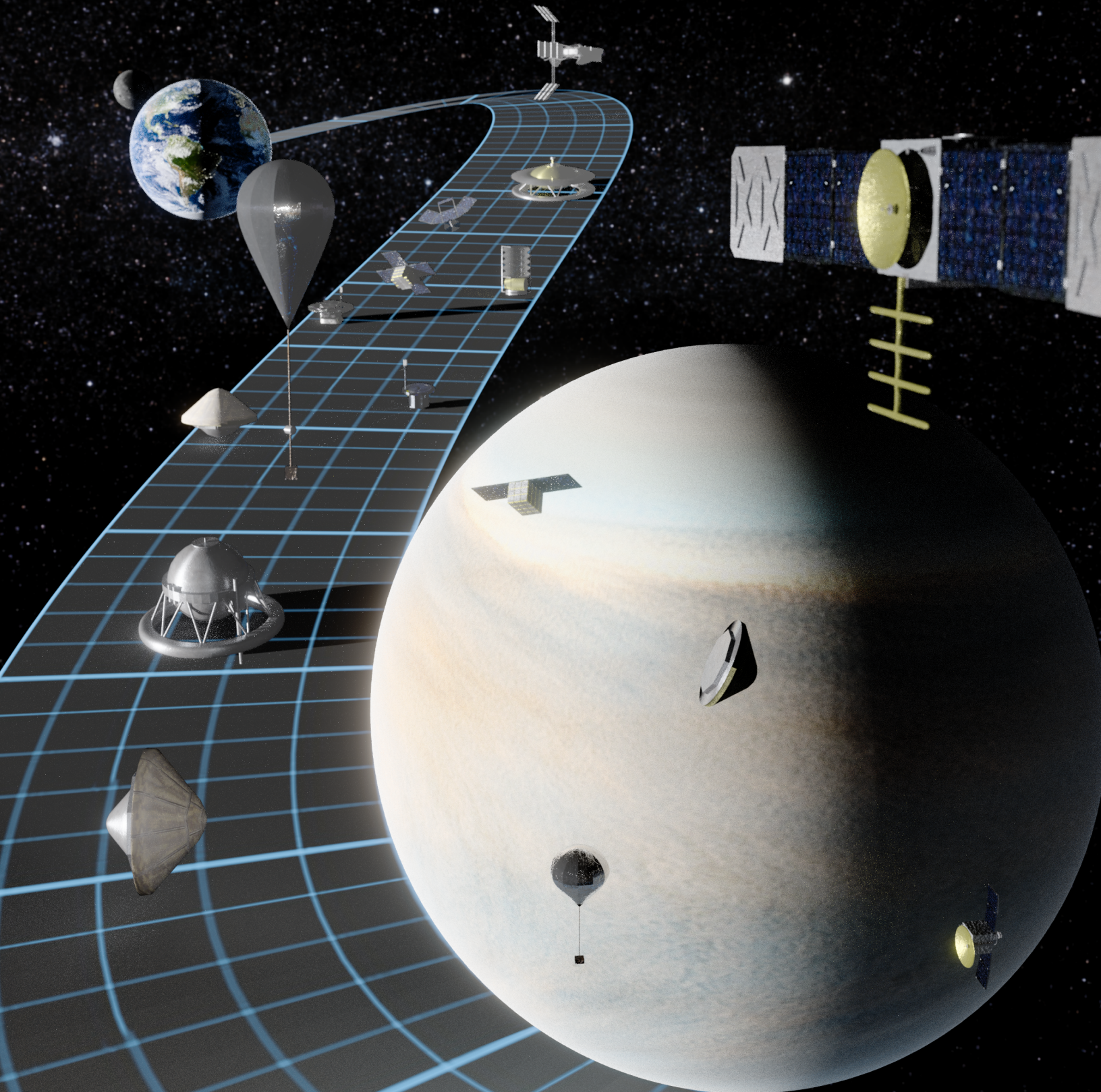


ROADMAP FOR VENUS EXPLORATION



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.

