Apply geophysical techniques to the study of the planetary interior including the use of passive electromagnetic sounding, infrasound, remnant magnetics and gravimetry.
- **Surface Imaging:** Obtain nighttime images of the surface from the base of the clouds and visual imaging from a few kilometers above the surface from sondes deployed from the platform.

A series of platforms of progressively advancing capability have been identified for this Roadmap. Technologies required for these concepts are described in the companion Venus Technology Plan.

B.4.1. Fixed Altitude Balloons: A fixed altitude balloon would be a more capable version of the Venera VeGa balloons mission of 1985. Advances in technology would enable the lifetime to be extended to up to 100 days using solar power to replenish batteries. The payload could be much larger and capable, including instruments to study the atmosphere and interior.

B.4.2. Variable Altitude, Mid-Cloud Balloons: With comparatively modest advances in technology, balloons can be implemented with the ability to control altitude in the range 50 to 60 km. This is still within the temperature range accessible with conventional electronics. The ability to change altitude will enable the atmospheric cloud layer to be studied more completely and will also enhance the value of some of the geophysical and atmospheric structure observations.

B.4.3. Variable Altitude, Cloud Base Balloons: A further increase in the altitude change capability would allow the platform to access the atmosphere below the base of the clouds. In addition to extending the atmospheric science that can be accomplished, this would also allow higher-resolution, (meter-scale) sub-cloud, night-time imaging of the surface in the infrared representing a dramatic gain over what can be accomplished from orbit. This concept would involve comparatively brief excursions to the deeper and hotter regions of the atmosphere using passive thermal control to protect batteries and other thermally sensitive components. Components exposed to the environment would have to be designed and qualified to survive the higher temperatures and corrosive gases.

B.4.4. Other Concepts: Vehicles with varying levels of three-dimensional control were considered in a trade study, but they do not compete favorably with the lighter-than-air vehicles in terms of overall scientific productivity for long duration flight. For highly targeted science, some of these platforms may have a role to play. Platforms that can operate close to the surface have also been considered but would require high temperature technologies for implementation and are viewed as candidates for the period after 2042 for a role in sample return and for regional scale near-surface mobility.

B.5. Venus Surface Sample Return

A long-standing objective across all planetary exploration is to return samples of the solid surface of a planet. Our VEXAG Focus Group considered how progress might be made towards this goal, in light of the inclusion of Venus Surface Sample Return (VSSR) as a Far Term objective in the previous 2014 Roadmap. This report draws on experience with the Mars Surface Sample Return (MSSR) mission.

Compared to sample return from the Moon, Mercury and Mars and even the moons of the outer planets, VSSR presents a formidable challenge due to the high gravity field (comparable to Earth), the dense atmosphere (~90 bars at the surface), and the high surface temperature (~460 C).

- High gravity field requires that even launches originating in tenuous reaches of the atmosphere have multi-stage Venus Ascent Vehicles (VAVs), comparable in capability to those for launching payloads into Earth orbit.
- High surface pressure mandates use of buoyancy systems with two or more stages to lift the sample from the surface to the upper atmosphere, where the atmospheric density is low enough to make launch of the VAV feasible.

- High surface temperatures require that any equipment accompanying the sample in its ascent (VAV, sampling, buoyancy systems) be protected from the near surface temperatures as well as pressures.

A number of VSSR studies were carried out in the past 30 years (e.g. Sweetser, 1999). In all of these concepts, the sample capsule launched by the VAV performs a rendezvous with an orbital spacecraft in Venus orbit. The orbital spacecraft then departs from Venus orbit on an Earth return trajectory. This approach is very similar to the current Mars Surface Sample Return (MSSR) architecture. However, the process of getting the sample to orbit is much more complex. In one approach, the VAV descends to the surface of Venus. An alternative is for the buoyancy system carrying the sample to rendezvous with the VAV in the high atmosphere. Regardless of which VSSR architecture is ultimately selected, it will be much more complex than that of MSSR. The individual architectural elements such as the VAV and the buoyant stage will much more technically challenging.

The last Planetary Science Decadal Survey recognized that MSSR required a sequence of at least three launches of mission elements, stretching out over more than one decade and building upon two decades of prior Mars surface exploration of progressively increasing capability. Because VSSR requires more mission elements and extremely difficult technologies, implementation of such a mission would extend far beyond the timeframe of this Roadmap. As a result, this Roadmap does not include VSSR. However, the recommended surface and aerial platform missions will demonstrate some of the technologies that will be needed to eventually carry out VSSR.

B.6. Surface or Near Surface Platform with Regional Mobility

A platform capable of conducting surveys of the surface was specified in the 2014 Roadmap for Venus Exploration (VEXAG, 2014). The companion 2014 Technology plan provides both a brief description of near surface and surface vehicles as well as the technologies required for their realization. However, for most of these technologies, maturity was deemed to be very low. It is useful here to review the principal challenges.

Mobility appears to be quite feasible. Buoyant vehicles have been envisaged that can plausibly traverse hundreds of kilometers drifting in the low-level Venus winds, such as the Venus Mobile Explorer (VME) that was studied in the last Decadal Survey. Generating power in the Venus environment is difficult; in particular, sufficient power for cooling components that cannot be implemented as high temperature components is needed.

Although this mission concept does not have the complexity of VSSR, it is nevertheless a very challenging mission and also considered to be beyond the time frame of this Roadmap. However, the recommended Surface and Aerial Platforms will be important stepping stones to this class of mission.

B.7. Technology Maturity of Selected Platforms

The companion technology plan provides an assessment of the key system and subsystem technologies needed for implementing the Roadmap platforms. Key systems and subsystems for the orbiter platforms are generally of very high maturity.

The earliest time-frame in which each of the exploration platforms could be deployed at Venus has been estimated using an assessment of technical readiness that considers:

- **Technology Maturity**: The maturity of the enabling and enhancing technologies required for each of the platform as determined in the companion Venus Technology Plan (see Table B.1).

- **Complexity:** The complexity of the platform systems including delivery, deployment and operation at Venus as well as the number of individual technologies required.
- **Resource Needs**: Estimates of the resources needs to bring the subsystem technologies to readiness and to validate the complex systems.

B.8. Readiness of Selected Platforms

The readiness of each type and subtype of platforms is described in Table B.1 below:

- Platforms with very high readiness can be proposed now with a high chance of success in the pre-Decadal time-frame prior to 2023.
- Platforms with moderate to high readiness could be ready for missions in the Decadal time-frame 2023 to 2032.
- Platforms with low to moderate readiness have been assigned to the Post Decadal period 2033 to 2042.

While the Venus Technology Plan specifically addresses technical readiness of different instruments and modalities for Venus exploration, Table B.1 supplements that information with the assessment of readiness, including not only technical readiness but also the complexity of platform systems (delivery, deployment and operation at Venus, as well as the number of individual technologies involved), and resource needs (estimates of resources needed to bring the subsystem technologies to readiness and evaluate them).

B.9. Summary

Exploration of Venus will depend on exploration platforms that can conduct both remote and in situ exploration. Orbital platforms are generally technically mature, although some advances are needed to handle the Venus environment. Continuing developments of SmallSats and CubeSats is encouraging. Probes are also mature, with needed developments mainly aimed at miniaturization to benefit (especially) the sonde class of probe deployed after atmospheric entry. Major developments with the greatest scientific payoff will be in surface and aerial platforms and will be focused on extending the lifetime of these vehicles and the range of environments that they can access. The assessment of technology maturity and technical readiness presented here is recognized as being preliminary and a more detailed assessment is required using well established methodologies (Frerking and Beauchamp, 2016).

Table B-1. Venus Exploration Platform – Readiness of System and Subsystems

Roadmap Mission Modalities		Class	Orbiter			Atmospheric Probes			Surface Platform Lifetime			Aerial Platform - Altitude Control		
Specific Technology Capability		Platform	Surface Interior	Atmosph Ionosph	Small Sat	Skimmer	Probe	Sonde	Short	Long	Advanced	Fixed Mid-Cloud	Variable Mid-Cloud	Variable Sub-Cloud
		Time Frame	Near	Mid	Near	Near	Near	Mid	Near	Mid	Far	Near	Mid	Far
System Technologies	Aerobraking													
	Aerocapture													
	Entry													
	Descent and Deployment													
	Landing													
	Aerial Platforms													
	Landers - Short Durations													
	Landers Long Duration													
	Mobile Platform - Surface													
	Ascent Vehicle													
	Small Platforms/Cubesats													
	Autonomy*													
Subsystem Technologies	Energy Storage- Batteries													
	Energy Generation - Solar													
	Energy Generation - Radioisotope													
	Energy Generation-Alternative													
	Thermal Control - Passive													
	Thermal Control - Active													
	High temperature mechanisms													
	High temperature electronics													
	Chemical Propulsion													
	Solar Electric Propulsion													
	Communications													
	Guidance, Navigation, and Control													
Insutrument	Remote Sensing - Active													
	Remote Sensing - Passive													
	In Situ Probe - Aerial Platform													
	In Situ Surface - Short Duration													
	In Situ Surface - High Temp													
	In Situ Surface - Mobile Lab													
	Maturity Assessment - Low End													
	Maturity Assessment - High End													

*Autonomy is assessed at the platform level. This assessment does not include the impact of autonomy on the use of multiple platforms which is much greater than for a single platform.

LEGEND

- Very High
- High
- Moderate
- Low to Moderate
- Low

Appendix C. GOI Platform Assessments

The experimental platforms described in this *Venus Exploration Roadmap* were identified based on assessment of their scientific potential, technology readiness, and programmatic considerations including a logical feed-forward of science and technology capabilities. This Appendix describes how these platforms address the Venus exploration scientific strategy in the companion GOI document (VEXAG, 2019a).

C.1. Format of the GOI-Platform assessment tables

The three tables in this Appendix describe the role of measurements made from a platform in addressing each of the 23 investigations contained within the GOI for each of Goals I, II and III. They represent expanded versions of Table 2 of this document. The table for Goal I (Table C.1) illustrates the format. Along the horizontal axis, short hand descriptions of the goals, objectives and investigations are given along with the code number and rating of each investigation. Roadmap platforms are grouped by class horizontally, following the scheme used in the main body of the text. To the right of these shorthand descriptions of each platform type are the earliest time-frames when each platform would be ready for deployment.

The contribution of each platform to the successful completion of each investigation is indicated by the color of the cell at the intersection of an investigation and a platform. Measurements made from the platform can be either:

- Vital – Providing the measurements that are vital alone or in combination for completing the investigation.
- Supporting – Enabling measurements that substantially contribute to completing the investigation.

It is important to recognize that this two-level classification necessarily oversimplifies complex assessments where the real world is made up of many “shades of gray”. Within the supporting category, there is a spectrum of possibilities from modest to very substantial. In some cases, a supporting designation has been made to dramatize the even more important contribution of another platform. Accordingly, not all designations as Vital or Supporting are equivalent and there may be substantial differences in the contributions that two platforms make even though their designations are the same. Finally, these assignments have been made based on our current understanding of platform and experimental capabilities. As these capabilities advance, so the assignments may change. The tables should be viewed as work in progress and not an assessment that is fixed for eternity.

For some investigations in the GOI, only one type of platform is suitable for the measurement. In other cases, alternative platforms can be used although, though they are not necessarily equivalent in their utility. Many of the GOI investigations require complementary measurements from more than one platform. In some cases, these complementary measurements must be made sequentially in order that the results from one can be included in the design and deployment details for the next platform. For other investigations, they must be synchronous with one another to be useful. There has been no attempt in the tables to indicate these complexities but it is explained in the text accompanying the tables.

The final column in each table assesses the current ability to address the investigation. In almost all cases, measurements that are deemed vital to the investigations are feasible.

C.2. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-sized exoplanets

Table C.1. summarizes the ability of Roadmap platforms to address the eight investigations that comprise Goal I. **Our overall assessment is that all these modalities are vital.** Measurements made from orbiters are vital to the completion of most of these investigations but the optimal orbit type depends on the investigation. Probes are effective for only one of the investigations, I.B.IS (Isotopes), which can be addressed also by most of the surface platforms as well as by all of the aerial platforms. Surface platforms address a number of the investigations with the advanced surface platform excelling in investigations of the lithosphere and core because of its seismology capability. All of the aerial platforms can make vital contributions to the investigations of magnetism, isotopes and lithosphere. Sub-Cloud Aerial Platform capability can also make a vital contribution to the investigation of hydrous origins of the surface.

