ROADMAP FOR VENUS EXPLORATION

FOR VENUS EXPLORATION COMMUNITY REVIEW

Venus Exploration Assessment Group

May 24, 2019
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Pre-Decisional Information -- For Planning and Discussion Purposes Only
The Venus Exploration Analysis Group 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 and reports its findings to NASA. Open to all interested scientists, technologists and engineers VEXAG regularly evaluates Venus exploration goals, scientific objectives, investigations, and critical measurement requirements, including recommendations on the NRC Decadal Survey and the Solar System Exploration Strategic Roadmap. This document, prepared by the VEXAG Venus Exploration Roadmap Focus Group is one of three VEXAG documents prepared to guide planetary exploration in 2019 and beyond.

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1 Introduction

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, however, Venus has gone down a very 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. Yet there is strong evidence that the planet was not always so inhospitable, and Venus may even have possessed significant water in the distant past. Thus, the study of Venus provides unique and important opportunities to understand not only the general processes that govern the inner planets, but it also serves as a comparison case to suggest how those processes affected Earth, and in particular why and how Venus and Earth diverged. Exploration of Venus is one of the great remaining challenges and opportunities of Solar System science. It will provide valuable insight into planetary processes, the past and future of the terrestrial planets, and the likelihood of habitable planets in other planetary systems around other stars.

This Roadmap for Venus Exploration lays out a framework for the future exploration of Venus, encompassing observations of the atmosphere, surface, and interior using a variety of mission modes ranging from orbiters and probes to aerial platforms, and long-duration landers. 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 of 2021, which is charged with framing a strategy for all of planetary exploration for the next decade and beyond. With the prolonged hiatus in U.S. led Venus exploration, the science and the technology are now ready for not just a single mission. In planetary exploration, the next decade can and should be the Decade of Venus.

Scientific guidance for this Roadmap for Venus Exploration is provided by the companion document Venus Goals, Objectives, and Investigations (GOI) (VEXAG_GOI_Focus_Group, 2018), which establishes the foundation and priorities for future Venus exploration. To facilitate the identification of specific mission concepts, the Exploration Roadmap considers the scientific contribution of different exploration platforms—orbiters, probes, surface platforms (landers) and aerial platforms. Many areas of progress in Venus exploration depends on advances in technology and the second companion document (Hunter & VEXAG Technology Focus Group, 2018), provides additional detail on the technologies that are propelling forward these capabilities—those which are now at hand and those which still represent formidable challenges. The process for generating the Roadmap is described in Appendix I.

This report first provides the programmatic context for developing the Roadmap (Section 2) and then describe the scientific platforms that the Roadmap Focus Group determined would be important for Venus exploration (Section 3). In Section 4, we evaluate the ability of these platforms to carry out the science defined in the GOI and the feasibility of the platforms based on the technology assessments in the Technology report. In Section 5, we bring in the programmatic considerations of Section 2 to lay out a Roadmap incorporating the scientific platforms that are needed to broadly address the goals identified in the GOI.

Implementation of missions by NASA takes place within a programmatic framework of competitive and assigned missions. The representative mission sets described in this Roadmap for Venus Exploration were derived based on assessment of their scientific potential, technology readiness, and programmatic considerations including feed-forward of science and capability in a logical fashion. This Roadmap is not a rigid prescription of mission implementations but a framework that can be used to choose the optimal pathway once the programmatic framework is better understood. We have focused on three planning periods: Pre-Decadal from 2019 to 2022, Decadal 2023 to 2032 and Post-Decadal 2033 to 2042 an identified candidate missions for each of those periods.
2 Venus Exploration in NASA’s Science Program

Important Venus science can be accomplished within all of the mission programs sponsored by the NASA Solar System Exploration Directorate. The diversity of compelling Venus science questions means that even highly focused measurements can be extremely productive, so even relatively low-cost missions can make major contributions. Conversely, the complex inter-relationships and variability of atmospheric, surface and interior phenomena on Venus make the planet an ideal candidate for larger multi-disciplinary missions. Our Venus exploration strategy, comprising missions from all classes, coupled with strategic technology investments, will enable major progress in the understanding of the key scientific issues. This Roadmap for Venus Exploration envisages NASA missions funded through the established programmatic lines complemented by missions led by other space agencies. International collaboration in the planning and implementation of these missions, taking advantage of the unique strengths and interests of each participating agency, provides an opportunity to make more rapid scientific progress than would otherwise be possible. In this section, we review each of the NASA Programs that can be a vehicle for Venus Exploration, the status of International Collaboration and the importance of advancing technology in future Venus exploration, a topic explored in much more detail in the companion report (Hunter & VEXAG Technology Focus Group, 2018)

2.1 Discovery Missions

The Discovery Program consists of Principal Investigator (PI)-led smaller missions that provide opportunities for targeted investigations with relatively rapid flight missions. The Discovery program is ideally suited for missions to Venus. The planet’s relative proximity means that flight times are short, and power and communications bandwidth are plentiful for orbital missions. The dense atmosphere can be used for aerobraking or aerocapture to reduce propellant requirements, and 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. Discovery missions (including orbiters, probes, and aerial platforms) will represent critical steps toward understanding Venus and its scientific relationship to Earth, and they will serve as pathfinders for more complex multi-disciplinary missions.

In 2017, two Venus missions – VERITAS, and DaVINCI, were selected for a phase A study. VERITAS was an orbiter spacecraft and included a radar mapper and infrared surface imaging instruments. DaVINCI was an entry probe mission that included compositional, atmospheric structure measurements and surface imaging. Neither proposal was selected for flight; the next round of Discovery proposals are due July 2019.

