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Venus Surface Platform Study

Final Report

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Venus Surface Platform Study Final Report

Submitted by

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Executive Summary

Venus surface conditions are exceptionally challenging for the use of surface platforms due to the high temperature and pressure and reactive atmosphere. Nonetheless, there are important science questions that can only be answered via in situ surface operations, both short and long durations. A main purpose of this Venus Surface Platform Study is to understand platform capabilities required to achieve desired Venus interior-, surface-, and surface-atmosphere-related science.

More generally, the original study purpose was to assess the science achievable by various surface platform capabilities, to describe the state of the technologies applicable to Venus surface exploration, and to lay out a high-level roadmap for the future exploration of the planet by this means. Given that the Venus Exploration Analysis Group (VEXAG) recently reviewed and released updates to its key documents (Figure ES-1), one of which was the exploration roadmap, the study team dropped the roadmap element from the objectives.

Major findings of the completed study include: 1) surface science is key to understanding Venus origin, history, climate, and interior; 2) some key data (like mineralogy and morphology) can continue to be acquired with short-duration landers and probes while other data (meteorology, seismology, and geological processes) need the long temporal baselines provided by long-duration landers. Further, other data will require measurements taken simultaneously at multiple locations; 3) current technology can support new short-duration missions; 4) increased science can be realized by increasing surface missions' capabilities in a) life on surface (time), b) mobility, c) sophistication and autonomous operations (smarts), and d) multiple copies of the same platform making simultaneous measurements at various locations (multiple simultaneous measurements or MSM). The potential impact to science by various capabilities is shown in Table ES-1. An "H" in a field signifies that the capability is highly impactful in realizing that aspect of the science. An "S" in a field signifies it is somewhat impactful. The descriptions and definitions of the capabilities are provided in Section 3.0.

The capabilities referenced previously are underpinned and made possible by a host of technologies, some current, some in development, and some still to be developed. The study team explored the relationship between technologies and capabilities and summarized the results in Table ES-2. The detailed discussion of technologies and their relationship to capabilities is discussed in Section 4.0.

The identified capabilities are not necessarily exclusive of each other and combinations of capabilities may be synergistic. An attempt was made at capturing that construct with Figure ES-2.

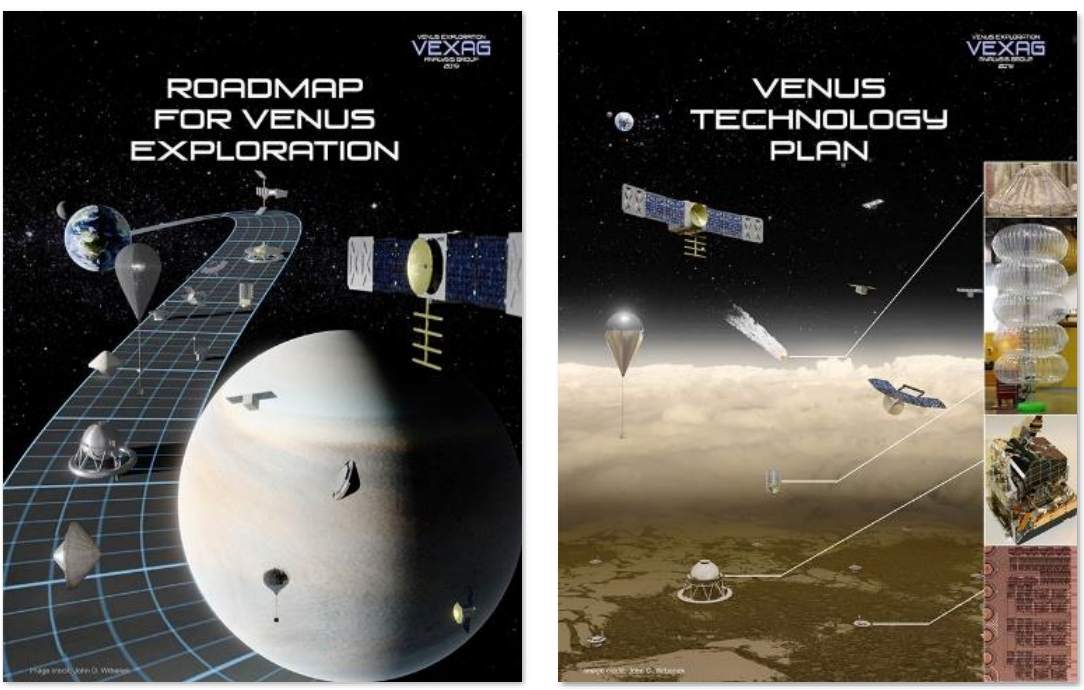

Figure ES-1. VEXAG documents (Refs. 1 and 2).