Table C.1 Goal One - Assessment of Ability of Roadmap Platforms to Address GOI Investigations

		Goal:	I. Early Evolution and Potential Habitability							
		Objectives:	A. Did Venus have liquid water?				B. How Venus informs pathways for planets?			
		Investigations:	Hydrous Origins	Re-cycling	Atmospheric Losses	Magnetism	Isotopes	Lithosphere	Heat Flow	Core
		GOI Code:	I.A.HO	I.A.RE	I.A.AL	I.A.MA	I.B.IS	I.B.LI	I.B.HF	I.B.CO
		GOI Rating:	1	1	2	3	1	1	2	2
Class	**Platform**	**Time Frame**								
Orbiter	**Surface-Interior**	**Near-term**								
	Atmosphere -Ionosphere	**Near-term**								
	SmallSat	**Near-term**								
Atmospheric Probes	**Skimmer**	**Near-term**								
	Probe	**Near-term**								
	Sonde	**Mid-term**								
Surface Platform Lifetime	**Short**	**Near-term**								
	Long	**Mid-term**								
	Advanced	**Far-term**								
Aerial Platform Alternate control	**Fixed Mid-Cloud**	**Near-term**								
	Variable Mid-Cloud	**Mid-term**								
	Variable Sub-Cloud	**Far-term**								
Overall Assessment										

There are important synergies between observations made by different platforms. However, because most of these investigations deal with surface, interior or global atmospheric properties, the measurements do not have to be made synchronously.

C.3. Understand atmospheric composition and dynamics on Venus

The atmosphere of Venus is a planet-sized heat engine. Energy deposition and the efficiency with which that energy is distributed throughout the planet are key constraints on potential habitability. For Earth, a fleet of in situ and orbital platforms provides for a complete, four-dimensional picture of atmospheric evolution. These investigations divide the atmosphere of Venus into regional areas, but these areas ultimately remain coupled in a planetary system. Table C.2 describes the two objectives and eight investigations defined to address this goal. **Our overall assessment is that all these modalities are vital.**

Orbiters play a vital role in all investigations the except for one case where the optimal orbit is the elliptical high eccentric orbit favored for most atmosphere observations. Short lived probes play a vital role in two investigations – those involving chemical interactions and aerosol properties. Long lived lander play a vital role in II.A.1 (Deep Dynamics and II.B.RB Radiation Balance), where the ability to measure surface wind speeds, temperature and radiation at one location on the surface through a solar day. Aerial platforms with the ability to change altitude within the cloud layer provide a vital role in all of the investigations except for I.A.UD (Upper Dynamics), which deals with the region of the atmosphere above 75 km that is inaccessible to aerial platforms.

There are important synergies between observations made by different platforms and particularly the orbiters and aerial platforms. Because the focus of these investigations is on the atmosphere, which is temporally and spatially variable, synchronous orbital and in situ measurements add substantial additional value to the investigations.

Table C.2 Goal Two - Assessment of Ability of Roadmap Platforms to Address GOI Investigations

		Goal:	**II. Atmospheric Dynamics and Composition**							
		Objectives:	A. What drives global dynamics?				B. What governs compositions, radiative balance?			
		Investigations:	Deep Dynamics	Upper Dynamics	Mesoscale Processes	Radiative Balance	Interactions	Aerosols	Unknown UV absorber	Outgassing
		GOI Code:	II.A.DD	II.A.UD	II.A.MP	II.B.RB	II.B.IN	II.B.AE	II.B.UA	II.B.OG
		GOI Rating:	1	1	2	1	1	2	2	3
Class	**Platform**	**Time Frame**								
Orbiter	**Surface-Interior**	**Near-term**								
	Atmosphere -Ionosphere	**Near-term**								
	SmallSat	**Near-term**								
Atmospheric Probes	**Skimmer**	**Near-term**								
	Probe	**Near-term**								
	Sonde	**Mid-term**								
Surface Platform Lifetime	**Short**	**Near-term**								
	Long	**Mid-term**								
	Advanced	**Far-term**								
Aerial Platform Alternate control	**Fixed Mid-Cloud**	**Near-term**								
	Variable Mid-Cloud	**Mid-term**								
	Variable Sub-Cloud	**Far-term**								
Overall Assessment										

C.4. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere

Unveiling the past requires understanding the present. Although the NASA Magellan mission provided the first global maps of Venus, many first-order questions regarding their interpretation and implications await answers, which motivates collecting higher-resolution imagery, topography, and many other datasets that are available for other terrestrial planets. The two objectives and formulate investigations formulated to address this goal are shown in Table C.3. **Our overall assessment is that all these modalities are vital.**

Table C.3 Goal Three - Assessment of Ability of Roadmap Platforms to Address GOI Investigations

		Goal:	**III. Geologic history and processes**							
		Objectives:	A. What geological processes shape surface?				B. How do atmosphere and surface interact?			
		Investigations:	Geologic history	Geo-chemistry	Geologic Activity	Crustal	Local Weathering	Global Weathering	Chemical Interactions	Geologic history
		GOI Code:	III.A.GH	III.A.GC	III.A.GA	III.A.CR	III.B.LW	III.B.GW	III.B.CI	III.A.GH
		GOI Rating:	1	1	2	2	1	2	3	1
Class	**Platform**	**Time Frame**								
Orbiter	**Surface-Interior**	**Near-term**								
	Atmosphere-Ionosphere	**Near-term**								
	SmallSat	**Near-term**								
Atmospheric Probes	**Skimmer**	**Near-term**								
	Probe	**Near-term**								
	Sonde	**Mid-term**								
Surface Platform Lifetime	**Short**	**Near-term**								
	Long	**Mid-term**								
	Advanced	**Far-term**								
Aerial Platform Alternate control	**Fixed Mid-Cloud**	**Near-term**								
	Variable Mid-Cloud	**Mid-term**								
	Variable Sub-Cloud	**Far-term**								
Overall Assessment										

Platforms with the broadest applicability for addressing these objectives are orbiters optimized for surfaces and interior observations and landed platforms with geochemical and seismological capabilities. Aerial platforms that can make infrared observations from below the clouds can also make vital contributions to investigations of Geochemistry (III.A.GC) and (near surface) Chemical Interactions (III.C.IN).

There are important synergies between observations made by different platforms and particularly the orbiters, surface and aerial platforms. Two of these investigations - III.A.GA (Geologic Activity) and III.A.CR (Crust) - relay at least in part on observing volcanic and seismic events and in these cases synchronous orbital and in situ observations can be very valuable.

VENUS EXPLORATION
VEXAG
ANALYSIS GROUP
2019

VENUS TECHNOLOGY PLAN

Cover image by John D. Wrbanek

At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major documents were selected to be updated: (1) the Goals, Objectives and Investigations for Venus Exploration: (GOI) document, providing scientific priorities for Venus, (2) the Roadmap for Venus Exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) the Technology Plan for future Venus missions. Here we present the 2019 version of the VEXAG Technology Plan.

Prepared by the VEXAG Focus Group on Technology and Laboratory Instrumentation: Gary Hunter (Chair), Jeffery Balcerski, Samuel Clegg, James Cutts, Candace Gray, Noam Izenberg, Natasha Johnson, Tibor Kremic, Larry Matthies, Joseph O'Rourke, and Ethiraj Venkatapathy.

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VEXAG Charter. The Venus Exploration Analysis Group (VEXAG) is NASA's community-based forum designed to provide scientific input and technology development plans for planning and prioritizing the exploration of Venus over the next several decades. VEXAG is chartered by NASA's Planetary Science Division (PSD) in the Science Mission Directorate (SMD) and reports its findings to NASA. Open to all interested scientists, VEXAG regularly evaluates Venus exploration goals, scientific objectives, Investigations, and critical measurement requirements, including recommendations for the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

1.0 Executive Summary

Venus exploration provides one of the most diverse sets of technical challenges in the solar system: an orbital environment allowing use of conventional orbiter platforms but with specialized instrumentation, an upper atmosphere with the most earthlike and accessible environment in the Solar System, and an extreme pressure/temperature environment on the surface.

This Technology Plan is simultaneously a status report, a development plan, and guiding document for the accompanying Goals, Investigations, and Objectives (O'Rourke et al., 2019) and Roadmap (Cutts et al., 2019) documents. The plan builds progressively from low to very high levels of maturity that could be accomplished over time with technology investments. Sections encompass both what is necessary for a single complete mission profile, and the broad array of technologies and components needed for wide range of mission proposals today and in the future. Needs for NASA investment arising from this study are summarized in Table 1.

Table 1. Major Needs Arising from This Study

Area	Needs
Entry Technology	Funding to ensure the entry technology capability does not atrophy
Subsystems	Development of high temperature electronics, sensors, and high-density power sources for the Venus environment with increasing capability
Aerial Platforms	A competitive program to determine which Variable Altitude balloons approach is most viable
In situ Instruments	Adaptation of flight-demonstrated technology and development of new instrument systems uniquely designed for the Venus environment
Communications and Infrastructure	Study of the feasibility of and methods for establishing a Venus communications and navigation infrastructure
Advanced Cooling	Investments in highly efficient mechanical thermal conversion and cooling devices
Descent and Landing	New concepts for adapting precision descent and landing hazard avoidance technologies to operate in Venus' dense atmosphere
Autonomy	Transitioning of automation and autonomous technologies to Venus-specific applications
Small platforms	Development of small platform as additions to larger missions, as well as a new mission type designed around small platforms
Facilities and Infrastructure	Support of laboratory facilities and capabilities for instrument and flight systems, including critical technologies to avoid atrophy of capabilities
Modeling and Simulations	Establishment of a system science approach to Venus modeling
Unique Venus Technology	Continued and expanded support for programs such as HOTTech, and other technology development

While many of scientifically important missions to the second planet can be implemented with existing technology, some fundamental science questions can only be successfully answered with new mission paradigms. Some ambitious missions require investment in and maturation of new technologies, while other new technologies can leverage recent advances and commercial developments. An effective Venus exploration technology program includes a balance of investments in short-term missions and technology, enabling new paradigms and more ambitious future missions in the medium- and long-term. This *Venus Technology Plan* performs a detailed assessment of the maturity of the technologies needed to conduct missions to Venus.

2.0 Technology Plan Overview

Common components comprise all mission types: instruments, power, operations, and communications, varying significantly depending on the type of mission. Technology developments from exploration of other planets and other fields enhance the missions that can now be conducted on Venus. In the future, developments across a range of fields will also enable new types of missions. An energetic Venus exploration program would combine well-established technologies and mission concepts with new capabilities to address core Venus science questions from a combination of orbital, aerial, and landed platforms.

Table 2 presents the framework for assessing technologies for Venus exploration. Time frames in the second column map to those used throughout the Venus Exploration Documents, and assume investments required for development are made:

N is Near-term: 2020 to 2022: Represents “existing” technologies that are ready today or with limited development. Missions using these technologies can be proposed now with fully developed science rationale.

M is Mid-term: 2023 to 2032 - First Decade: Technology will be ready with moderate development. Mission concepts using these technologies can be proposed and executed during the period of the next Decadal Survey.

F is Far-term: 2033 to 2042+ - Second Decade: Science rationale exists for technology and these missions, concepts of operation, science instruments, and associated technology require additional time and resources for development. Moderate to high levels of investment are required, and as a result, missions are likely to be executed after the next Decadal Survey.

Table 2 shows a range of technology areas discussed in subsequent sections. Categories include systems technologies (Section 3) at the scale of the spacecraft/platform; Subsystems technologies (Section 4) for particularly important components of these systems; and Instruments (Section 5) to be tailored to Venus’ unique conditions.

Table 3 describes possible Generic Mission Modes in the Near-, Mid-, and Far-term, with possible mission classes from 2020 to 2042 based on development progress from Table 2. Further discussion on the correlation between the GOI, Roadmap, and Technology Plan is in Appendix B. Table 4 color-codes the maturity of each technology relative to the Generic Mission Mode. An up arrow denotes a technology that has been notably advanced since the last Technology Plan. Lack of color-coding indicates that a technology is not applicable to that specific mission type. (Mobile Surface and Sample Return missions require significantly more technology development, and are thus far-term capabilities beyond the Decadal-after-next.)

For Near-term missions, technology maturity is very high (dark green).

For Mid-term missions, ready technologies need only limited (light green), or moderate (yellow) investment with defined pathways to achieve the generic missions described.

For Far-term missions, maturity ranges from being ready (green) to technology pathways nearing realization in that timeframe (yellow), to those needing basic research (red).

Table 4 shows a progression with increasing capabilites and increasingly complex missions. Near-term baseline missions could be proposed today, while new mission types and science could be proposed and flown in the next Decadal period with adequate technology development. Far-term Venus exploration will require, building from the Mid-Term, overcoming major technical challenges. Technology investment can surmount previous challenges of Venus exploration and enable new frontiers in Venus science and exploration.