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. The Decadal Survey of 2011 recommended a single Venus New Frontiers mission, the Venus In Situ Explorer (VISE) with science goals.

The New Frontier NF-4 AO released in December 2016 included a Venus In Situ Explorer (VISE) as one of the mission themes. The mission theme is focused on examining the physics and chemistry of Venus’s 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. Three Venus concepts were submitted to the call. The Venus In Situ Atmospheric and Geochemical Explorer (VISAGE) and Venus In Situ Composition Explorer (VICI), which were both landed missions. The Venus Origins eXplorer (VOX) was an orbiter mission similar in concept to VERITAS and including a skimmer probe as an integral part of the mission and not just as a technology experiment. Only the VOX mission was determined to be Category 1 but it was not one of the two proposals that advanced to Step 2 in the call.
The NF-4 experience indicates that there is a high level of interest in Venus as a target for New Frontiers and there are highly competitive mission options. However, NASA and the next Decadal Survey should consider updating the description of the Venus mission theme to be less prescriptive with respect to the mission implementation and to place more emphasis on the nature and scope of the science that can be accomplished at Venus within the New Frontiers cost cap.

2.3 Flagship Mission Concepts

Flagship missions address those high-priority investigations that are so challenging that they cannot be achieved within the resources allocated to the Discovery and New Frontiers Programs. The 2011 Decadal Survey - Visions and Voyages -Inner Planets Group selected a single small Venus flagship mission concept, the Venus Climate Mission (VCM), requiring little new technology, for the period 2013–2022. The 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). In Spring 2019, NASA initiated a series of competitive pre-decadal studies study that will revisit concepts for categories of missions larger than Discovery. The role of these studies in providing additional definition for New Frontiers and Flagship concepts for Venus exploration is discussed in Section 5.

2.4 Small Missions - Missions of Opportunity

As the pressure on space science budgets grows more severe, it is important that NASA consider alternative mission modes that may be able to make contributions to Venus science at lower cost—perhaps less than half the cost of a Discovery mission. In 2018, VEXAG completed the Venus Bridge study (Grimm & Gilmore, 2018), and identified potential mission with highly focused objectives. However, many technology challenges still need to be overcome if the potential of these small missions is to be realized. In addition, the scientific payoff of small missions in science per dollar relative to Discovery and larger missions remains to be demonstrated.

2.5 International Opportunities

The international community has demonstrated a strong interest in Venus, and future exploration of Venus is enhanced through international cooperation. The European Space Agency’s Venus Express, which ended in December 2014, and the ongoing Japanese Space Agency’s Akatsuki, both had NASA participation. Looking forward, the Indian Space Research Organization (ISRO) is planning a Venus mission Shukrayaan-1, that that is targeted for launch in 2023. A call for international participation in the experiment payload was issued in November 2018 with selections made in May 2019. The mission includes an orbiter with a large payload focused on both atmospheric and surface objectives and a balloon platform. As noted in Section 2.3, Russia’s Roscosmos and Space Research Institute entered into a collaboration with NASA’s Planetary Science Division on Venera D, on a Flagship class mission with both landed and orbital elements. A second report from the Joint Science and Technology Definition Team (JSDT) was completed in early 2019 (JSDT, 2019) but Venera D the mission is still a pre-Phase A mission concept study. NASA is also collaborating in a Phase A study of the ESA Envision mission concept, which is one of three candidate concepts 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 firm plans from other space agencies for a Venus mission. NASA leadership in Venus exploration will be a prerequisite for the success of the Decade of Venus.
2.6 Technology Developments

The key challenges facing future Venus orbital missions include the extreme environments that they must accommodate. New technologies as described in the companion technology plan (Hunter & VEXAG Technology Focus Group, 2018) must play a vital role in future Venus exploration. Some of the key developments that have occurred and new capabilities that have emerged since the 2014 Roadmap was completed are as follows:

- Heatshields for Extreme Entry Environment Technology (HEEET), under development for the last five years has now been deemed to have reached TRL 6. With this new capability, entry into the Venus atmosphere will once again make entry into the Venus atmosphere feasible and with much less restrictive conditions than before.
- Long-duration surface platforms enabled by the development of 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 not only investigating the atmosphere but also the surface and interior.
- 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.

In the next section, we describe the Venus Exploration Platforms, including those described above, that we believe will be feasible for use at Venus in the time frame of interest for this Roadmap (through 2042) and can make important contribution to the investigations identified in the GOI. 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 may also be launched on a single launch vehicle, as occurred with the Venera and VeGa mission, and this may offer scientific and technical synergies as well as cost savings.

3 Venus Exploration Platforms

The Roadmap Focus Group has identified four categories of Venus Exploration Platforms for carrying out the scientific investigations identified by the GOI Focus Group: Orbiters, Atmospheric Probes, Surface Platforms and Aerial Platforms. Only those platforms deemed feasible by the Roadmap Focus group 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 entry and atmospheric entry, descent and deployment are described in detail in a companion document (Hunter & VEXAG Technology Focus Group, 2018). That document also includes capabilities feasible beyond 2042.

The earliest time-frame in which each of these platforms could be deployed at Venus has been based on an assessment of technical readiness. We have weighed a number of factors in this assessment:

- Technology Maturity: The maturity of the enabling and enhancing technologies required for each of the platform as determined in the companion Venus Technology Plan.
- 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 advance technologies and demonstrate complex systems which will dictate how soon they might be ready for flight.

Table 3-1 Platforms included in the Venus Exploration Roadmap.