The conclusions drawn are that enhanced capabilities along dimensions of mobility, smarts, and especially time and MSM will provide the foundations to address more decadal science questions related to Venus's interior, surface, and the surface-atmosphere interactions. To enhance future lander platform, time, smarts, mobility, and MSM will require consistent support to develop relevant technologies. The most impactful near-term technology investments will target solutions to power needs (especially supporting long-life platforms), high-temperature electronics, memory, and autonomous operations and navigation.

Table ES-1. Potential Science Impact Relative to Capability

Science field	Capability			
Interior	**Time**	**Smarts**	**Mobility**	**MSM**
Structure	H			H
Composition	H	S		H
Dynamics	H			H
Heat flux	S			S
Surface				
Composition		S		S
Dynamics (eruptions, flows, …)	H	S	H	
Diversity (spatial)	H	S	H	S
Morphology	H	H	S	H
Stratigraphy	H	H	H	H
Surface-atmosphere interactions				
Gas and surface composition	H	H		H
Winds	H			H
Reactions	H	H		S
Momentum exchange	H		S	H

Table ES-2. Relationship Between Technologies and Capabilities Enabled

Critical underlying and supporting technology	Capability		
	Time	**Smarts**	**Mobility**
Power (low—10s of watts or less)	H	H	
Power (high—100s of watts)			H
Cooling (will also need power (high))	S	H	S
High-temperature electronics/memory/power processing	H	H	H
Mechanisms (drills, wheels, …)			H
Autonomous operations and navigation		H	H
State-of-art instruments		H	