Table 2. Framework for assessing technologies for Venus exploration

	Technology Area	Time Frame	Assessment
System Technologies	Aerobraking	N, M	Aerobraking is a mature technology and autonomous aerobraking can reduce the cost and risk while improve the time to achieve the desired orbit.
	Aerocapture	N, M	A large gap in aerocapture has been met with a nearly mature HEEET technology.
	Entry (Upper Atmosphere)	N,M	ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus.
	Descent and Deployment	M,F	Controlled descent of probes, drop-sondes, and aerial platforms in development for future use in atmospheric profiling. Incorporating guidance, with improved navigation, could enable more accurate targeting for these and lander systems.
	Landing	N,M,F	Hazard tolerance allows a wide range of near term missions. In the future, pin-point landing and hazard avoidance technologies will allow new mission scenarios.
	Entry, Descent, and Landing (EDL) Modeling & Simulation	N,M, F	Updates are needed for multiple modeling systems, including modeling for descent GNC pin-point landing and hazard avoidance.
	Aerial Platforms	N,M, F	Technology for near-term missions is mature. Technology investments are needed including new science instrumentation, and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show stoppers to impede the development of these capabilities.
	Atmospheric Entry Platforms	N,M, F	Methods to explore the atmosphere that are not aerial platforms include skimmers, probes, and sondes. These are advanced technologies, and future system may include targeted descent and surveying.
	Landed Platforms	N,M,F	Three classes of landed platform are envisioned involving increasing technical challenges: short duration containing analytical instruments (near term, current technology), long duration with sensors (mid term), and long durations with a complex instrument suite (far term). Significant advances have been made to enable longer term surface platforms.
	Orbiters	N,M,F	In general, orbiters are mature, capable, and can be adapted for different mission profiles. Potential technology enhancements include instrument advances, optical communications, and improved on-board computing.
	Mobile Platforms	F	Mobile systems would require a range of subsystems technology to allow, e.g., motion, power, cooling, and actuation, for extended periods. These are major challenges for mobile systems on the surface, but achieving these objectives with floating platforms may be more viable but also challenging.
	Ascent Vehicles	F	Ascent vehicles are only needed for Venus sample return. This is a very immature technology and much more demanding than for Mars surface sample return. Some concepts for Venus Surface sample return require the Venus Ascent Vehicle to descend to the surface. Atmospheric return missions are more feasible but significant challenges remain.
	Small Platforms	N, M, F	SmallSat, CubeSat and other small platform technology can make important contributions to Venus exploration. The development of small platform concepts as an addition to larger missions, as well as a new mission type or mission augmentation, is an integral part of a complete multistage Venus exploration program.
	Automation and Autonomy	M, F	Increasing capabilities for automation and autonomous decision-making combined with increasing computing power can change the way missions are conducted. Efforts to transition automation and autonomous technologies to Venus specific applications would enhance science delivered and mission success.

	Technology Area	Time Frame	Assessment
Subsystem Technologies	Power	M,F	Battery development is on-going for long-lived surface lander systems. Thermoelectric generators capable of operating in a 460 C environment are needed and maturing the capability of a mechanical converter (e.g., Stirling cycle) can be enabling for multiple mission types. Novel power concepts are also in development for future missions e.g., wind and other mechanical methods, solar power, or alternate chemical methods.
	Thermal Control	N,M,F	Extending lander life by a factor of 10 (to 25 hours) is feasible in the mid-term with passive cooling. Active cooling using mechanical coolers is essential for vehicles that must operate for periods of weeks to months with their payloads at Earth ambient.
	Extreme Environments	N,M,F	Advances in high-temperature mechanisms would be enhancing for a first-generation lander. High temperature electronics have been advanced for simple platforms.
	Communications	N,M,F	Optical communications have advanced notably and are expected to ready to enhance future missions. Proximity communications are needed to enhance data return from all *in situ* missions including on-surface communications.
	Guidance, Navigation, and Control	M	Miniaturized low power systems are needed for localization and attitude knowledge on probes, aerial platforms, dropsondes and for pinpoint landing.
Instruments	Orbital Remote Sensing	N	Technology for implementing these missions is here today. Advances in radar and infrared techniques would be enhancing.
	Probe and Aerial Platforms	N,M,F	Instruments for middle atmosphere exist but should be miniaturized. Sensors for chemistry in the lower atmosphere need improvement.
	Surface *in situ*	N,M,F	Need technologies in near term for "rapid petrology". In mid term, need maturation of sensors that operate at Venus ambient. In far term, need totally new approaches for mobile laboratory.

Table 3. Generic Mission Modes descriptions for Near-, Mid-, and Far-term Missions

	Mission Mode	Generic Description
Near-Term	Orbiters- Fixed	Orbiters for investigations including surface, interior, atmospheric, and ionosphere
	Small Sat	A single small or cube sat conducting a focused science investigation
	Deep Probe	A probe characterizing the environment down to the surface
	Multiple Shallow Probes	Shallow probes or skimmers characterizing the upper-mid atmospheres
	Short Lived Large Lander	A short lived lander comprised of a conventional electronics instrument suite
	Aerial Platform Fixed	Aerial platforms with ability to operate in the atmosphere for sustained periods, but without flight control
Mid-Term	Advanced Orbiters	Highly complex orbiter systems with increasingly capable instrument array and limited ability to independently carry out and optimize investigations
	Multiple Deep Probes	Deep probes and sondes coordinated with aerial platform operations and each other
	Subsatellite/ Small Sat Platforms	Communication and observations systems able to provide a multiple scientific investigations as well as a communications and navigation infrastructure
	Aerial Platforms: Altitude Control Upper and Mid Cloud	Aerial platforms operating in mid and upper clouds with ability to control altitude
	Increased Duration Large Lander	A lander comprised of advanced thermal thermal protection extending life to 12 hours or more, and increasingly capable conventional electronics instrument suite
Far-term	Small Platform Lander- Long Duration	Small in situ platforms capable of operating at Venus ambient conditions to accomplish focused science investigations
	Advanced Orbiter /Smallsat Networks	An orbiter network composed of advanced orbiters and small sats providing coordinated science and mission communications support
	Aerial Platforms: Altitude Control All Cloud	Aerial platforms with ability to operate in the atmosphere for sustained periods throughout the various cloud altitudes
	Lander -Cooled Long Duration	A complex long-lived cooled landed systems with a suite of advanced earth-ambient temperature instruments
	Lander Network	A number of lander systems coordinated and linked in multiple scientific investigations, which are composed of a mixture of increasingly complex high temperature landers
	Mobile Surface	Mobile laboratory systems able to travel significant distances on the surface
	Sample Return Clouds	Sample recovery and return from the upper atmosphere
	Sample Return Surface	Sample recovery and return from the surface

Table 4. Mission modes and applicable technologies for Near-, Mid- and Far-term missions

	Mission Mode	Near-term Missions						Mid-Term Missions						Far-Term Missions						
		Orbiters	Small Sat	Deep Probe	Multiple Shallow Probes	Short Lived Large Lander	Aerial Platform Fixed	Advanced Orbiters	Subsatellite/ Small Sat Platforms	Multiple Deep Probes and Sondes	Increased Duration Large Lander	Small Platform Lander- Long Duration	Aerial Platforms Altitude. Control Upper and Mid Cloud	Advanced Orbiter /Smallsat Networks	Aerial Platforms Altitude Control All Cloud	Lander - Cooled, Long Duration	Lander Network- Long Duration	Mobile Surface	Sample Return Clouds	Sample Return Surface
System Technologies	Aerobraking																			
	Aerocapture																			
	Entry ⬆																			
	Descent and Deployment ⬆																			
	Landing																			
	Aerial Platforms																			
	Flight ⬆																			
	Landers ⬆																			
	Mobility																			
	Ascent Vehicle																			
	Small Platforms ⬆																			
	Automation and Autonomy ⬆																			
Subsystem Technologies	Energy Storage- Batteries ⬆																			
	Energy Generation- Solar ⬆																			
	Energy Generation - Radioisotope Power																			
	Energy Generation-Alternative Sources																			
	Thermal Control - Passive																			
	Thermal Control - Active																			
	High temperature mechanisms ⬆																			
	Moderate temperature electronics ⬆																			
	High temperature electronics ⬆																			
	Communications																			
	Guidance, Navigation, and Control			MM		MM	MM													
Instrument	Remote Sensing - Active																			
	Remote Sensing - Passive																			
	Remote Sensing - Surface																			
	Remote Sensing - Atmosphere																			
	In-Situ Aerial Platform and Probe																			
	In Situ Surface - Short Duration ⬆																			
	In Situ Surface - High Temperature Sensors																			
	In Situ Surface - Long Duration Mobile Lab																			

Color		⬆		MM				
Title	Not applicable	Notable advancements since the last Rodamap	Very High. Ready for flight in this timeframe. Same as TRL 6	Mix of maturity. Some ready for flight, others at various maturity levels	Moderate to High. Limited development and testing still needed	Moderate. Active on-going R&D effort needed for readiness in this given timeframe	Moderate to Low. Significant R&D effort needed for readiness in this timeframe	Low. Major R&D effort needed with notable technical challenges
Description			Established for flight. May require resource commitment to maintain readiness or continuity of expertise		Defined transition to flight	Presently understood technical pathway to achieve capability by this timeframe	A viable foundation exists, but more than one technical pathway in consideration to achieve capability by this timeframe	It not clear how to achieve the targeted capability and basic research activities in multiple fields may be needed to achieve this capability by this timeframe

3.0 System-Level Capabilities

3.1 Aerobraking

Aerobraking technology uses atmospheric drag to modify the orbit of a spacecraft as it dips into the upper atmosphere of a planet. Information about density and winds is gleaned from spacecraft instruments, such as an inertial measurement unit (IMU) during flight through the atmosphere. Aerobraking was used by the *Magellan* mission to lower the spacecraft orbit to a radar mapping configuration, and to circularize the orbit for gravity observations. The *Venus Express* mission from the European Space Agency (ESA) performed aerobraking maneuvers to characterize variability in the upper atmosphere. Multiple mars missions, e.g., the *Mars Reconnaissance Orbiter,* used aerobraking to obtain proper orbital timing and altitudes for science measurements while significantly reducing propellant requirements. The Mars *MAVEN* mission utilizes aerobraking techniques to raise its periapsis and lower its apoapsis to facilitate relays with Mars landers. Recent Mars spacecraft have been equipped with onboard algorithms that use periapsis timing estimation to provide automated orbital sequencing updates. Advances in onboard software, which include atmosphere and aerodynamic models as well as guidance and maneuver calculation algorithms, offer additional capabilities while ensuring aerobraking mission constraints are satisfied (Murri et al., 2010, Murri, 2013). Although aerobraking technology is now mature, spacecraft design (particularly solar panels) and orbital mechanics must be compatible with the Venusian heat and stresses generated.

3.2 Aerocapture

Aerocapture uses a deep pass through the upper atmosphere in one single orbit. A properly designed entry system with efficient thermal protection systems (TPS) protects the payload from mechanical and thermal loading arising from the single large velocity reduction during entry. Aerocapture has not yet been employed in planetary missions, but it could enable larger payloads to be quickly placed in orbit around Venus, especially those requiring orbits closer to the planet. Novel aerocapture approaches to achieve velocity reduction through drag modulation could enable small spacecraft missions in the near term. A scalable design could lead to middle and large class payloads that place an orbiter, allowing for single or multiple probe or balloon deployment. ADEPT technology (see below) combined with drag-modulated aerocapture is highly scaleable.

3.3. Entry (Upper Atmosphere)

Entry technologies need to be implemented for all mission modes in Table 3 except remote sensing missions. Although successful entry at Venus has been accomplished many times, some of the thermal protection technologies used in prior mission are no longer available. In addition, entry technologies are needed for single or multiple science instruments being proposed with cube-sat small spacecraft constructs. Even orbital missions using small spacecraft could be accomplished using both traditional rigid as well as novel deployable entry systems. Entry risks must be retired to realize potential missions of opportunity. This has been recognized by recent SMD funding of advances in entry system technology, including the following approaches:

3.3.1. Heritage Carbon Phenolic: This solution requires a descent into Venus at high entry angles to mitigate the cumulative heat load imposing high-g loads on payloads (Venkatapathy etal. 2012). Although successful in the past, this technological capability has atrophied. Raw materials are not readily available, so reproducing appropriate materials would require expensive revival of retired manufacturing processes and qualification of replacement materials. Thus, this solution is prone to premature obsolescence.