<table>
<thead>
<tr>
<th>Platform Type/Subtype</th>
<th>Description of platform and primary scientific objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORBITER</td>
<td>Supports investigations from orbital vantage points optimized for the scientific objectives</td>
</tr>
<tr>
<td>Surface/Interior Near Term</td>
<td>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.</td>
</tr>
<tr>
<td>Atmosphere/Ionosphere Near Term</td>
<td>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.</td>
</tr>
<tr>
<td>SmallSat or CubeSat Near Term</td>
<td>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).</td>
</tr>
<tr>
<td>ATOMIC ENTRY</td>
<td>Supports experiments during a traverse or descent in the Venus atmosphere</td>
</tr>
<tr>
<td>Skimmer</td>
<td>Skims the atmosphere, sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay.</td>
</tr>
<tr>
<td>Probe</td>
<td>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.</td>
</tr>
<tr>
<td>Sonde</td>
<td>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.</td>
</tr>
<tr>
<td>SURFACE PLATFORM</td>
<td>Supports experiments on the surface of Venus in the high temperature high pressure environments</td>
</tr>
<tr>
<td>Short-Lived Near term</td>
<td>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.</td>
</tr>
<tr>
<td>Long-Lived, Pathfinder Mid term</td>
<td>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.</td>
</tr>
<tr>
<td>Long-Lived, Advanced Mid term</td>
<td>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.</td>
</tr>
<tr>
<td>AERIAL PLATFORM</td>
<td>Supports extended duration experiments in and from the atmosphere including sonde deployment.</td>
</tr>
<tr>
<td>Fixed Altitude – Mid Cloud Near Term</td>
<td>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.</td>
</tr>
<tr>
<td>Variable Altitude – Mid Cloud Mid term</td>
<td>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.</td>
</tr>
<tr>
<td>Variable Altitude-Cloud Base Far Term</td>
<td>Controls altitude in the range ~40–60km using passive thermal control systems to enable use of conventional electronics. Sensors in exposed locations must tolerate temperatures up to 150 °C.</td>
</tr>
</tbody>
</table>

The technical readiness of each type and subtype of platforms described in Table 3-1 is depicted as a color code box in Figure 3-1 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 3-1 Time frame in which exploration platforms could be ready for deployment are ordered in time based on their technical readiness. Technical readiness is a composite measure based on technology maturity, complexity and resource needs.

4 Scientific Assessment of Venus Exploration Platforms

In this section, we describe how the Venus Exploration Platforms described in Section 3 can be used to address the Goals, Objectives and Investigations identified by the GOI Focus Group. The two focus groups worked together to perform this assessment. In Table 4-1, the contribution that can be made by each platform to addressing the investigations in the GOI is indicated with a color code as either Vital or Supporting. An identical table appears in Appendix C of the GOI document. In this section, we review the contributions that each platform can make to the GOI and the potential for synergy between observations with different platforms. A more detailed exposition of these contributions appears in Appendix B.

4.1 Orbiters

The three orbiter subtypes will play complementary roles in the further exploration of Venus. As Figure 3-1 indicates, orbiters are technically ready now although advances in Smallsat and CubeSats in particular are needed to exploit their full potential.

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.
Orbiter - Atmosphere-Ionosphere: This class of orbiter makes its vital contributions to Goal II although it plays 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 (through infrasound) of seismic events.

SmallSats: 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 choice 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:

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.U.D).

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

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 similar payloads to 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.

**Short Lived:** With the ability to make geochemical measurements during a short lifetime of a few hours, this type of platform builds on the accomplishments of past Venera and Vega surface missions with modern, highly capable instruments. Since this platform follows a very similar flight path to 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 instruments to do so.

**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 the time frames considered here, 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)

**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 will be needed to accomplish this. If successful, the platform can make vital 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 are made over a period of about 100 days as the aerial platform circles every five to six days in the RZS flow.

**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 EM waves, remanent magnetism, gravity and seismic sourced infrasound.

**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)

**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 investigation in Table 4-1, there are multiple entries indicating that several platforms can 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. In those cases, the complementary measurements may need to be made sequentially, in other cases they may need to be synchronous. In this section, we consider some of these measurement synergies. 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 within the time frame defined here only one or two landed missions can be expected and so the context provided by orbital and aerial measurements will be key to setting landed measurements in a global context. There is no particular benefit to be gained from making these orbital, aerial and surface measurements of the surface synchronous. In fact, if the orbital experiment is conducted first, it can be valuable in 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 complement 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 Venus Exploration Roadmap has been formulated within a programmatic framework dominated by competitive missions in the Discovery and New Frontiers programs. Accordingly, in this Roadmap, our goal is not to prescribe a specific series of missions but rather to lay out a credible option space to guide planning and technology investments and to identify some of the consequences of different choices. We consider how these platforms might fit with the existing NASA competitive opportunities and NASA Flagship missions and international collaborations. We anticipated that the mission scenarios described here can be refined through responses to NASA’s recent call for Pre-decadal mission concepts under the Planetary Mission Concept Studies ROSES call.

5.1 Pre-Decadal Proposal Opportunities – 2019 to 2022

There are potentially two Discovery opportunities before the Planetary Science Decadal Survey makes its recommendations. We have adopted the following criteria for the candidate missions for these opportunities:

- The scope should include multiple investigations in the GOI while still retaining the scientific focus appropriate to a Discovery mission.
- The exploration platform technical readiness must be very high
- The size and complexity of the mission must be compatible with the Discovery opportunity

Using these criteria, we have identified three platforms from those in Table 3.1:

- Orbiter Surface and Interior (2019 opportunity)
- Orbiter- Atmosphere and Ionosphere (2019 opportunity)
- Atmospheric Entry – Probe (2019 opportunity)

Although Orbiter-SmallSat and the Probe-Skimmer reached the technical readiness criteria, the range of investigations that they would address is much more limited. If there were an opportunity for a low-cost mission, then these concepts might be considered but they should not be viewed as an alternative to one of these Discovery candidates in our Roadmap. In addition, to these missions, the Aerial Platform – Fixed Altitude mission might be considered for the potential 2021 opportunity if resources were made available to advance technical readiness more rapidly than anticipated here.