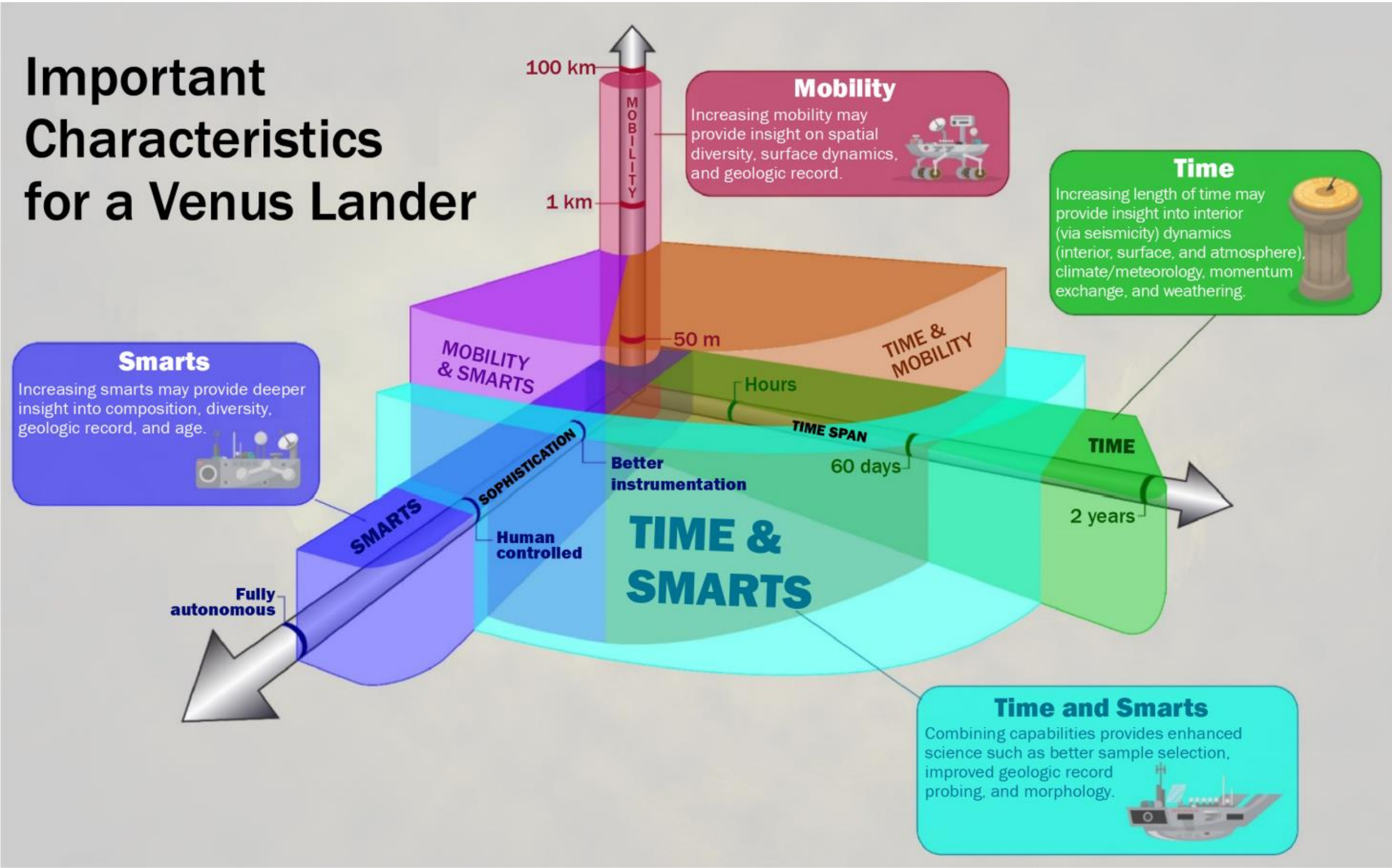

Figure ES-2. Driving synergistic capabilities of Venus surface platforms.

1.0 Introduction

One of the most intriguing planets in our solar system for both solar and extra-solar systems science is Venus. Venus is the planet most similar to Earth in several important ways and many believe Venus-like planets are more common around other suns than are Earth-like planets. Therefore, scientific understanding of our sister planet is a high priority. To address many questions, in situ measurements are required; this is true for any planet but particularly true for Venus due to the unique challenges that the atmosphere poses for remote sensing. The environmental challenges at the Venus surface have made it difficult to address the interior-, surface-, and deep-atmosphere-related science questions posed in the Planetary Decadal Survey report (Ref. 3) and VEXAG goals and objectives documents (Ref. 4) so there still remains the need for in situ data. This has been recognized in recent workshops such as the Venus modeling workshop held at Glenn Research Center (GRC) in 2017 (Ref. 5). Perhaps the most notable challenge at the surface is the extreme temperature. The extreme temperature has relegated the surface life of all Venus landers to date to be no more than 127 minutes (Ref. 6). The drive to understand the range of science needs and how those relate to the combination of environmental challenges and technical capabilities became the impetus for initiating the Venus Surface Platform study. The main purpose of the Venus Surface Platform study is to assess the science that needs to be achieved by various surface platforms, the capabilities needed to achieve that science, and the technologies needed to enable those capabilities.

1.1 Study Organizational Structure

Study-related work was executed by an organizing committee and four subgroups. The organizing committee consisted of (alphabetically) Jeff Balcerski (Ohio Aerospace Institute), Noam Izenberg (Johns Hopkins University Applied Physics Laboratory), Natasha Johnson (Goddard Space Flight Center (GSFC)), and Tommy Thompson (Jet Propulsion Laboratory (JPL)). The study was co-chaired by Mike Amato (GSFC) and Tibor Kremic (GRC). Each of the target science areas had a lead that helped encourage and steer discussions and make the needed progress. Science-driven subgroups were organized and targeted to surface-related topics, namely, 1) interior, 2) surface, and 3) surface-atmosphere interactions. There was also a fourth subgroup organized that focused on capability/technology topics. Leads for the subgroups were: 1) interior—Walter Kiefer (Universities Space Research Association/Lunar and Planetary Institute), 2) surface—Martha Gilmore (Wesleyan University), and 3) surface-atmosphere interactions—Natasha Johnson (GSFC). Jonathan Sauder (JPL) was the lead for the capabilities/technology subgroup. The organizing team and leads for the subgroups are reflected in Appendix A. To achieve study goals, two face-to-face meetings (one at GSFC and one at GRC) were organized including one where invited scientists, technologists, and mission planners participated in a 2-day working meeting to systematically address and discuss relevant topics. Several telecoms were also conducted to discuss content, assign and report on actions, make decisions, and discuss work progress.