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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 <i>Near-term</i>	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 <i>Near-term</i>	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 <i>Near-term</i>	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 <i>Near-term</i>	Skims the atmosphere, sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay.
Probe <i>Near-term</i>	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 <i>Mid-term</i>	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 <i>Near-term</i>	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 <i>Mid-term</i>	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 <i>Far-term</i>	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 <i>Near-term</i>	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 <i>Mid-term</i>	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 <i>Far-term</i>	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.

Roadmap for Venus Exploration (2019)

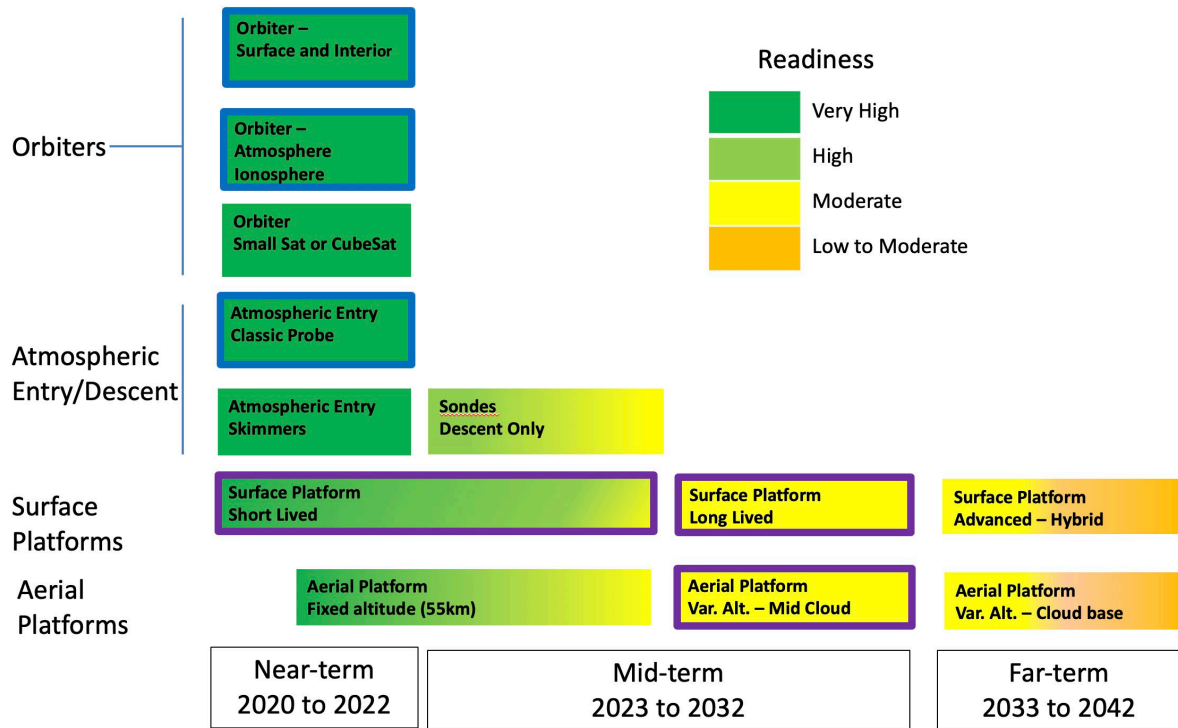


Figure 1. Time frames in which exploration platforms could be ready for deployment are ordered based on their readiness. Readiness is a composite measure based on technology maturity, complexity and resource needs. Near-term Roadmap missions have very high and high readiness. Mid-term Roadmap missions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

Roadmap for Venus Exploration (2019)