5.2 Decadal Survey Period – 2023 to 2032

During this period we anticipate up to four Discovery opportunities, two New Frontiers announcements at least and two Flagship class new starts. 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 pre Decadal period, the following ones can be considered for this timeframe:

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

The New Frontiers and Flagship opportunities available in this time-period would make it possible to carry out missions involving multiple exploration platforms. Deploying several platforms on a single launch rather than sequentially in separate launches can provide both operational and scientific synergy if they
are functioning at Venus at the same time. The three example concepts described below were chosen based on the following criteria:

- The science should represent a substantial gain over that feasible in a single Discovery mission
- The missions must be technically ready in the time-frame of the next Planetary Science Decadal Survey (2022 – 2032) which we have interpreted to mean at least moderate now.
- The missions should be more costly than Discovery ($>500M), include the New Frontiers category $1B and extend to approximately $2B.

The three multi-platform concept considered resemble concepts previously studied by or proposed to NASA however there are significant differences reflecting recent scientific and technological advances.

**Figure 5-1 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 3.1)**

**Multi-Platform Mission - 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. The mission resembles but is not identical to the Venera D mission studied by a Joint U.S. Russian Science Definition Team.

**Multi-Platform Mission - 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 relayed data through the aerial platform. The science would emphasize coordinated remote and in situ measurements of the surface and geophysical investigations of the interior.
Multi-Platform Mission - 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 down to the surface and for surface imaging. The science would emphasize in situ measurements of the atmosphere and remote sensing measurements of the Venus surface and interior.

5.2.1 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 5-1.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Platforms included</th>
<th>Scientific Complementary and Synergy</th>
<th>Mission Synergy - Communications</th>
<th>Mission Synergy Guidance and Localization</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM2-A</td>
<td>Surface Platform - Short lived</td>
<td>Compare diurnal measurements of surface temperature with orbital remote sensing</td>
<td>Orbital relay is essential for recovering data from long lived surface platform</td>
<td>Enable refinement of entry and descent trajectory for the surface platforms</td>
</tr>
<tr>
<td></td>
<td>Surface Platform - Long lived</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orbiter Atmosphere-Ionosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM2-B</td>
<td>Aerial Platform-Variable Altitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Descent Probe</td>
<td>Compare orbital spectral signatures and cloud tracking with in situ observations</td>
<td>Orbital relay increases data return by 100X from the aerial platform relative to direct-to-Earth</td>
<td>Enables accurate localization of the position and velocity of the aerial platform as it is propelled by the RZS</td>
</tr>
<tr>
<td></td>
<td>Orbiter Atmosphere &amp; ionosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM2-C</td>
<td>Descent probe</td>
<td>Radar imaging from orbit provides context for high resolution probe visual images</td>
<td>May supplement data returned from the cruise stage deploying probe</td>
<td>May enable precise determination of point of entry and descent trajectory</td>
</tr>
<tr>
<td></td>
<td>Orbiter - Surface and Interior</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These advantages 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 (MPM-A and MPM-B) the presence of an orbiter may be an absolute requirement or highly enhancing to the 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.
- Orbiter can provide a vital role in monitoring the position of the aerial platform particularly when it is on the far side of Venus relative to the Earth.
- Multiple platforms provide a more complete scientific investigation of interior/surface/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 PMCS program provides an excellent opportunity to carry the recommendations of this Road Map to the next level.
5.3 Missions for the Decade 2033 to 2042
For this timeframe, we have defined the platforms that would be available for deployment to Venus. The platforms and the required technologies are discussed in more detail in Appendix B as well as in the Venus Technology Plan. While we have not identified specific mission concepts for this time frame here, it should be apparent that candidates for single platform and multiple platforms can be defined using a similar approach to that for the earlier 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, so these capabilities are well beyond the time frame of this Road Map 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 to us 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 Summary
Past missions of exploration have revealed that Venus is hellishly hot, devoid of oceans, apparently lacking plate tectonics, and bathed in a thick, reactive atmosphere. When and why did Venus and Earth’s evolutionary paths diverge? Did Venus have an ocean like the Earth and can we find fossil evidence for that in the ancient rocks preserved at the surface? Was the surface of Venus ever habitable? What explains the mysterious ultraviolet properties of the Venus clouds — an exotic chemistry or an alien biology? Today, the scientific strategy and the technology plan is now in place for a systematic effort to address these questions. However, the mysteries of a planet as complex as Venus cannot be answered by one platform or even one mission. It will require the multimission strategy outlined in this Roadmap. Many of these platforms and missions needed are ready now; others will require technology investment. After a long hiatus, we are now ready to resume exploration of our sister planet. Indeed, in planetary exploration, the next decade can and should be the Decade of Venus.
Appendix A Roadmap Development Process

Three focus groups were formed by VEXAG in May 2018 and were assigned the task of revising VEXAG’s guiding documents. 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 Fig A.1, and is described in more detail below.