1.2 Study Approach

The approach for this study was to engage those with prior or current activity related to Venus surface exploration and the experts in the field, enlisting them to work together to address the original study purpose to:, to assess the science desired by various surface platforms, the technologies required, and to lay out a high-level roadmap for the future exploration of the planet by surface platforms. During the study process, it was discovered that there were a few key capabilities that drove the ability to achieve Venus science goals. Those key capabilities in turn could be realized by one, or more often, a combination of specific technology developments. Identifying the key capabilities became a product of this study.

During the course of this study, VEXAG reviewed and updated their guiding documents including the Roadmap for Venus exploration (Ref. 1). There were discussions between this study team and the teams updating the VEXAG documents and some of the early results of this study were inputs to the VEXAG teams updating the documents. Given this exchange and the release of the VEXAG roadmap document, this study team did not develop its own separate exploration roadmap as originally planned, therefore, that objective was dropped from this effort.

This study report is organized around the three target science areas, consistent with the subgroup structure, these again are:

1. Interior (e.g., geophysics and geodynamics)
2. Surface (e.g., geology, weathering, minerology, and petrology)
3. Surface-atmosphere interactions (e.g., minerology, petrology, atmospheric composition, and geochemistry)

After a discussion of the science needs, the focus turns to the capabilities required to meet the respective target science goals. Finally, the underpinning and/or enabling technologies are discussed.

For each of the three target science areas, the respective study subgroup formulated science objectives; discussed in Section 2.0. The discussion centers on the science objectives, capability, and functionality necessary for a surface platform to get the measurements to achieve the science goals.

This required an understanding of the state of the art (SOA) of what is presently known about Venus, including information provided by various platforms such as orbiters. Understanding by the science subgroups of the SOA of applicable technologies was also necessary. In fact, this was a discussion topic at each face-to-face meeting. Once the key capabilities, as described in Section 3.0, were identified by the study team, the supporting and underpinning technologies were also discussed among the technology and science subgroups. This helped drive out what the technologies are that enable the capabilities to achieve the science.

The capabilities/technology subgroup looked at a variety of areas and how those enabled capabilities or direct measurements for science. Some of the discussed capability and technology topics included: instrumentation, avionics, communications, power, and mobility.

It was found there was an interplay between various basic lander parameters and how that translates to implementation capabilities. The following example subset are some parameters that can lay a foundation for a set of key capabilities required.

- Time duration (hours to months)
- Distance between measurements (point measurements to 100s of kilometers)
- Depth (surface to 10s of meters)
- Terrain accessed (flat plains to tesserae)
- Autonomy (simple preprogrammed mission to humans in the loop)
- Points/network (single lander through lander networks)

The science that can be addressed changes dramatically depending on conditions, for example, duration of the mission or how many landers are coordinated in the mission.

The set of key capabilities identified in this study came about through discussing various science needs and mission parameters. The approach then involved deeper discussion, on what specific technologies enable the key capabilities.

Some examples of specific technologies discussed that enable key capabilities include suitable power systems, a cooling system that could keep sensitive subsystems within an acceptable temperature range, and high-temperature electronics. Further discussion of underpinning technologies is provided in Section 4.0.

1.3 Challenges

The relative lack of knowledge of Venus's surface and interior is a direct result of the challenging environment, which has temperatures hot enough to melt lead and zinc, pressures equivalent to nearly a kilometer under Earth's oceans, and a reactive chemical atmosphere (Ref. 7). Remote sensing of the surface and portions of the atmosphere is difficult at best (Refs. 2 and 6) due to the thick layers of sulfuric acid clouds and the high-pressure supercritical CO_2 atmosphere below those clouds. This has hampered the ability of orbiting missions to provide desired insight into surface features and processes, thus hiding potential clues regarding climate, surface processes, and the interior.