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

VEXAG Goals, Objectives and Investigations					Roadmap Mission Modalities													Overall Assessment
Goals	Objectives	Investigations	GOI Code	GOI Rating	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	
					Time Frame	Near	Near	Near	Near	Near	Mid	Near	Mid	Far	Near	Mid	Far	
I. Early Evolution, and Potential Habitability	A. Did Venus have liquid water?	Hydrous Origins	I.A.HO	1														
		Recycling	I.A.RE	1														
		Atmospheric Losses	I.A.AL	2														
	B. How does Venus inform pathways for planets?	Magnetism	I.A.MA	3														
		Isotopes	I.B.IS	1														
		Lithosphere	I.B.LI	1														
II. Atmospheric Dynamics and Composition	A. What drives global dynamics?	Heat Flow	I.B.HF	2														
		Core	I.B.CO	2														
		Deep Dynamics	II.A.DD	1														
	B. What governs compositions and radiative balance?	Upper Dynamics	II.A.UD	1														
		Mesoscale Processes	II.A.MP	2														
		Radiative Balance	II.B.RB	1														
III. Geologic History and Processes	A. What geological processes shape the surface?	Interactions	II.B.IN	1														
		Aerosols	II.B.AE	2														
		Unknown UV Absorber	II.B.UA	2														
	B. How do the atmosphere and surface interact?	Outgassing	II.B.OG	3														
		Geologic History	III.A.GH	1														
		Geochemistry	III.A.GC	1														
C. Crustal	Geologic Activity	III.A.GA	2															
	Crustal	III.A.CR	2															
	Local Weathering	III.B.LW	1															
D. Global Weathering	Global Weathering	III.B.GW	2															
	Chemical Interactions	III.B.CI	3															

■ 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

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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.

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- 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).

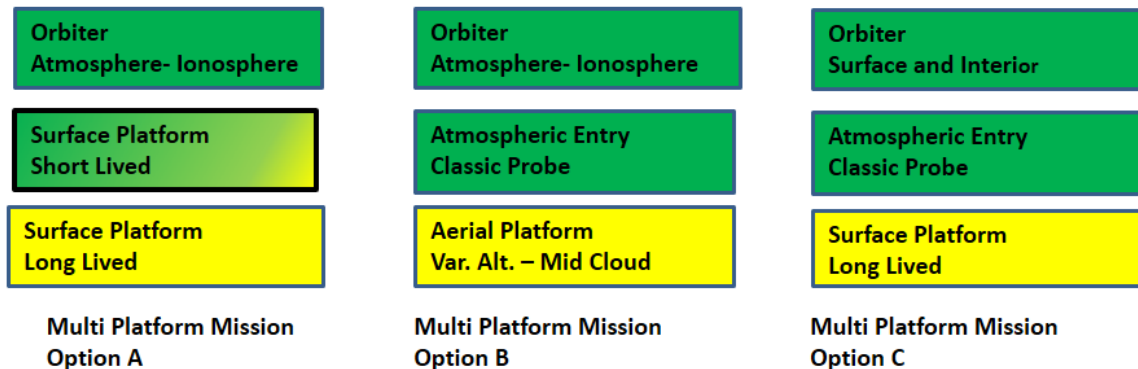


Figure 2. Options for Multi-Platform Missions for the Decadal Survey Period (2023 to 2032). Each mission includes three exploration platforms delivered to Venus with a single spacecraft. The in situ platforms (landers, probes and aerial platform) would be delivered into the atmosphere in a single aeroshell.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

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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.

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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.