Initial Inputs

The starting point for the Roadmap Focus Group was the Venus Exploration Roadmap of 2014. As it awaited inputs from the GOI Focus group, which began work contemporaneously, the Roadmap Focus Group was briefed on new mission and experimental concepts that had emerged since the 2014 Roadmap was completed. These concepts included, but were not limited, to developments in small satellites and CubeSats, aerial platforms and high temperature electronics technologies enabling long duration *in situ* missions. In addition, to the development of new platforms, 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 the VEXAG 2018 Roadmap*

Interactions with the GOI Focus Group

When the GOI Focus Group developed its draft Goals, Objectives and Investigations in Mid October 2018, the Roadmap Focus group provide feedback. This process benefited from the cross-cutting membership of the GOI and Roadmap focus groups. Following the completion of the GOI, the two focus groups worked
together to develop a consensus on how Roadmap missions would address investigations in the GOI. A key issue for the Roadmap Focus Group was assuring that investigations were defined with sufficient specifically that a platform and experimental approach could be identified. A number of iterations took place with the GOI Focus Group to achieve this. The Roadmap Focus Group also identified investigations that were enabled by either new experimental techniques or new platform technologies. These were communicated to the GOI focus group and incorporated in the GOI.

Interactions with the Technology Focus Group
These interactions spanned the topics of technology needs, technology capabilities and technology maturity assessment. The process also benefited 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. Because the formal Roadmap technology needs emerged later in the overall process, the Technology focus group had to rely on the prior Roadmap until then. 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 was conducted by the Technology focus group but it involved assessments of cost and risk tolerance that were provided by the Roadmap focus group.

Roadmap Group – Key Products
The key products of the Roadmap Focus Group activities are depicted in Fig A.1 nd are described in the three sections of the report.

Venus Exploration Platforms (Section 3)
This section describes the platforms that deploy the instruments that carry 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 the roadmap are considered.

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 platform investigations are important is key to mission definition.

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 that involve multiple platforms where required and provide the feedforward needed to effectively and efficiently addresses the Goals, Objectives and Investigations. The Roadmap considers mission 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 means of missions that can carry out the investigations called for in the companion GOI document (VEXAG_GOI_Focus_Group, 2018). These investigations are implemented with different types of instrument platforms, orbiters, probes, surface platforms (landers) and aerial platforms. In this appendix, we provide more details on the capabilities of the platform than can be incorporated in the main body of the text. In particular, we expand on the descriptions of the exploration platforms in Table 3.1 and Figure 3.1.

Orbiters

The three orbiter subtypes will play complementary roles in the further exploration of Venus. As Figure 3-1 indicates, orbiters are technically ready now although advances in Small sat and CubeSats in particular are needed to exploit their full potential.

Orbital-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, a tremendous amount can be learned about the surface and interior of Venus from orbit.

- Radar imaging at an order of magnitude better than Magellan, providing an opportunity to observe entirely new processes.
- Topography using radar interferometry and stereo imaging that is 2 orders of magnitude better than available from Magellan. Improved topography is critical to many geophysical 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, weathering reactions, and search for recent and active volcanism.
- Global scale gravity field with sufficient spatial resolution to determine elastic thickness.
- Radio sounders to probe the shallow (~100m) subsurface stratigraphy.

The next step in orbital surface exploration should be a global mapping mission that would improve the 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 could be 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 but for 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. This mission would utilize the precision global topography maps to remove surface clutter. The Envision Mission, which is now being considered for the 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 mission from a near polar and circular or near circular orbit with a period near 90 minutes. Because of the slow rotation of Venus, it
is possible to obtain images of the same surface locations in order to detect any temporal changes during several successive orbits.

Global reconnaissance supports landed missions by identifying high priority and high science value venues for detailed examination. NASA has promoted 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. Global reconnaissance serves to

**Orbiter - 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 comparatively recent ESA Venus Express mission and the ongoing JAXA Akatsuki mission have contributed the most current knowledge of the planet. To address a broad set of GOI objectives will require a comprehensive payload including spectroscopy, hyperspectral imaging, solar/stellar/radio occultations and particles and fields measurements. Typically to provide the ability to carry out both nadir viewing and limb scanning observations a highly eccentric and high inclination orbit is desirable for this purpose. However, low inclination and low eccentricity orbits are 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.

**Orbiter - SmallSats and CubeSats**

The successful MarCO flights supporting Mars InSight in 2018 have demonstrated the feasibility of interplanetary flight with very small spacecraft. In that same year, there was a VEXAG-led study of the applicability of SmallSats with a mass ~ 100 kg and CubeSats with mass ~10 kg to Venus exploration called Venus Bridge (Grimm & Gilmore, 2018). Necessarily, by using a SmallSat or CubeSat, the science payload is much more constrained. As a consequence, the orbit may be tailored to specific objectives rather than representing a compromise between many. With CubeSats, it is also possible to contemplate missions with multiple platforms sampling different parts of the space environment contemporaneously or performing mutual radio occultations in order to dramatically increased spatial and temporal sampling.

In addition to the traditional form of radio occultation technique such as implemented on Venus Express and Akatsuki, where the radio signal from the spacecraft is observed by a single ground-based antenna or conversely, we have explicitly included the potential of CubeSats and SmallSats performing mutual occultations. This can vastly increase the number of locations where the atmosphere is probed over what is possible with a single spacecraft and does not require a commitment of costly ground based antennas.

**Atmospheric Probes**

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

**Skimmers**

A skimmer is a vehicle that passes through the upper reaches of the Venus atmosphere acquires a gas sample and then analyses the sample after it emerges 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. In the Venus application, the primary interest is measurement of noble gases and their isotopes. There is no need to return the samples to Earth because the analysis can be performed on the spacecraft. A skimmer concept studied in NASA’s Planetary Science Deep Space SmallSat Studies (PSDS3) known as Cupid’s Arrow (Sotin, Avice, & Baker, 2018). Similar concepts have appeared under other names as part of Discovery and New Frontiers proposals.