3.3.2. 3-D Woven Thermal Protection System: Heatshield for Extreme Entry

Environment Technology (HEEET) systems use 3-D woven materials infused with resin to withstand a broad range of entry environments, resulting in mass-efficient ablative thermal TPS. Two companies are capable of, and one has been certified to produce, flight-ready components for future Venus missions. The HEEET dual-layer system creates a robust and mass-efficient heat-shield compared to Carbon-Phenolic system. HEEET material has been tested at the arc jet Interacting Heating Facility (IHF) and can be tailored to 10's of gs rather than 100s of gs with Carbon Phenolic, enabling use of more sensitive optics in instruments. The HEEET project is now fully matured at TRL 6 due to technology investments.

3.3.3. Adaptable Deployable Entry and Placement Technology (ADEPT): This innovative approach involves protecting the payload during entry with a large deployed entry system to reduce the ballistic coefficient due to larger surface area. The ADEPT concept has the potential to provide significant payload mass capability compared to conventional rigid entry systems. Because the ADEPT configuration can be folded into a much smaller cross section during launch, it is well suited for delivery of small spacecraft to orbit, or for a secondary payload adapters where packaging is a constraint. The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) (Bose et al., 2013) is an inflatable version of ADEPT that has been tested for Earth re-entry. The Venus Atmospheric Maneuverable Platform (VAMP) concept envisages using an inflatable structure for entry and flotation. ADEPT development for Venus is at TRL 5. Completion of ADEPT technology with a focus on secondary payload will enable small spacecraft aerocapture and entry missions.

It is critical that the SMD-PSD ensure the entry technology capability does not atrophy, and that periodic assessment and small investments be made to ensure that the necessary technologies continue to be available.

3.4. Descent and Deployment (from upper atmosphere to destination)

Descent/deployment capabilities are relevant to the same mission modes as those for entry. For probes, aerial platforms, and landers, rate of descent is controlled to stabilize vehicle attitude during passage to the surface through a progressively denser atmosphere. For probes and landed missions, velocity and attitude must be controlled during descent to provide time to sample different regions of the atmosphere, while limiting the dwell time at altitudes where the environment is harsh. This may require different sizes of parachutes or other aerodynamic structures. Special materials must be used to accommodate the high temperature acidic atmosphere, but these materials are available. For a landed mission with conventional electronics, the vehicle is brought quickly to the surface to minimize thermal input to the landing module. Maintaining attitude stability and minimizing jitter during descent are important for acquiring images with minimal motion blur. To date, all Venus descent systems studied/flown have been unguided, but incorporating guidance could enable more accurate targeting.

There is also a need to establish requirements for successful deployment of different aerial platforms. A successful balloon deployment/inflation test was conducted in the Earth's atmosphere during parachute descent (Hall et al., 2011) as a proxy for the Venus mid-cloud level. Descent velocity for a Venus airplane deployment depends on aircraft-specific design. Dropsondes deployed from an aerial platform could sample the atmosphere in multiple locations. Deep dropsondes can descend close to the surface relaying large amounts of high-resolution imaging data on potential landing sites. This technology requires further development for image generation.

3.5 Landing

By analyzing geomorphology data from previous missions (i.e., Magellan radar, Venera/VeGa lander imagery), models of the worst-case scenarios of slope have been developed to gain a better understanding of what types of terrain might be encountered. This method is meant for a semi-targeted landing in a broad region and will be the tool of choice for near-term landed missions. Hazard tolerance was the mode selected for the ViTaL study (Gilmore and Glaze, 2010) as well as for the recently proposed New Frontiers 2018 VICI Venus proposed lander mission (Glaze, 2017). Going forward, it should be feasible to draw on technologies developed by the Mars Program and the Space Technology Mission Directorate (STMD) under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program. Considerations related to pinpoint landing and hazard avoidance include:

3.5.1. PinPoint Landing involves guiding the vehicle to a designated surface location by correlating its own images with prior orbital reconnaissance. This capability is TRL 8 for Mars and will be employed by Mars 2020. For Venus, the descent images could be acquired in the near infrared through windows near 1 μm (Helbert et al., 2014) and/or using radar. Using heterogeneous data sets like this has been studied and appears feasible (Ansar and Matthies, 2009). The control function would be quite different from landing on Mars and would use a steerable parachute or aerodynamic control surfaces. Steerable parachutes have been used on Earth in precision drops from aircraft for decades and have been studied for Mars. For Venus, it would be necessary to study how precise the ultimate landing could be.

3.5.2. Hazard Avoidance could be used independently or in combination with pin-point landing. It would acquire surface information (imaging, Light Detection and Ranging LIDAR, and radar) during the final stages of descent to identify areas of hazard and use onboard Guidance, navigation, and control (GN&C) capabilities to avoid them. These capabilities are beyond TRL 7 for lunar applications (Jiang et al. (2016). Hazard avoidance will be part of the *Mars 2020* lander using hazard maps generated on Earth. Hazard avoidance is now being studied for Europa, including onboard hazard detection. Analogous guidance and navigation capabilities have also reached a high level of maturity for navigating to the surface of primitive bodies. Rapid progress in miniaturization of high-performance processors, cameras, and inertial measurement units for Earth applications may be applicable for Venus descent and enable significant reduction in the avionics size and power consumption for guided descent.

3.6 Entry, Descent, and Landing (EDL) Modeling & Simulation (M&S)

EDL M&S capabilities are critically needed for implementation of all Venus mission modes designated in Table 3 except for remote sensing missions. Venus entry missions can leverage ongoing investments in aerosciences and material response modeling capabilities, but there are several unique aspects of the Venus environment that require dedicated development:

3.6.1 Aerothermal Models: Predicting the convective aerothermal environment during Venusian entry will rely on NASA tools such as Data-Parallel Line Relaxation (DPLR) code (Wright et al., 2009) and LAURA (Mazaheri et al., 2010). Those largely include models for Venus presently, although updates may be required, esp. for entry conditions encountering turbulent flow. Required updates are largely in-plan in the currently funded Entry Systems Modeling (ESM) Project (https://gameon.nasa.gov/projects-2/entry-systems-modeling/**)**.

3.6.2 Shock Layer Radiation Models: Entry velocities are much higher than for Mars, which greatly increases the importance of shock layer radiation to overall heating levels. Databases in the NASA workhorse radiation codes NEQAIR (Cruden and Brandis, 2014) and HARA (Johnson et al., 2008) include relevant models for Venus shock layer heating, but are based on limited validation data. Required updates are not currently in-plan in the ESM Project.

3.6.3 Thermal Protection Material Response Models: Phenolic Impregnated Carbon

Ablator (PICA) and HEEET are two heatshield TPS materials for future Venus entry missions. PICA has flown in CO_2 (Mars) and air environment and the thermal response model for PICA is flight validated. HEEET is a new material and the thermal response model developed is considered medium fidelity as ground tests are limited to testing in air and do not provide the ability to "test as we fly". While the simulation tools allow for extrapolating from air testing to CO_2 (Venus), if the entry conditions are far beyond ground test conditions, then use of HEEET carries unknown risks. However, the thermal response models can be much improved for future use of HEEET if TPS flight data is obtained to develop high fidelity thermal response models to either reduce margin or identify areas of risks to mitigate them through better margin.

3.6.4 Descent Aerodynamics Models: At lower speeds, models are needed to ensure stable behavior of the entry vehicle before and after deployment of the parachute (or other aerodynamic structure). Required updates are largely in-plan in the ESM Project.

3.6.5 Flight Dynamics Models: Flight dynamics codes, such as the Program to Optimize Trajectories (POST) II (Powell et al., 2000), provide end-to-end simulation of the entire EDL sequence, including the impact of errors or dispersions. Current capability is likely largely sufficient for future mission needs.

3.6.6 Descent GN&C Models: Models and simulations are needed for pin-point landing and hazard avoidance, including performance of navigation sensors, hazard detection sensors, and the entire guidance, navigation, and control subsystem. Versions of such modeling and simulation capabilities have already been developed for guided descent for other planetary bodies, but such models must be updated to include relevant characteristics of Venus.

3.7 Aerial Platforms-Flight

A recent Venus Aerial Platform (VAP) Study (Cutts et al., 2018) examined the importance of mobility in the future exploration of Venus. Concepts examined range from fixed altitude platforms that are swept around Venus in the super-rotating flow, variable altitude platforms that can change altitude but have no other dimension of control, and platforms with some degree of three-dimensional control. The study found that variable altitude platforms preferably offer a significant increment in science over the fixed altitude platforms without the major increment in size, complexity, and associated low technology maturity of the platforms with lateral control. In addition, improvements in instruments, power, communications, and support capabilities for specific mission architectures are needed. There are multiple types of aerial platforms at different levels of maturity (Appendix B). They include a fixed-altitude (~55 km) super-pressure balloon (Hall and Yavrouian, 2013) as well as variable altitude platforms. The latter are referred to as aerobots because of their controllability; possibilities include pumped helium aerobots, pumped atmosphere aerobots, mechanical compression aerobots and phase change balloons.

Balloon navigation and autonomy require advances in satellite-based or on-board guidance and control. A program to determine which concepts are most suited to Venus operation while yielding the best scientific performance is needed. Superpressure balloons are a component of variable altitude balloons and represent a lower cost, lower risk alternative for a Venus mission.

3.8 Atmospheric Entry Platforms

Several atmospheric exploration methods are alternatives to sustained aerial platforms:

Skimmers are targeted vehicles with minimal thermal protection that enter and emerge from the atmosphere one or more times. The primary payload is typically a mass spectrometer or meteorological sensors. Sampled material analysis and data relay occur after the vehicle emerges from the atmosphere. Entry heating of the skimmer is modest, so TPS requirements can be relaxed and materials like PICA are quite adequate.

Probes are capable of surviving to surface contact, like Pioneer Venus. Possible payloads include a mass spectrometer, radiometer, nephelometer, etc. The high energy entry environment requires the use of HEEET technology.

Sondes with low mass can be deployed from an existing aerial platform. Sondes using conventional electronics as small as 5 kg can reach the surface of Venus and still remain operational. More advanced sondes would have the ability to navigate to surface features of interest in order to follow up survey investigations conducted with remote sensing.

3.9 Landers

3.9.1 Landers – Short and Increased Duration: Seven Soviet seven probes accomplished ~1-2 hour lifetimes with thermally insulated vehicles that maintained imaging sensors, communications systems, computers, and energy storage systems at temperatures below 100°C. The vehicles used insulated pressure vessels containing solid-liquid phase-change material (PCM) to extend surface lifetime. Improved passive thermal control allows survival on the surface of Venus for a period of hours with improved instrumentation.

The lifetime of these landers could be increased to 20 to 25 hours using technologies such as PCMs employing the liquid-vapor transition in water and ammonia (Bugby et al., 2009). This would allow scientists to make decisions based on limited follow-up observations. These technologies should be considered for lander mission development.

3.9.2 Landers – Long Duration: Recently developed high temperature electronics, sensors, and other technologies have matured to a state where a simple long-life scientific probe would be feasible for Venus operations. Concepts have been developed for deploying this type of small platform as a technology experiment, as a payload attached to a short-duration lander such as Venera-D (Zasova et al., 2019), or a platform that can be deployed in different configurations targeted for multiple types of science (NASA, 2017 and Grimm et al., 2018).

The Long-Lived In-Situ Solar System Explorer (LLISSE) (Kremic et al., 2018a) could monitor conditions for up to one full Venus day, observing day to night cycles of illumination, surface winds, and temperatures, as well as short-term changes in atmospheric gases. Even small day-night temperature shifts at the surface may change certain chemical stability regions if the surface-atmosphere composition is very near the equilibrium chemistry of some constituents (Kremic et al., 2018b). The potential of a long-lived seismometer system on the surface of Venus has also been studied (Kremic et al., 2018b).

Bringing high temperature electronic circuits for sensors, data handling, communications, and power management to TRL 6 by 2019-2021 (Kremic et al., 2018b) would enable operation of such a long-lived lander. Because there is presently no viable low-power data storage, periodic transmission of data would be needed for long-term monitoring along with a coordinated orbiter to support lander telecom. High temperature technology development to improve power sources, develop low power memory, improve communications throughput, and support an in-situ camera system would enhance long-lived missions. Active cooling of a lander with Stirling power generation and refrigeration is also possible but likely in the far-term given the technical challenges and amount of radioisotope material needed.

Development of the high temperature electronics, sensors, and high density power sources designed for operating in the Venus environment with increasing levels of capability would be enabling for future missions.