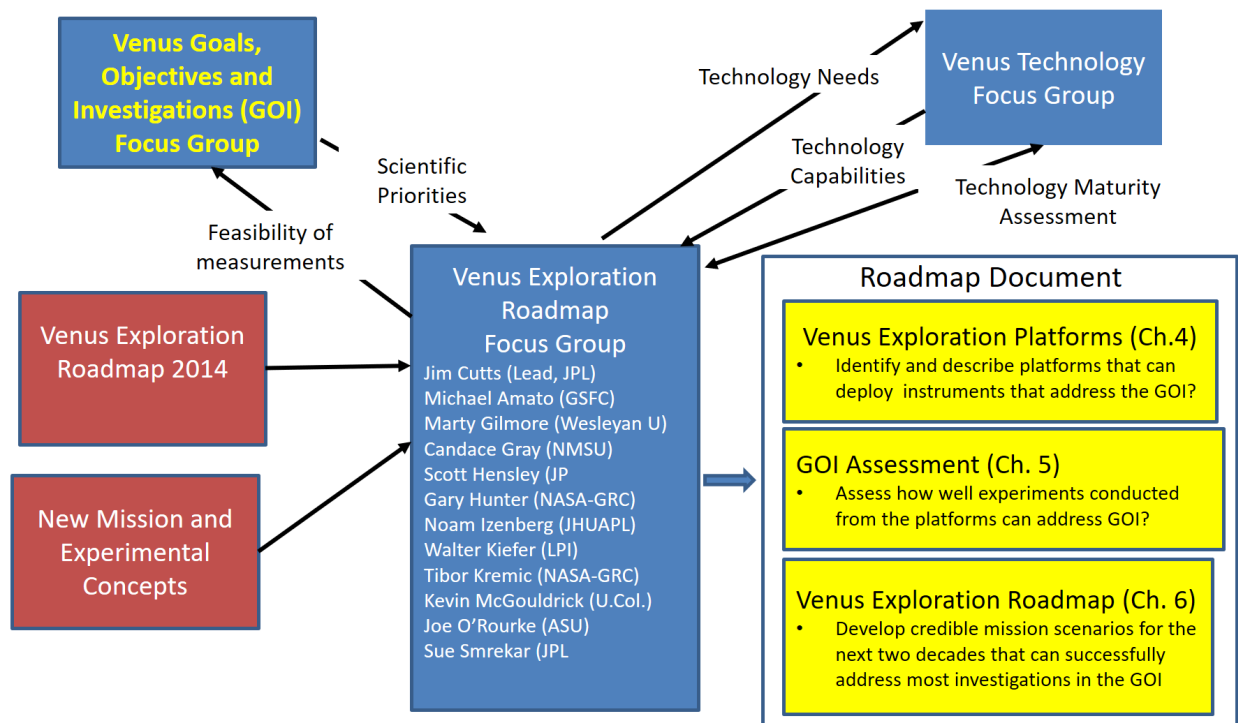


Figure A.1. Process for developing this VEXAG 2019 Roadmap.

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 be 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.

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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

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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

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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.

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- **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 be 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 magnetism 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.

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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.

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- 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 be 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).

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- **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

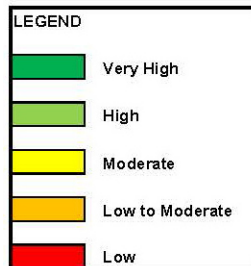
Exploration of Venus will depend on exploration platforms that can conduct both remote and in situ exploration. Orbital platforms are generally technically mature, although some advances are needed to handle the Venus environment. Continuing developments of SmallSats and CubeSats is encouraging. Probes 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).

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

Roadmap Mission Modalities													
Specific Technology Capability	Class	Orbiter			Atmospheric Probes			Surface Platform Lifetime			Aerial Platform - Altitude Control		
	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 - Radiosotope												
	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													
Instrument	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	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.



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	Blue	Blue				Blue	Blue	Blue
	Atmosphere-Ionosphere	Near-term	Yellow		Blue	Yellow		Yellow		
	SmallSat	Near-term	Yellow							Yellow
Atmospheric Probes	Skimmer	Near-term					Blue			
	Probe	Near-term					Blue			
	Sonde	Mid-term					Blue			
Surface Platform Lifetime	Short	Near-term	Blue	Blue		Yellow	Blue			
	Long	Mid-term				Yellow		Yellow	Yellow	Yellow
	Advanced	Far-term	Blue	Blue		Yellow	Blue	Blue	Blue	Blue
Aerial Platform Alternate control	Fixed Mid-Cloud	Near-term		Yellow		Blue	Blue	Blue		
	Variable Mid-Cloud	Mid-term		Yellow		Blue	Blue	Blue		
	Variable Sub-Cloud	Far-term	Blue	Yellow		Blue	Blue	Blue		
Overall Assessment			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue

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

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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

			II. Atmospheric Dynamics and Composition							
Goal:										
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

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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) - rely at least in part on observing volcanic and seismic events and in these cases synchronous orbital and in situ observations can be very valuable.