Over the period from 1970 to 1984, 10 lander missions to Venus were successfully executed, yet the longest surviving asset (Venera 13) lasted only 127 minutes (Ref. 8) before succumbing to the extreme temperature. While this and other landers provided valuable new data at the time, key measurements remain poorly constrained. In addition, the short life prevented understanding many of the temporal near-surface processes on Venus, for example meteorology and seismic activity, therefore, very little is known about the activity of the crust, the interior structure or composition, and the surface-atmosphere interactions.

2.0 Venus Surface Science Gaps and Desired Measurements

2.1 Overview

Significant scientific investigation of Venus has historically involved the use of multiple platforms including orbital, aerial (balloon), and lander missions. The use of orbital and aerial platforms has been facilitated through the leveraging of core technologies relevant to other planetary studies including those of Earth. Given the environmental conditions on the Venus surface and the capabilities enabled by technologies at the time, lander

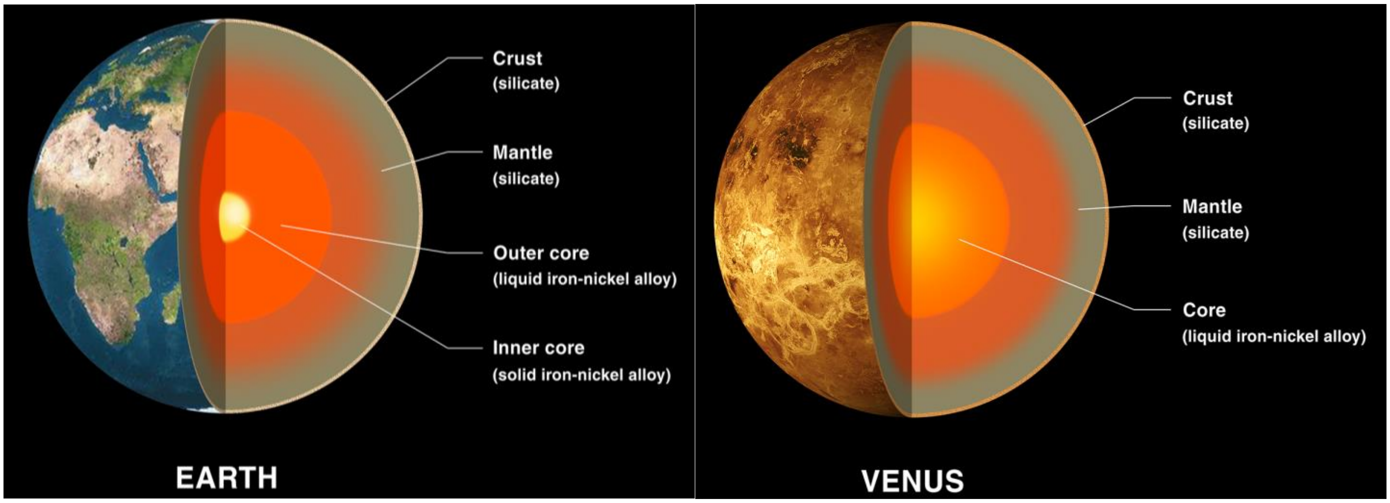

Figure 2.1. Earth versus potential Venus interior structure Credit: Lunar and Planetary Institute (Ref. 9).