3.10 Orbital Spacecraft

In general, orbiters are mature, capable, and can be adapted for different mission profiles. For example, an orbiter in a circular, low altitude, near-polar orbit can include high-resolution global imaging radar global coverage, or very high resolution in targeted regions, combined with global radar sounding. These orbiters can also perform global infrared mapping and acquire improved gravity data. An orbiter in an eccentric, long-period orbit would facilitate remote sensing (e.g., nadir and limb viewing) and include *in situ* sensors of the ionosphere and induced magnetosphere. Technology for implementing these missions is available now, although engineering challenges include thermal management for the low orbit and reducing the time needed to aerobrake into the circular orbit. Potential technology enhancements include optical communications and advanced onboard computing.

3.11 Mobility – Surface or near surface

Mobile platforms that operate on the surface or in the lower atmosphere could analyze surface compositional variations on a regional scale. They could conduct geochemical and mineralogical measurements at multiple sites, undertake remote sensing from low altitudes (<1 km), and provide panoramic and high-resolution images correlated with composition. These systems include payload compartments maintaining temperatures at or below Earth ambient for imaging instruments. Currently, these high fidelity, visible imaging, and remote sensing infrared measurements require cooling. Operation at Venus surface temperatures would require high temperature sensor maturation. Other instruments may be operable in the range 150° to 200°C. Both power and cooling systems operable at Venus temperatures would need to be developed.

Concepts for floating platforms traversing the altitude range of the Venus surface and accessing all terrain types have been devised. Wheeled or legged vehicles require many mechanisms vulnerable to surface conditions. Issues of long-term near surface exposure to the corrosive conditions needs to be explored. Attaining a 10 to 100 km range would be challenging.

3.12 Ascent Vehicles

Venus Surface Sample Return (VSSR) is a long-range objective beyond 2043. Past studies of VSSR (Sweetser et al., 2003) have used architectures modeled on Mars Surface Sample Return. However, Venus sample return is significantly more challenging and is at a very low level of maturity, but will benefit from ongoing development of ascent vehicles for Mars.

3.13 Small Platforms

Rapid advances in spacecraft miniaturization have led to the development of CubeSats that create new opportunities for Venus exploration. The Venus Bridge Study (Grimm et al., 2018) concluded that SmallSat and CubeSat technologies for orbiters and various kinds of *in situ* vehicles (skimmers, probes, balloons and landers) and small platforms can make important contributions to Venus science (Grimm et al., 2018; Kremic et al., 2018). Technology is immature for some of these platforms, and any SmallSat at this stage is limited in size, weight, and power.

Propulsion systems enabling both injection on a Venus-crossing orbit and insertion into useful orbits or to Venus itself will be needed. Both ion propulsion and chemical propulsion systems, as well as aerocapture, are crucial. In addition, deployable antennas providing improved telecommunications links are highly desirable. Methods of achieving low cost for these missions without incurring a reliability penalty are needed. Small companies spearheading SmallSat and CubeSat development may be the key to small platforms fulfilling their potential.

Small simple lander platforms for extended surface operations periods may provide significant science return at greatly reduced costs. These lightweight systems could be delivered as a secondary launch from lunar missions, and may be deployed to the Venus surface from an aeroshell, balloons, or a lander. Investigations considered with these platforms range from meteorology, atmospheric chemistry, and seismology. **Development of small platform concepts as an addition to larger missions, as well as a new mission type or mission augmentation, is an integral part of a complete multistage Venus exploration program.**

3.14 Automation and Autonomy

Many aspects of Venus exploration are challenged by limited time and lack of human interactions during the mission. Machine-based intelligence can optimize science return by providing operation independent of human intervention. Automated systems can carry out set sequences of actions or make autonomous decisions with the capability for situational awareness, decision-making, and response. These advanced systems are rapidly increasing in capability and applicability and have great potential for Venus exploration, including 1) automated location of a desired surface target for image navigation and reduction of data volume, 2) altitude and mission control of a Venus balloon, and 3) autonomous lander operation on the surface. Autonomous systems can also collect and correlate data from the same phenomena observed from different vantage points on Venus to potentially identify events and patterns. Advances in automation and autonomy will broaden future Venus mission options. **Transitioning automation and autonomous technologies to Venus specific applications would enhance science delivered and mission success.**

Advanced automation, autonomy, and GN&C capabilities typically require advanced onboard computing capabilities, which must have minimal size, weight, and power (SWaP) consumption. Venus systems that face less extreme environments can be enhanced by advanced processors and other avionics. NASA's High-Performance Space Computing (HPSC) (Powell, 2018) is developing advanced computing systems useful for Venus aerial platforms and descent systems. Commercial-grade electronics may also offer improvements in performance and SWaP, such as processors developed for smart automobiles.

4.0 Subsystem Technologies

4.1 Power Subsystems

4.1.1. Energy Storage – Batteries: Many of the mission modes described in Table 3 could be implemented successfully with existing technology. Batteries for long-duration missions as well as work addressing requirements for missions such as LLISSE (Kremic et al., 2018a) are in development (Nguyen and Hunter, 2017). Batteries with high power density, reduced self-discharge, and rechargeability would expand mission capabilities. Secondary batteries may also handle peak loads accompanying a radioisotope power system.

4.1.2. Energy Generation – Solar: Remote sensing from space with orbital or flyby missions could be implemented with existing capabilities. Solar power is not needed for short-duration probes/landers. For long-lived landers, the limited solar energy reaching the surface poses significant challenges to developing efficient energy converters that operate at these temperatures. The limited power return from standard solar cells at higher temperatures return has motivated exploration of other approaches (Landis and Haag, 2013). HOTTech program solar cell development supports concepts including low-altitude balloons (0 to ~20 km) as well as aerial platforms at high altitudes (Grandidier et al., 2018). Advances in solar power technology could be enabling for aerial platforms. Airplanes require efficient, lightweight, and acid-resistant panels clad on both sides of the deployable. Long-duration aerobots (balloons) need very lightweight, acid-resistant systems to minimize the payload mass.

4.1.3. Energy Generation – Radioisotope Power Source (RPS): Radioisotope power may play an important part for extended *in situ* Venus exploration. Applications include aerial platforms, which may spend considerable time on the nightside of Venus but would operate at moderate temperatures (-20° to 150°C), and lander missions with temperatures are up to 460° C. Given the recent selection of the *Dragonfly* mission and plans for Mars sample return, both of which rely upon RPS, availability of sufficient mass for additional missions is uncertain.

4.1.3.1. High Temperature Thermoelectric Converter: Both Mars *Curiosity* and *Mars 2020* use a Multi Mission Radioisotope Thermoelectric Generator (MMRTG). An enhanced version- the eMMRTG - is also under development. Either could be used for aerial platform missions. For surface operations, requalification or redesign would be needed to tolerate high temperatures because the cold end of the RPS is at Venus ambient. Efficiency of thermoelectric systems is low under these conditions and a more efficient RPS system is desirable.

4.1.3.2. Advanced Stirling Radioisotope Generator (ASRG): A highly efficient Stirling engine coupled with linear alternators would be able to convert radioisotope heat to electrical energy. This technology could be implemented on an aerial platform at Venus provided it uses a low ballistic coefficient entry system, such as ADEPT, to mitigate the g loads on entry. The development of ASRG flight units was cancelled in November 2013.

4.1.3.3. ASRG for High g and High T Conditions: For entry systems, the ASRG would need to be ruggedized. Lacking current development work, feasibility of this has not been assessed. For operation near the Venus surface, a version of the ASRG capable of operating with its cold end near ~500° C is needed. A design of a Stirling power/cooler for Venus was formulated (Sierra Lobo, 2012). Materials (Ritzert et al., 2011) and availability of radioisotope power units pose challenges.

While all three of these options are technically feasible, the qualification challenges associated with the use of radioactive sources are formidable.

4.1.4. Alternative Energy Sources: For long-duration operations deep within Venus' atmosphere, wind shear and temperature gradients can be exploited to harvest energy. A wind turbine concept (Kremic et al., 2018a) is being developed to provide up to ~0.4W (Landis et al., 2017). Additional energy sources include 'lithium candles' using ambient atmosphere as an oxidizer for a thermal engine, and clockwork power using gravity or buoyant forces to drive mechanical generators (Nguyen and Hunter, 2017; Oleson and Paul, 2016). Another approach (Bachelder et al., 2014) involves a reversible fluid balloon, cycling up and down using the Venus atmospheric temperature gradient as a heat engine while harvesting power with a rotor beneath the balloon. There are certainly other approaches that could be considered.

NASA should continue and expand support for programs such as HOTTech, and identify where joint sponsorship and dual use development can be leveraged that would result in new mission capabilities.

4.2 Thermal Control

4.2.1. Passive Thermal Control: Thermal control systems minimize heat transfer from the environment to the probe. They also accommodate the heat generated by the internal components (e.g., power system, transmitter, and instruments). Passive thermal control was used on each of the Venera landers that operated for up to ~two hours on Venus. Contributing elements are: a) insulating materials to prevent heat leaking into the lander, b) the thermal capacity of the lander, and c) phase-change materials (PCMs) to absorb the heat entering the lander to mitigate the temperature rise. Minimizing heat leaks due to windows and cabling is an important part of the design process.

4.2.1.1. Large Landers: Technological readiness is very high for lifetimes of 2 to 3 hours. Liquid vapor PCMs (water or ammonia) may extend this by a factor of 10. PCM may also be coupled with a lithium getter to avoid the need to vent to the atmosphere.

4.2.1.2. Microprobes/Dropsondes: Thermal control technology advances will extend performance. Analyses for the Venus Aerial Platform study indicated that a streamlined vehicle as small as 5 kg could reach the surface and return surface images. Advances in insulation and phase change materials could extend the lifetime of such a vehicle.

4.2.1.3. Aerial Platforms: Aerial platforms could repeatedly descend to the base of the Venus clouds near 40 km, where temperatures approach 127º C. Passive cooling systems would be used repeatedly as the platform cycled to and from upper clouds (-23º C).

4.3 *Active Thermal Control*

An approach has been identified for a scalable, efficient, powered refrigeration/cooling system to maintain temperatures at operational levels for time periods as long as months (Kolowa et al., 2007). The current state of development of active thermal control technologies capable of operating in the Venus near-surface environment is low. At present, active coolers also need very high power, requiring that the efficiency of, e.g., a Stirling-type radioisotope generator be high. **Investments in advanced cooling technology are needed to enable future missions.**

4.4. Extreme Environment Technologies

4.4.1 High-Temperature Electronics:

4.4.1.1 Medium-Temperature Semiconductor-Based Electronics**:** Electronics stable at 200–300°C are commercially available with a broad set of options. Their use with cooling systems in Venus surface missions would significantly reduce the required delta-T, and hence reduce the power required for long-duration surface missions vs. systems cooled to Earth-ambient temperatures. They could be used without cooling systems for aerial platforms operating at temperatures too high for conventional silicon electronics.

4.4.1.2. High Temperature – Silicon Carbide Semiconductor-based electronics: The first microcircuits of moderate complexity that have shown extended operation *in situ* in Venus simulated surface conditions (Neudeck et al., 2016) and for thousands of hours at 500°C in Earth air ovens (Spry et al., 2017) have recently been implements. These circuits can be up scaled in complexity. Circuits with near 200 transistors per chip operated for 60 days in simulated Venus surface conditions (Neudeck et al., 2018; Voosen, 2017). Development is ongoing to demonstrate circuits and materials (Lukco et al., 2018) to provide operations for a long-lived surface lander, including all aspects needed to conduct a simple mission: power management circuits, signal conditioning electronics for multiple sensors, conversion into digital signals, and communication of the data at up to 100 MHz in frequency. Proof-of-concept demonstration of these technologies is ongoing to provide a complete, although simple, operational system. These developments in high temperature electronics represent a paradigm shift for Venus surface operations, extending functionality from ~2 hours to months. However, these electronics are 1980's levels; these systems do not have internal memory and so data are broadcast periodically to an orbiter. While ROM and RAM high temperature memory is in development (Nguyen and Hunter 2017), decreased power consumption and increased storage is needed for some mission scenarios.

4.4.1.3. Other High Temperature Electronics: Carbon nanotube electron sources can operate as field emitters without the need for a heated cathode. This field is immature but shows potential for low-powered, high-temperature memory and logic devices with no temperature-dependent leakage currents (Manohara et al., 2010). Diamond is a wide band gap semiconductor with outstanding semiconductor properties. Diamond PIN diodes operating at >500°C have been fabricated and tested as part of the HOTTech program. In Gallium Nitride Electronics, high electron-mobility transistor devices with pinch-off values <2 V have been demonstrated at 500°C, and more advanced circuits are under development (Nguyen and Hunter 2017). Substrates, passive components, and integration techniques (as well as packaging) require development and are at a lower level of maturity.