The skimmer concept is clearly limited to sampling the higher reaches of the atmosphere and studies are ongoing with respect to whether the atmosphere at the sampled altitude is representative of the bulk composition as well as whether the hypervelocity sampling process induces fractionation. The 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 where improved counting statistics possible during the months that the skimmer spends in solar orbit after exiting the Venus atmosphere could be applied to measurement of isotopes present in trace amounts.

**Entry Probes**

Atmospheric probes that descend through the Venus atmosphere and reach the surface were used in the Pioneer Venus program in the early 1970s. Decades of instrument development have made it possible to implement a deep probe mission with greatly improved instrumentation including descent imaging. A key difference from the skimmer probe is the need to remove all of the energy of the probe as it enters the atmosphere and not just a small fraction. The 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 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 the solar and thermal radiation environment as a function of altitude. Tracking of the probe from Earth or from an orbiter can be used to determined wind velocity. Finally, it will be possible to image the surface during the terminal stages of descent below 5 km when degradation of contrast by atmosphere scattering drops to acceptable levels.

**Sondes**

The advent of Aerial Platforms enables a class of atmospheric probe that can be delivered to Venus with an aerial platform and hence does not require a separate entry and descent system. As a result, these types of atmospheric probes, which we refer to as sondes, can be smaller and much lower cost than conventional entry probes. Because the sondes are typically less than a few 10s of kilometers from the aerial platform while they are operating, data relayed through the aerial platform can be transmitted at much higher data return than direct to Earth or by using 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. The VCM included a large sonde that was released soon after entry of the aerial platform and a smaller sonde that was carried by the aerial platform and subsequently released from it. Sondes can capitalize on technologies developed for CubeSats. Missions with multiple sondes, released at different times and that probe 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 decade mission (2033 to 2042). Because of the proximity of the aerial platform relay station, much larger volumes or imaging data can be retrieved for a sonde than an entry probe.

**Surface Platforms**

Vehicles that descend to the surface and then conduct investigations on the surface of Venus constitute a key element of our Roadmap. In 2018, NASA’s Planetary Science Division initiated a Venus Surface Platforms study (Amato & Kremic, 2019). This report includes information presented during this study most recently at a meeting held on Nov 28-29 2018 at Glenn Research Center. 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 and long-lived platforms capable of months of operation that are being enabled by NASA’s technology programs.

**Short Duration Landers**

A short duration lander, as considered here, is a vehicle that relies on conventional electronics and sensors for carrying out its missions and these sensors are maintained in their operational temperature range by means of passive thermal control. Passive, in this context, means a combination of thermal insulation and the use of phase change materials. These two approaches mitigate the temperature rise resulting from heat leaking into the payload compartment and that generated by power dissipation by the payload. The typical lifetime of these landed missions is presently measured in hours and not days.

A series of Venera and Vega lander missions of progressively advancing capability was carried out by the Soviet Union in the 1970s and 1980s. These missions form the primary basis for what we know about the elemental composition of the Venus surface and some missions included color images once the spacecraft had landed. 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 a mission concept called Venera D 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 by JP for NF-4L, 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 Pre-Phase A study but the Jan 2019 report of the JSDT (JSDT, 2019) calls for samples to be brought inside the lander and elemental analysis to be conducted remotely using a gamma ray spectrometer.

**Long Lived – Surface Platforms**

Long-lived platforms as conceived here are platforms that operate on the Venus surface for up to one Venus solar day (using systems and components that can survive and function at Venus surface temperatures and in the high-pressure sulfuric environment. The model for this concept is the Long-Lived In Situ Surface Explorer (LLISSE) developed at Glenn Research Center. The 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 in the companion technology plan (Hunter & VEXAG Technology Focus Group, 2018). The selection of instruments that can operate at Venus surface temperatures that will be available in the next decade will be limited and provide measurements of temperature, pressure, wind speed and atmospheric chemistry. The ability to make these measurements over a period up to or including a complete Venus day would represent a major step forward. A technology demonstration of a seismic experiment including measurements of the seismic background in the Venus surface environment is also possible.

Surface Platforms - Advanced Landers

Advances in technology, described in more detailed in the companion technology plan, can have a dramatic impact on the capabilities of surface platforms. This concept, which is at low to moderate maturity now can be brought to maturity in the Far Term of post decadal period (2033-2042)

- 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.

Several concepts for conducting a surface seismology investigation were considered in the Venus Surface Platforms study (Amato & Kremic, 2019). A surface seismology experiment, which requires major development of instrument components that can operate for months or even years in the Venus surface environment, will complement and build upon the 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
- 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:

- Entry descent and landing capability enhanced with Terrain Relative Navigations to safe areas of scientific interest identified in orbital radar images
- Enhanced thermal 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 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 the sampling drill hole.
Aerial Platforms

Aerial platforms conduct their measurements from a vantage point within the Venus atmosphere. This makes it possible to make measurements that cannot be made from orbit as well as to provide in situ verification of analyses based on orbital data. In addition, aerial platforms can be used to deploy sondes (and to capture data from them 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). The types of measurements that can made from aerial platforms and sondes have been grouped into five categories:

- **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, remanent 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. The technologies required for these concepts are described in the companion Venus Technology Plan.

**Fixed Altitude**

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 include instruments to study the atmosphere and interior.

**Variable Altitude – Mid Cloud**

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.