4.4.2 High-Temperature Mechanisms: Robotic mechanism technology enables short-duration (<1 Earth day) surface mission sample acquisition, drilling, and delivery. A general-purpose electromagnetic actuator (motor, feedback sensor and gearbox) has been tested in environmental chambers that operate at full Venus surface temperature and pressure.

For long duration (60+ days) surface and low atmosphere missions, even high-performance aerospace grade materials, coatings and lubricants need to be re-evaluated for compatibility with corrosive chemical species found in the near-surface atmosphere. Extended exposure to high ambient temperatures also causes over-aging of high strength metals. Ceramics offer a partial solution, but rigorous design and analysis methods need to be developed, and material formulations, processing steps, and test methods need to be standardized. A broad range of higher-level mechanisms are required for Venus, including the following:

4.4.2.1. High-temperature mechanisms for surface missions: Motors and encoders exist today that have operated for long periods at Venus surface temperatures. Many of the required mechanism components, materials, lubricants, etc. have been developed for operation at Venus temperatures. Significant materials development, along with testing and qualification for the full Venus environment is still required, especially at the system-level.

***4.4.2.2. High-temperature mechanisms for sample acquisition and storage*:** Sample handling and caching techniques need to be tested with the mechanisms and instruments for the full Venus surface environment, including control and fault algorithms.

4.4.2.3. High-temperature mechanisms for descent guidance and control. Guidance during descent will require mechanisms that can steer during at least some portion of the descent, facing temperature and corrosion challenges. This would be a relatively short-duration application, because Venus descent takes roughly less than one hour.

4.5 Communications

Communications for the "Trunk Line" between Venus and Earth, and among assets deployed to accomplish specific science activities will be required:

4.5.1 Communications for orbiters: Systems exist today for Venus orbiters to communicate with Earth at rates up to 10 Mb/s. Optical communications would enhance that data rate by at least a factor of 10. Component technologies developed for a Deep Space Optical Communications (DSOC) are now being integrated into the DSOC Flight Laser Transceiver (FLT) and ground-based receiver to enable photon-efficient communications. The DSOC payload is scheduled to launch in 2022 aboard the *Psyche* mission, reaching its destination in 2026. Optical communications could greatly enhance the capabilities of any future Venus mission involving radar imaging and interferometry provided an optical communications ground infrastructure is also developed.

4.5.2. Proximity Communications - probes, sondes and aerial platforms: For *in situ* atmospheric missions with direct-to-Earth communications, development of phased-array and other more efficient antennas would greatly enhance data return. The IRIS V2.1 Deep Space Transponder is targeted for Class-D space flight projects, utilizing COTS-grade components with minimal SWAP fully transponding at 3.8 W radio frequency output interoperable with NASA's Deep Space Network and will be used on MarCO. This technology will be important for future SmallSat and CubeSat orbiters, small low-cost probes, and aerial platforms.

4.5.3. Communications on the Surface: Surface-to-orbit communications systems for long-duration surface missions are under development for long-lived landers. Communication frequencies up to ~100 MHz are planned by 2021, closely coupled with electronics development (Kremic et al., 2018a,b). Reduction of power needs for data transmission and increases in both frequency and data rates are areas of future development.

Studies of the feasibility of and methods for establishing a Venusian communications and navigation infrastructure are recommended.

4.6 *Guidance, Navigation, and Control*

Guidance, navigation, and control (GN&C) for orbital spacecraft present no unusual requirements. For *in-situ* elements, GN&C is needed for a range of motion planning, sensing, and vehicle control tasks. A recent assessment of these technologies for *in-situ* missions (Riedel and Aung, 2013; Quadrelli et al., 2013) concluded for Venus:

4.6.1. Landed Missions: Application of pin-point landing and hazard avoidance technologies would be important for safe landing of a mission to the Venus tesserae. Venus-unique needs include infrared sensors for imaging the surface during much of the descent phase, techniques for matching heterogeneous (infrared and radar imaging) data sets to support pin-point landing, and methods for achieving control authority in thick, hot atmospheres, including various forms of gliding decelerators. Work is required on hazard detection sensors that survive and operate in the Venus low-altitude thermal environment, and on methods to achieve control authority in the dense Venus atmosphere that are efficient.

4.6.2. Aerial Platforms: Knowledge of the position, velocity, and attitude (especially azimuth) of a platform is important for scientific objectives and high-gain communications. This is possible by radiometric tracking from Earth when aerial platforms are in line-of-site from Earth. Beyond line-of-sight for aerial platforms descending below the cloud deck, position estimation, possibilities include using radiometric measurements from orbiters (SmallSats and CubeSats), onboard registration of night-side images of the surface, and global radar maps of the surface created from orbiters (Ansar and Matthies, 2009). For attitude, tilt is readily measurable with inertial sensors, but azimuth is difficult to obtain within or below the cloud deck. Potential onboard solutions include radio direction-finding on signals from Earth or orbiters, and registration of surface imagery to global radar maps when the platform is below the clouds on the night side. Miniaturized onboard navigation grade IMUs could sustain position, velocity, and attitude after each external source measurement for at most a few hours.

4.6.3. Mobile Platforms on The Venus Surface or in the Lower Atmosphere: These classes of mobility platforms require position and heading knowledge to control their motion. Depending on the level of autonomy, they may also require onboard perception systems.

New concepts are needed for adapting precision descent and landing hazard avoidance technologies to operation in the dense, hot Venus atmosphere.

5.0 Instruments

5.1. Remote Sensing—Active

Radar was used on both NASA (Magellan) and Soviet-era Venera spacecraft to characterize the Venus surface. Improvements since that time enable much higher resolution images to be obtained. Since then, ESA Venus Express (Gilmore et al., 2015) and new laboratory data (Helbert et al., 2017) have demonstrated the ability of an orbiter to collect emissivity spectra and interpret rock type (Dyar et al., 2017) and oxidation (Dyar et al., 2018) through windows ca. 1 μm in Venus' CO_2-rich atmosphere. SmallSats and CubeSats will enable cross-links between pairs of spacecraft. The number of transects will increase as the square of the number of spacecraft making it possible to greatly increase atmospheric coverage.

5.2 Remote Sensing – Passive

Advances in techniques for passive remote sensing have been accompanied by progress in miniaturizing instrumentation. Seismic events couple to the atmosphere as infrasound, so the dissipation of the waves can be observed from space as they modulate electron densities and optical emission. In the dense atmosphere of Venus, seismic waves are coupled 60 times more efficiently than on Earth, making smaller quakes detectable. Infrared spectral imaging techniques could detect events on both the nightside and dayside of Venus. Probing the tenuous reaches of the upper atmosphere on Venus may now be possible using miniaturized submillimeter sensors.

5.3 Aerial Platform and Probe

Many instruments needed for atmospheric probes and higher-altitude aerial platforms that maintain internal temperatures well below Venus surface ambient are relatively mature. Needed advancements are engineering challenges specific to missions or measurements. Miniaturization of instruments would reduce mass, power, and volume for these applications. The Venus Aerial Platform study (Cutts et al., 2018) identified several of these categories of observation:

5.3.1. Atmospheric Composition: Mass spectroscopy is the standard method for precision measurements coupled with targeted measurements using a Tunable Laser Spectrometer (TSL*)*. Progress in development of Quadrupole Ion Trap Mass spectrometers (QITMS) could enable aerial platforms with small science payload capability to do high caliber science.

5.3.2. Cloud Particle Size and Composition: Comprehensive understanding of Venus' cloud-forming aerosols and their precursors remains elusive. Optical techniques for characterizing particle sizes can be coupled with mass spectrometry techniques for measuring particle composition, but no such hybrid instruments exist. Cloud composition may be critical to detection of life in Earth-like environments (Limaye et al., 2018). Several methods might be used for life detection, including mass spectrometers that can investigate multiple aspects of the cloud composition (Baines et al., 2018).

5.3.3. Atmospheric Structure: Not all techniques for measuring atmospheric structure are applicable to a floating or flying platform. Most critical are methods for measuring position and velocity of the platform so that the velocity of the winds can be inferred.

5.4.3. Aerial Platform Geophysics: The proximity of a platform to the surface and its atmospheric contact enable several important geophysical techniques: infrasound seismology, remnant magnetism, electromagnetic (EM) sounding and gravimetry. Miniaturized instruments are needed and where feasible be demonstrated in Earth analog experiments.

5.4 Landed Missions: Ambient Temperature Operation

Landed missions focus on elemental, mineralogical, and petrologic analysisof surface materials. Due to limited lifetimes on the surface, the speed of these measurements is vital. The Venus Science Priorities for Laboratory Measurements and Instrument Definition Workshop report (Kremic and Singh, 2015) suggests that miniaturization and increased sensitivity of heritage instruments, such as mass spectrometers, will be key. A new generation of mature optical instruments can undertake chemical analysis with fewer moving parts and lower power requirements than traditional approaches. But these instruments must be tested against harsh Venus conditions. Calibration of these instruments with Venus reference atmosphere chemistry and physical environment is needed, as are technical developments:

5.4.1. Measurements of Chemistry: Two techniques are feasible for measuring the composition of elements. X-ray fluorescence (XRF) was used by the APXS instrument on *Curiosity* and will be used by the Planetary Instrument for X-ray Lithochemistry (PIXL) on *Mars 2020* (Allwood et al., 2014). Laser-induced breakdown spectroscopy (LIBS) generates a plasma from the heat of a laser and performs its measurements at standoff distances. The LIBS analysis ablates material, also investigating the depth of surface weathering by probing below the rock surface. Both ChemCam on *Curiosity* and SuperCam on *Mars 2020* use this technology (Clegg et al., 2012, 2014; Maurice et al., 2012, Wiens et al., 2012), and are coupled with a Raman spectrometer. Venus LIBS is being studied by the Venus In Situ Compositional Investigation (VICI) (Glaze, 2017) to investigate near-surface atmospheric gradients that could affect the focus of the LIBS ablation laser.

5.4.2. Measurements of Mineralogy: Both x-ray diffraction (XRD) and Raman spectroscopy can measure mineralogy. XRD was used by CheMin on *Curiosity* (Bish et al., 2013); it currently requires sample collection and transport into the lander for analysis. The Venus Flagship Mission Study (Hall et al., 2009) recognized that speed of operation would be critical for a short lifetime Venus mission and identified the use of a high-flux X-ray source based on a carbon nanotube X-ray emitter as a technology solution. Raman analysis (Clegg et al., 2014; Sharma et al., 2010 and 2011) under Venus surface conditions is not affected by the supercritical atmosphere. It is used on *Mars 2020* by SuperCam and the Scanning Habitable Environments with Raman Luminescence for Organics and Chemicals (SHERLOC) (Beegle et al., 2014) instrument. Any of these techniques would be highly useful on Venus.

5.4.3. Fine-Scale Contextual Elemental and Mineralogical Analysis: Context for geochemical and mineralogical measurements is critically important, and can be provided by a microscopic imager analogous to the Mars Hand Lens Imager (MAHLI) instrument on *Curiosity*. The ability to do such measurements *in situ* is technologically challenging.

The adaptation of flight demonstrated technology to Venus applications and the development of new instrument systems uniquely targeted to the Venus environment should continue to be supported. Establishing and maintaining laboratory, modeling, and simulation capabilities is strongly recommended.

5.5 Landed Missions: High Temperature Operational

Long-duration measurements on the surface of Venus are challenging with existing technology. But focused investigations will likely be viable by the mid-2020's using small long-lived platforms with electronics and sensors designed to operate without thermal, chemical, or pressure protection. One SmallSat mission concept (Kremic et al., 2018b) proposes to deliver two landers to the surface of Venus for 120 days of operation. Active development of Venus surface-appropriate technology (e.g., a meteorology suite, ruggedized MEMS seismometer and heat flux sensor, as well as high bandwidth communications) would enhance the viability of such a mission.

Extending camera operation beyond the short-term would also require technology development because conventional camera systems are not viable under Venus conditions. A simple approach using the high temperature technology from *Viking* could be considered (Huck et al., 1975). A solid-state magnetometer that measures magnetic field induced changes in current within a SiC pn junction is also being considered (Cochrane et al., 2016, 2018). Both of these instruments would require novel approaches and sustained development.

5.6 Long Duration Mobile Laboratory

Most concepts for a long-duration surface laboratory have assumed that much of the instrumentation is contained in a protected temperature-controlled volume at near-Earth ambient with active cooling. Challenges for long-duration missions still apply e.g. increased mass/power, but are more difficult due to the power needed to operate instruments in constant listening modes.

Significant thermal control advancements enabling use of mature sensors or high-temperature electronics systems, sensors, and memory specific to those instruments are needed. The ability to reliably mobilize a platform on the Venus surface for a long period of time requires advances in motors using permanent magnets with high Curie temperatures, and windings resistant to the corrosive atmosphere. Less conventional approaches include wind-driven sails (Landis et al., 2017), balloon "bouncers" (Bachelder et al., 1999), or mechanical walkers (Landis and Mellott, 2007; Sauder et al., 2015). A near-surface floating laboratory could rise to high altitudes for cooling, or operate near the surface but at cooler temperatures, reducing demands on the cooling system or high temperature mechanisms. In either case, new sensors for imaging and geophysical measurements (magnetic fields, gravity and infrasound) would broaden science return.

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Appendix A
Reading Between The Venus Exploration Documents

The GOI, Roadmap, and Technology Plan are correlated documents with different purposes. This is illustrated in Table A.1, which correlates the Roadmap's primary scientific objectives (based on the GOI), with Technology Plan Table 2. The Roadmap is more specific on, *e.g.,* multiple types of orbiters or surface lander platforms, than the Technology Plan. Table A.1 shows that there is a general correlation in the science delivered between the Roadmap and Technology Plan for comparable missions/mission modes. The Technology Plan then goes beyond the roadmap in the far term to discuss enabled new types of missions, capabilities, and science.

Table A.1. Science Payload Capability of Roadmap correlation with Technology Plan Mission Modes

Mission Mode		Generic Description	Example Roadmap Science Objectives
Near-Term	Orbiters	An orbiter using radar for surface mapping, and active remote sensing	Surface and Interior: Global and Targeted; Atmosphere and Ionosphere: Synoptic for for topography, emissivity, gravity, radar sounding, etc.
Near-Term	Aerial Platform Fixed	Aerial platforms with ability to operate in the atmosphere for sustained periods, but without flight control	Fix Altitude: Atmopsheric and Interior Investigations
Near-Term	Deep Probe	A probe characterizing the environment down to the surface	Classic entry probe or sonde: Broad suite of instruments includiing mass spectromenter, nepholometer, temperature, pressure, and surface imaging
Near-Term	Multiple Shallow Probes and Skimmer	Shallow probes characterizing the upper-mid atmospheres	Skimmer: Sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay
Near-Term	Lander Short Lived	A short lived lander comprised of a conventional electronics instrument suite	3-5 hour lander: Broad suite of instruments focused on atmospheric and interior investigations
Mid-Term	Advanced Orbiters	Highly complex orbiter systems with broad instrument array and limited ability to independently carry out and optimize investigations	Atmosphere and Ionosphere: Optimized for atmospheric remote sensing and in situ sensors of the ionosphere and induced magnetosphere
Mid-Term	Subsatelite/ Small Sat Platforms	Communication and observations systems able to provide multiple scientific investigations as well as a communications and navigation instrastructure	Highly targeted investigations requiring tailored orbits. May also provide relay, navigation support, and synergistic science for surface and aerial platforms
Mid-Term	Aerial Platforms- Altitude Control Upper and Mid Cloud	Aerial platforms operating in mid and upper clouds with ability to control altitude	Variable Altitude: Atmopsheric and Interior Investigations below 60 km and ability to tolerate higher temperatures
Mid-Term	Increased Duration Large Lander	A lander comprised of advanced thermal thermal protection extending life to 12 hours or more, and increasingly capable conventional electronics instrument suite	12 hours lander: Advanced suite of instruments with interaction with earth to optimize science delivered.
Mid-Term	Small Platform Lander- Long Duration	Small in situ platforms capable of operating at Venus ambient conditions to accomplish focused science investigations	Temperature, wind, chemical species for extended durations

In particular, the Roadmap identified a range of specific platforms that embody the Generic Mission Modes described in the Technology Plan. These are specific categories of platforms for deploying investigations from orbit, from within the atmosphere, and on the surface that employ the capabilities in the Technology Plan for specific mission functions. **The Roadmap Mission Platforms are embodiments of the Generic Mission Modes of Technology Plan Table 2.** These include:

- Lander capabilities grouped as short-lived, long–lived, and advanced:
  - **Short-lived landers**: Patterned on the technologies used in past Soviet era lander missions but with improved instrumentation.
  - **Long-duration landers:** Use high temperature electronics capable of operating at 500°C, which are still under development and have never been used at Venus.
  - **The Advanced Lander**: Envisaged for the post decadal period would incorporate both kinds of capabilities with extensions to the useful lifetime of both as well as the progress in precision landing. In the post decadal period, the Roadmap envisages Advanced landers being developed that include part of the instrument payload implemented with conventional electronics that would function for up to an Earth day and part of it with high temperature electronics which would operate for up to a Venus years.

- Three types of platform for making measurements of no more than a few hours in the atmosphere:
  - **Skimmer:** A targeted vehicle with minimal thermal protection that enters and emerges from the atmosphere one or more times. The primary payload is a mass spectrometer but could also include meteorological sensors. Analysis of the sampled material and data relay would occur after the vehicle emerges from the atmosphere. The entry heating experienced by a skimmer is modest and consequently thermal protection system requirements can be relaxed and materials like PICA are quite adequate.
  - **Probe:** This is the classic (e.g., Pioneer Venus) probe capable of surviving to surface impact. Possible payloads include a mass spectrometer, radiometer, nephelometer, or other instruments for surface imaging and atmospheric studies. The high energy entry environment requires the use of HEEET technology discussed in Section 5.3.
  - **Sonde:** A low-mass sonde deployed from an aerial platform that has already entered and deployed in the atmosphere. Possible payloads are similar to those indicated for the Atmospheric Entry (Probe) mission but would be limited in mass. Analysis suggests that sondes using conventional electronics as small as 5 kg can reach the surface of Venus and still remain operational. More advanced sondes would have the ability to navigate to surface features of interest in order to follow up survey investigations conducted with remote sensing.
- Three categories of orbital spacecraft to conduct investigations:
  - **Orbiter – Surface and Interior:** The spacecraft is in a circular, low altitude, near polar orbit. Imaging radar could provide global coverage with high resolution, or very high resolution in targeted regions combined with global radar sounding. These orbiters could also perform global infrared mapping and acquire improved gravity data. The technology for implementing these missions is available now although engineering challenges include thermal management for the low orbit and reducing the time needed to aerobrake into the circular orbit. Potential technology enhancements include optical communications and advanced onboard computing.
  - **Orbiter -Atmosphere and ionosphere:** The spacecraft in an eccentric, long-period orbit. Extensive instrument suites would facilitate remote sensing (e.g., nadir and limb viewing) and in situ sensors of the ionosphere and induced magnetosphere. Typically, the spacecraft technology is less demanding than for investigations of the surface and interior and the data return requirements are typically less demanding. Advanced onboard computing would be an asset for performing event detection onboard (lightning, quakes, volcanic eruptions).
  - **Orbiter – SmallSat or CubeSat:** An orbiting SmallSat (or CubeSat), or multiple SmallSats to measure different locations at the same time. SmallSats may potentially host a wide variety of instruments. However, any single SmallSat is limited in size, weight, and power in comparison to conventional orbiters. Developments in miniaturization will be needed to fully exploit these capabilities. Access to Venus orbit could be enabled by advances in solar electric and chemical propulsion as well as aerocapture (Section 5.2).

Overall, the VEXAG "Roadmap for Venus Exploration" describes a program of Venus exploration featuring twelve mission modalities as presented in O'Rourke et al. (2019) in the Goals, Objectives, and Investigations document. Table A2 indicates those that are potentially useful to each GOI Investigation. VEXAG GOI is not designed to prescribe particular missions; the omnibus table is only intended as a general guide.

Table A3 examines the various Roadmap Platforms based on their technology maturity (similar to Table 4.3). **These Roadmap Platforms are deemed viable based on the Technology Plan and based on their technology maturity and timeframes considered.** The Venus Roadmap assumes a higher level of maturity required for mission consideration. For example, it requires enabling technologies to have advanced beyond the stage of basic research (i.e. invention required to be included), and it does not assume progressive technology development to enable a vision of future missions. Thus, Table A3 is a more conservative estimate of Technology Maturity than Table 4.3 above.

Table A.2 Mapping Between GOI and Roadmap Related To How Various Roadmap Missions Address GOI Science

VEXAG GOI			Roadmap Mission Modalities											
Goal	Objective	Investigation	Orbiter Surface/ Interior Near-term	Orbiter Atmosphere Near-term	Orbiter SmallSat Near-term	Atmospheric Entry Skimmer Near-term	Atmospheric Entry Probe Near-term	Atmospheric Entry Sonde Mid-term	Surface Platform Short-lived Near-term	Surface Platform Long-lived (Pathfinder) Mid-term	Surface Platform Long-lived (Advanced) Far-term	Aerial Platform Fixed Altitude Near-term	Aerial Platform Variable Altitude Mid-term	Aerial Platform Variable+ Altitude Far-term
I. Early evolution and potential habitability	Did Venus have liquid water?	I.A.HO. (1)	Vital	Supporting	Supporting				Vital		Vital			Vital
		I.A.RE. (1)	Vital						Vital		Vital	Supporting	Supporting	Supporting
		I.A.AL. (2)		Vital	Vital									
		I.A.MA. (3)		Supporting	Supporting				Supporting	Supporting	Supporting	Vital	Vital	Vital
	How does Venus inform pathways for planets?	I.B.IS. (1)				Vital	Vital	Vital	Vital		Vital	Vital	Vital	Vital
		I.B.LI. (1)	Vital	Supporting	Supporting					Supporting	Vital	Vital	Vital	Vital
		I.B.HF. (2)	Vital								Vital			
		I.B.CO. (2)	Vital		Supporting					Supporting	Vital			
II. Atmospheric dynamics and composition	What drives global dynamics?	II.A.DD. (1)		Vital	Vital		Supporting	Supporting		Vital	Vital	Supporting	Vital	Vital
		II.A.UD. (1)		Vital	Vital	Supporting								
		II.A.MP. (2)		Vital	Supporting		Supporting	Supporting				Supporting	Vital	Vital
	What governs composition and radiative balance?	II.B.RB. (1)		Vital	Vital		Supporting	Supporting	Supporting	Vital	Vital	Supporting	Vital	Vital
		II.B.IN. (1)		Vital	Supporting		Vital	Vital		Supporting	Supporting	Supporting	Vital	Vital
		II.B.AE. (2)		Supporting	Supporting		Vital	Vital	Supporting	Supporting	Supporting	Vital	Vital	Vital
		II.B.UA. (2)		Vital	Vital		Supporting	Supporting				Supporting	Vital	Vital
		II.B.OG. (3)	Vital	Vital	Vital		Supporting	Supporting	Supporting	Supporting	Vital	Supporting	Vital	Vital
III. Geologic history and processes	What geologic processes shape the surface?	III.A.GH. (1)	Vital	Vital	Vital									Supporting
		III.A.GC. (1)	Supporting	Supporting	Supporting		Supporting	Supporting	Vital	Vital	Vital			Vital
		III.A.GA. (2)	Vital	Supporting	Supporting		Supporting	Supporting		Supporting	Vital	Supporting	Supporting	Supporting
		III.A.CR. (2)	Vital	Supporting	Supporting					Supporting	Vital	Vital	Vital	Vital
	Atmosphere and surface interactions?	III.B.LW. (1)	Supporting	Vital	Vital		Vital	Vital	Vital	Vital	Vital			Supporting
		III.B.GW. (2)	Vital	Vital	Vital				Supporting	Supporting	Supporting	Supporting	Supporting	Vital
		III.B.CI. (3)	Supporting	Supporting	Supporting		Vital	Vital	Vital	Vital	Vital	Supporting	Supporting	Vital

Color Code	Meaning
(blue)	**Vital:** Mission modality enables measurements that are vital (either alone or in combination) to completing the investigation.
(yellow)	**Supporting:** Mission modality enables measurements that substantially contribute to completing the investigation.

Table A.3 Technology Maturity of technologies needs for Venus Roadmap Platforms.