**Variable Altitude – Cloud Base**

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 during which passive thermal control would be used to protect batteries and other thermally sensitive components. Components exposed to the environment would have to be designed and/or qualified to survive the higher temperatures and corrosive gases.
Other Concepts

Vehicles with varying levels of three-dimensional control were considered in a trade study but 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. 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.

Venus Surface Sample Return

A long-standing objective across all of planetary exploration is to return samples of the solid surface of a planet and the Roadmap Focus Group considered how progress might be made towards surface sample return from Venus. Venus Surface Sample Return (VSSR) was included as a Far Term objective in the 2014 Roadmap. In this Roadmap we have taken a more critical look at VSSR drawing on experience with the Mars Surface Sample Return (MSSR) mission.

Compared to sample return from the Moon, Mercury and Mars and even for the moons of the outer planets, VSSR is a formidable goal. There are three aspects of the Venus environment that makes VSSR so challenging - the high gravity field (comparable to Earth), the dense atmosphere (90 bars at the surface) and the high surface temperature (460°C).

- The high gravity field means that even for launches that originate in tenuous reaches of the atmosphere, multi-stage Venus Ascent Vehicles (VAVs) comparable in capability with those for launching payloads into Earth orbit are needed
- The high pressure (90 bars) means that buoyancy systems with two or more stages are needed to lift the sample from the surface to the upper atmosphere where the atmospheric density is low enough that launch of the VAV is feasible
- The high surface temperatures means that if any equipment accompanies the sample in its ascent (VAV, sampling, buoyancy systems) must be protected from the near surface temperatures as well as pressures

A number of studies of VSSR were carried out in the late 1990s (Sweetser, 1999) and the early years of this century. In all of these concepts, the sample capsule launched by the VAV performs a rendezvous in Venus orbit with an orbital spacecraft. Then, the orbital spacecraft 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 the VSSR architecture ultimately selected, it will be more complex than that of MSSR and 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 Mars surface exploration of progressively increasing capability. Since VSSR is much more complex, 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, we are not including VSSR in this
roadmap. However, we note that the surface and aerial platform missions we are recommending will demonstrate some of the technologies that will be needed to carry out VSSR.

**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 (RVE2014). 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. For most of the technologies, maturity was deemed to be very low. It is useful here to review the principal challenges.

Mobility appears to be the least of the challenges. 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) which was studied in the last Decadal survey. The difficulty is generating power in the Venus environment and in particular sufficient power for cooling components that cannot be implemented as high temperature components.

Although this mission concept does not have the complexity of VSSR, it is nevertheless a very challenging mission and we also consider it to be beyond the time frame of this Roadmap. However, the Surface and aerial Platform capabilities that we do recommend will be important stepping stones to this class of mission.

**Technology Maturity of Selected Platforms**
The companion technology plan has provides an assessment of the key system and subsystem technologies needed for implementing the Roadmap platforms. A summary of that assessment appears in Table B.2. The key systems and subsystems for the orbiter platforms are generally of very high maturity. Surface and Aerial platforms on the other hand display a range of maturity with the more capable platforms on the right side of each group including not only the least mature technologies but with the greatest number of low maturity technologies.

The earliest time-frame in which each of the exploration platforms could be deployed at Venus has been based on an assessment of technical readiness. We have weighed a number of factors in this assessment:

- **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 validate the complex systems.

**Technical Readiness of Selected Platforms**
The technical readiness of each type and subtype of platforms described in Table 3.1 is depicted as a color code box in Figure 3-1 which also displays the earliest time frame when the platforms could be sent 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 period 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 infeasible within the 25 year timeframe of the this roadmap.

**Table B-1 Venus Exploration Platform – Technology Maturity of System and Subsystems**

<table>
<thead>
<tr>
<th>Specific Technology Capability</th>
<th>Platform Time Frame</th>
<th>Roadmap Mission Modalities</th>
<th>Class</th>
<th>Orbiter - Surface and Interior</th>
<th>Orbiter Atmosph &amp; Ionosphere</th>
<th>Atmospheric Probes</th>
<th>Surface Platforms</th>
<th>Aerial Platform - Altitude Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobraking</td>
<td></td>
<td></td>
<td>Near</td>
<td>Near</td>
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<tr>
<td>Aeroscavaging</td>
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<td>Mid</td>
<td>Med</td>
<td>Med</td>
<td>Mid</td>
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</tr>
<tr>
<td>Descent and Deployment</td>
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<td>Mid</td>
<td>Near</td>
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<td>Med</td>
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</tr>
<tr>
<td>Landing</td>
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<td>Near</td>
<td>Med</td>
<td>Med</td>
<td>Med</td>
<td>Far</td>
</tr>
<tr>
<td>Aerial Platforms</td>
<td></td>
<td></td>
<td>Mid</td>
<td>Near</td>
<td>Med</td>
<td>Med</td>
<td>Med</td>
<td>Far</td>
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<tr>
<td>Landers - Short Durations</td>
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<td></td>
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<td>Mid</td>
<td>Med</td>
<td>Med</td>
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<td>Far</td>
</tr>
<tr>
<td>Landers - Long Duration</td>
<td></td>
<td></td>
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<tr>
<td>Mobile Platform - Surface</td>
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<tr>
<td>Autonomous (Note 1)</td>
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<tr>
<td>Thermal Control - Active</td>
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<tr>
<td>High temperature mechanisms</td>
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<tr>
<td>High temperature electronics</td>
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<tr>
<td>Chemical Propulsion</td>
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<td>Far</td>
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<tr>
<td>Solar Electric Propulsion</td>
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<tr>
<td>Guidance, Navigation, and Control</td>
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<td>Far</td>
</tr>
<tr>
<td>Remote Sensing - Active</td>
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<td>Far</td>
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<tr>
<td>In Situ Probe - Aerial Platform</td>
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<td>Mid</td>
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<td>Far</td>
</tr>
<tr>
<td>In Situ Surface - Short Duration</td>
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<td>Mid</td>
<td>Med</td>
<td>Med</td>
<td>Med</td>
<td>Far</td>
</tr>
<tr>
<td>In Situ Surface - High Temp</td>
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<td>Mid</td>
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<td>Med</td>
<td>Far</td>
</tr>
<tr>
<td>In Situ Surface - Mobile Lab</td>
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<td>Platform Maturity Assessment - Low End</td>
<td></td>
<td></td>
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<td>Platform Maturity Assessment - High End</td>
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<td>Mid</td>
<td>Med</td>
<td>Med</td>
<td>Med</td>
<td>Far</td>
</tr>
</tbody>
</table>