	Roadmap Mission Modalities													
		Class	Orbiter			Atmospheric Probes			Surface Platform Lifetime			Aerial Platform - Altitude Control		
Specific Technology Capability		Platform	Surface Interior	Atmosph Ionosph	Small Sat	Skimmer	Probe	Sonde	Short	Long	Advanced	Fixed Mid-Cloud	Variable Mid-Cloud	Variable Sub-Cloud
		Time Frame	Near	Mid	Near	Near	Near	Mid	Near	Mid	Far	Near	Mid	Far
System Technologies	Aerobraking		Very High	Very High										
	Aerocapture													
	Entry					Very High	Very High	Very High	Very High	Very High	Very High	Very High	Very High	Very High
	Descent and Deployment								Very High	Very High	Moderate	Very High	High	High
	Landing								Very High	Very High	Moderate			
	Aerial Platforms											High	Moderate	Low to Moderate
	Landers - Short Durations								Very High		Moderate			
	Landers Long Duration									Moderate	Moderate			
	Mobile Platform - Surface													
	Ascent Vehicle													
	Small Platforms/Cubesats				High	High		High				High		Moderate
	Autonomy*		Very High	Very High	High	Very High	Very High	Moderate	Very High	High	Moderate	Very High	High	Moderate
Subsystem Technologies	Energy Storage- Batteries		Very High	Very High	Very High	Very High	Very High	Very High	Very High	Moderate	Moderate	Very High	Very High	High
	Energy Generation - Solar		Very High	Very High	Very High							Very High	High	Moderate
	Energy Generation - Radioisotope													
	Energy Generation-Alternative										Moderate			
	Thermal Control - Passive		Very High	Very High	Very High		Very High	Very High	Very High	Very High	Moderate	Very High	High	Moderate
	Thermal Control - Active													
	High temperature mechanisms								Very High	High	High			
	High temperature electronics									Moderate	Low to Moderate			
	Chemical Propulsion		Very High	Very High	Moderate									
	Solar Electric Propulsion		Very High	Very High	Moderate									
	Communications		Very High	Very High	Very High	High	Very High	High	Very High	Moderate	Moderate	High	Moderate	Moderate
	Guidance, Navigation, and Control		Very High	Very High	Very High	High	Very High	Moderate	Very High	High	Moderate	High	Moderate	Low to Moderate
Insutrument	Remote Sensing - Active		Very High	High	Moderate									
	Remote Sensing - Passive		Very High	High	High									
	In Situ Probe - Aerial Platform					Very High	Very High	High				Very High	High	Moderate
	In Situ Surface - Short Duration								High		Moderate			
	In Situ Surface - High Temp									Moderate	Low to Moderate			
	In Situ Surface - Mobile Lab													
	Maturity Assessment - Low End		Very High	High	High	Very High	Very High	Moderate	Very High	Moderate	Low to Moderate	High	Moderate	Low to Moderate
	Maturity Assessment - High End		Very High	High	High	Very High	Very High	High	High	Moderate	Moderate	High	Moderate	Moderate

*Autonomy is assessed at the platform level. This assessment does not include the impact of autonomy on the use of multiple platforms which is much greater than for a single platform.

LEGEND

- Very High
- High
- Moderate
- Low to Moderate
- Low

Appendix B
Infrastructure Overview

1. **Ames Research Center (ARC) Arc Jet Interaction Heating Facility (IHF) Facility Enhancement:** The new 3" nozzle funded by SMD enhanced the NASA ARC IHF capability considerably and the capability allowed HEEET to be demonstrated for entry conditions ~ 5000 W/cm2 and > 5 atm. Missions (NF-4) that planned to use HEEET have opted to fly low entry flight path angle taking advantage of the mass efficiency of HEEET to achieve low entry g load. In order to verify/qualify HEEET design for future missions, it is necessary to have a slightly bigger (~ 4.5" dia.) nozzle. This will be the lowest cost to address future mission risks.

2. **Glenn Extreme Environment Rig (GEER):** The GEER vessel, operated by Glenn Research Center, has been operational since spring of 2015. This 0.8 m3 pressure vessel is capable of maintaining the physical and chemical conditions of the surface of Venus for an indefinite period of time, with continuous tests thus far of up to 80 days. Multiple user ports and a large hatch allow for accommodation of test articles ranging from 1 mm diameter geologic samples to complete instruments. Power and data feedthroughs have been custom developed to operate in the unique thermochemical environment, and a suite of candidate spacecraft component materials have been characterized for resistance to the Venus environment. Additionally, science investigations have used the vessel to recreate the surface conditions of Venus in order to study the unique behavior of surface-atmosphere interactions. GEER continues to gain new functional and analytic capability and is guided by annual reviews by an independent science advisory panel. GEER provides unmatched capability to mix and maintain an eight-component gas mixture in a large pressure vessel with precise thermal and chemical control.

3. **Goddard Flight Center:** A small Venus pressure test chamber, also known as VICI (Venus In-situ Chamber Investigations) available for testing of small components/instruments and running short-term experiments. The operating range of the chamber is room pressure to ~1380 psi (~96 bar), 25°C to 490°C, and the 'working' gas is typically CO_2. Gas mixtures that incorporate the three most abundant gases on Venus, CO_2, N_2, and SO_2, are also used depending on the experiment. The chamber interior or functional work volume is a five-inch diameter 316 stainless steel cylinder with approximately 11 inches of vertical space. Electrical/tubing feedthroughs and small sight windows are options that can be incorporated as needed into any particular test. There are pending plans to upgrade the chamber to a more resistant alloy.

4. **NASA JPL:** Multiple chambers exist of varying sizes and capabilities. 1) Venus Weathering Chamber. A 1.5 cm diameter by 15 cm long. chamber capable of exposing small material samples. Test conditions of up to 1000 °C and 1000 bars with mixtures of CO_2, N_2 and SO_2 gases are possible. 2) Small Venus Test Chamber. Provides a 10 cm diameter by 1.6 m long cylindrical working space using 460 °C, 92 bar CO_2 gas. An optional window facilitates optical experiments and pneumatic sample transfer experiments are accomodated. 3) Venus Materials Test Facility (VMTF). This chamber provides an 18 cm diameter by 56 cm tall cylindrical space suitable for a variety of testing purposes including testing of motors, drills and other electrical devices. It can provide 460 °C, 92 bar test conditions with CO_2 gas. 4) Large Venus Test Chamber (LVTC). A working space 31 cm in diameter and 2.4 m long. It

can provide 460 °C, 92 bar test conditions with CO_2 gas. Supports full scale Venus drilling and sample transfer experiments that include linear deployment of a drill assembly to the surface in addition to the drilling operation itself.

5. **Venus Optical Analysis Chamber:** Los Alamos National Laboratory has two – 2 m long, 110 mm diameter chambers that are capable of optically probing samples under 92 atm of supercritical CO_2 at 465ºC. These two chambers can be operated independently (2 m long path length) or together (4 m long path length). The chamber can be capped with sapphire, quartz or a steel plug on one or both ends of the chamber. It enables both active remote sensing with a laser as well as passive spectroscopy.

6. **Johns Hopkins APL:** The APL Venus Environment Chamber (AVEC) is a 0.7 L, portable, Inconel, vessel capable of maintaining conditions of 4000 psi at 500 C. Gases for the vessel are user-supplied and AVEC is expected to support the atmosphere of Venus and other planets. The vessel has a single feedthrough that is capable of supporting 2 and 4 wires for monitoring and operating active interior components, while physical conditions are monitored by a thermocouple (set in a 6” thermowell) and integrated pressure transducer.

Appendix C
Technology Highlights Since 2014

Venus Technology Roadmap presented in this document has notable differences from the previous version in 2014. Recent technology advancements have changed the landscape of Venus exploration and thus the Findings of this present Venus Technology Plan. In particular, Table A4 shows 2014 Findings and a 2019 State-of-The-Art Summary. This Table highlights that, although further development is needed due to the unique challenges of Venus exploration, advancements in Venus relevant technology in the last four years have been significant.

Table A4. 2014 Technology Plan Findings and 2018 Summary of the Present State-of-the-Art

2014 Finding	2019 State-of-the-Art Summary
Entry Technology for Venus: The thermal protection system (TPS) technology developed for missions involving entry into the Venus atmosphere has not been used for many decades, and the ability to easily replicate it has been lost. Two attractive options for replacing the prior technology, 3D Woven TPS and ADEPT technology, are currently under development under the sponsorship of the Space Technology Missions Directorate (STMD).…**This development needs the continued endorsement of the Planetary Science Division (PSD).**	HEEET is fully mature technology and ready for mission infusion. This closes a very large gap for Venus aerocapture, entry, descent and landed missions. ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus. See Section 3.3.2.
High-Temperature Subsystems and Components for Long-Duration (months) Surface Operations: Advances in high-temperature electronics and thermo electric power generators would enable long-duration missions on the surface of Venus operating for periods of as long as a year, where the sensors and all other components operate at Venus surface ambient temperature. …. **Development of the high temperature electronics, sensors and the thermo-electric power sources designed for operating in the Venus ambient would be enabling for future missions.**	Notable advancements have been made in moderately complex high temperature electronics with demonstration Venus simulated conditions for up to 60 days. These electronics are the foundation for development of a long-lived lander with an array of high temperature sensors intended for Venus surface operation for up to 120 days or more. See section 5.5.
Aerial Platforms for Missions to Measure Atmospheric Chemical and Physical Properties: Aerial platforms have a broad impact on exploration of Venus. After more than a decade of development, the technology for deploying balloon payloads approaching 100 kg with floating lifetimes in excess of 30 days near 55 km altitude is approaching maturity. Vehicles for operation at higher and lower elevations in the middle atmosphere and with the ability to change and maintain specific altitudes are much less mature and need development. A buoyant vehicle, operating close to the Venus surface requires major development. Aerial platforms would be an essential part of any atmospheric or surface sample mission. ***Development of these aerial platform technologies is enabling for mid-term and far-term missions.***	Technology investments are needed including new science instrumentation and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show stoppers to impede the development of these capabilities. Flight tests using the Earth environments as an analog for Venus will be needed to optimize both the vehicles and science experiments. See section 3.7.
***In Situ* Instruments for Landed Missions:** Since the Planetary Science Decadal Survey in 2011, there has been significant progress in instruments for surface geology and geochemistry (e.g., laser induced breakdown spectroscopy [LIBS] in conjunction with remote Raman spectroscopy has been demonstrated). Advances in other instruments for "rapid petrology" also appear possible spurred in part by developments	A workshop focused on instruments for Venus surface was conducted. Laser induced breakdown spectroscopy (LIBS) and Raman spectroscopy has been demonstrated. NASA awarded technology development funding to the VICI

underway for investigating the surface of Mars. ***A workshop focused on instruments for Venus surface operations would be helpful for defining future directions and such a workshop is planned for January 2015.***	New Frontiers 4 mission to mature the VEMCam (Raman and LIBS) instruments. See Section 5.4.
Deep Space Optical Communications: Development of deep space optical communications technology would enhance the performance of missions involving high resolutions radar imaging of the surface of Venus enabling mapping to be completed much more rapidly than with RF communications systems. NASA STMD is currently developing the key component technologies for deep space communications and NASA's Space Communications and Navigations Directorate (SCaN) is planning on a 10-m optical ground station by 2015**. Implementation of a flight experiment of optical communications would represent a major step forward in the adoption of the technology, and if implemented on a Venus orbiter mission, it could significantly enhance the science return.**	Development of three key enabling components of a Deep Space Optical Communications (DSOC) were developed by the Space Technology Missions Directorate (STMD) Game Changing Development program: a low frequency vibration isolation platform; a ground-based photon counting array; and a flight photon counting receiver for the uplink signal. These technologies are now being integrated into a system scheduled to launch in 2022. See Section 4.5.
Advanced Power and Cooling Technology for Long-Duration Surface Operations: Most scientific objectives at the Venus surface require sensors that operate at temperatures well below 100ºC. Current passively cooled systems are limited to a lifetime of 3 to 5 hours. Advanced liquid-vapor phase change cooling could extend lifetimes to 24 hours and could benefit the Tesserae lander conceived as a mid-term mission. Highly efficient mechanical thermal conversion and cooling devices (typified by the Stirling cycle-engines and capable of operating in a 460ºC environment) are required for this purpose. With lifetimes of months, these are enabling for the Venus mobile surface and near-surface laboratory mission concepts. ***Investments in advanced power and cooling technology are needed to enable both mid-term and far-term missions.***	Investments are presently on-going in battery and power technology with the objective of enabling small platform long-lived surface landers. Some advancements have been made in passive cooling approaches, but overall limited work has been done in advancing technologies such as Stirling cycle-engine to enable power and cooling since the 2014 Technology Plan. See Section 4.1
Advanced Descent and Landing: Lander missions for the mid-term would target the tesserae regions of Venus which radar imaging indicates to be extremely rough and irregular topography. Following the Mars model, achieving safe landings in regions of complex topography will require the development of improved targeting accuracy and precision landing techniques potentially accompanied by hazard avoidance during the terminal-descent phase. ***New concepts are needed for adapting methods of terrain relative navigation and guidance to operation in the dense Venus atmosphere.***	Precision landing and hazard avoidance technologies have reached TRL 7 to 8 for missions to the Moon and Mars and are under development for Europa. These methods require significant further work for adaptation to the dense, hot atmosphere and long descent time at Venus. See Sections 3.5 and 3.6.