**LEGEND**

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

Note 1. Autonomy is assessed at the platform level. Does not include the impact of autonomy on the use of multiple platforms which is much greater.
Figure B.1 Time frame in which exploration platforms could be ready for deployment are ordered in time based on their technical readiness. Technical readiness is a composite measure based on technology maturity, complexity and resource needs.

Summary

Exploration of Venus will depend on exploration platforms that can conduct both remote and in situ exploration. The orbital platforms are generally technically mature although some advances are needed to handle the Venus environment and developments on SmallSats and CubeSats are continuing. Probes are also mature with the developments mainly aimed at miniaturization which will specifically benefit the sonde class of probe which is deployed after atmospheric entry at Venus. The 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 & Beauchamp, 2016)
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 capability. In this section, we describe how these platforms address the Venus exploration scientific strategy described in the companion Goals, Objectives and Investigations document (VEXAG_GOI_Focus_Group, 2018).

Format of the GOI-Platform assessment tables

For each of the three goals, we have generated tables described 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. The table for Goal I (Table C.1) illustrates the format. Along the vertical 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. Directly beneath the shorthand description of each platform type is the earliest time-frame when this 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.

For some investigations in the GOI, only one type of platform is suitable for the measurement. In other cases there are alternative platforms that can be used although 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 the table provides an assessment of the ability to address the investigation. In almost all cases, measurements that are deemed vital to the investigations are feasible.

Goal One – Evolution, Habitability, and Exoplanets

Understand Venus’ early evolution and potential habitability to constrain the evolution of Venus-sized exoplanets.

Venus and Earth possibly both hosted liquid water oceans for billions of years—or alternatively these celestial cousins may have trod distinct evolutionary paths from the birth of the Solar System. 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.
A summary assessment of the ability of Roadmap platforms to address the eight investigation that comprise Goal I appears in Table C.1. Measurements made from orbiters, are vital to the completion of most of these investigations but the type of orbit that is optimal, 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 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. The Aerial Platform Sub Cloud capability can also make a vital contribution to the investigation of hydrous origins.

Table C.1 Goal One – Assessment of ability of Roadmap Platforms to address GOI Investigations

<table>
<thead>
<tr>
<th>GOI Code</th>
<th>GOI Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.A.HO</td>
<td>1</td>
</tr>
<tr>
<td>I.A.RE</td>
<td>1</td>
</tr>
<tr>
<td>I.A.AL</td>
<td>2</td>
</tr>
<tr>
<td>I.A.MA</td>
<td>3</td>
</tr>
<tr>
<td>I.B.IS</td>
<td>1</td>
</tr>
<tr>
<td>I.B.LI</td>
<td>1</td>
</tr>
<tr>
<td>I.B.HF</td>
<td>2</td>
</tr>
<tr>
<td>I.B.CO</td>
<td>2</td>
</tr>
</tbody>
</table>

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

Goal Two - Atmospheric Dynamics and Composition

Understand atmospheric dynamics, composition and climate history 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 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. Orbiters play a vital role in all investigations but one but the except for one case 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. Since the focus of these investigations are on the atmosphere which is temporally and spatially variable, synchronous orbital and in situ measurements add substantial additional value to the investigations.

**Goal Three – Surface and Atmosphere**

*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 as shown in Table C.1

**Table C.3 Goal Three - Assessment of Roadmap Platforms for addressing Roadmap Objectives**

The platforms with the broadest applicability for addressing these objectives are an orbiter 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.

**Summary**

The Roadmap Focus Group are continuing to interact to refine the understanding of how measurements from the different platforms can effectively address the GOI investigations and the detailed content of Tables C.1, C.2 and C.3 may change but this is unlikely to change the overall conclusions about the role of the different exploration platforms in Venus exploration.

**Acronyms and Abbreviations**

DAVINCI Deep Atmosphere Venus Investigation of Noble Gases Chemistry and Imaging  
AO announcement of opportunity  
EM electromagnetic  
*GOI (Venus) Goals, Objectives, and Investigations*  
H/D hydrogen/deuterium  
LLISSE Long-lived In-situ Solar System Explorer  
PDR preliminary design review  
SAR synthetic aperture radar  
TRL technology readiness level  
VCM Venus Climate Mission  
VERITAS Venus Emissivity, Radio Science, InSAR, Topography and Spectroscopy  
VEXAG Venus Exploration Analysis Group  
VIRTIS (Venus Express) Visible and Infrared Thermal Imaging Spectrometer  
VISAGE Venus In Situ Atmospheric and Geochemical Explorer  
VISE Venus In Situ Explorer  
VOX Venus Origins Explorer  
VSSR Venus Surface Sample Return

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