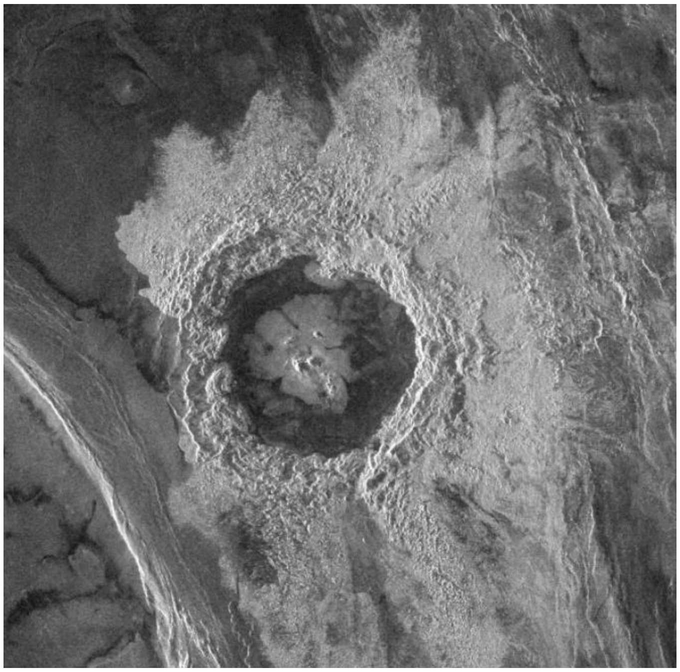
Figure 2.2. Magellan image of Dickinson Crater, one of the relatively small number of Venus craters (Ref. 10).

missions to date have had limited durations (~2 hours). Although substantial advancements have been made in understanding Earth's sister planet, given such missions, there are significant science questions that still need to be investigated, and in many cases uniquely answered, through the use of in situ measurements. Examples of questions from the recently updated VEXAG Venus Scientific Goals, Objectives, and Investigations (Ref. 4) related to different aspects of Venus planetary exploration include:

- Interior: "Seismic measurements via a long-lived lander of seismicity induced by active tectonism or volcanism would also be invaluable. Measurements by a single lander would be sufficient to detect such activity, but measurements by a network would enable more quantitative analysis of the activity" (III.A.GA) (e.g., Figure 2.1).
- Surface geology: "Landers can provide detailed determinations of rock type and physical inter-relationships using high-resolution imagers and chemical analysis instruments (e.g., x-ray fluorescence, gamma ray spectrometry, or LIBS [laser-induced breakdown spectroscopy]). Landers could potentially remove surface coatings caused by chemical weathering to determine the detailed mineralogy of a Venus rock." (I.A.HO) (e.g., Figure 2.2 and Figure 2.3).
- Surface-atmosphere interactions: "In-situ direct measurements of the deep Venus atmosphere would provide clarity to questions of the concentrations and distributions of gases whose lowest scale height concentrations have only been inferred. This Investigation could be accomplished via landers or descent probes with suitably designed mass spectrometers", (III.B.CI). … "Finally, landers and descent probes capable of simultaneously measuring meteorological parameters and the mixing ratio of carbon dioxide (and other species) in the lowest ~10 km can study supercritical carbon dioxide." (II.B.IN)

Questions about key science questions and gaps were posed to each subgroup in the study. Table 2.1 gives a sampling of the science questions associated with the Venus surface, which are related to rock composition, atmospheric chemistry, climate and weather, and interior dynamics and structure. These questions are key to understanding Venus. In some cases, the questions can be answered using current lander technology with upgraded instrumentation. However, to answer a number of science questions data from longer duration missions, new capabilities, multiple measurements at various locations, or long-distance mobility may be required. These capabilities in turn may require advances in relevant technologies (Ref. 2).

Given the limited number and duration of previous Venus surface missions, even incremental steps toward achieving these advanced surface mission capabilities would be useful. However, the use of surface platforms that have the enhanced capabilities in areas of time, smarts, mobility, and/or MSM are needed to go beyond incremental science advancements and achieve major or even breakthrough advancements in Venus science. Key capabilities that impact science return are defined and discussed in detail in Section 3.0.

Figure 2.3. Venus surface image taken by Venera 13 (Ref. 11).

Table 2.1. Examples of Science Questions, Missions, and Associated Measurements

	Science	Mission	Measurements
Interior diversity and structure	What is the physical structure and rheology of the deep interior?	Long lived, single and multiple, stationary	Seismology (long-duration stationary platform)
	What is the physical structure, composition, and dynamics of the crust?	Long lived, single and multiple, stationary	Seismology (long-duration stationary platform
	What is the heat flux from the interior to the surface?	Single, multiple, stationary, long or short lived	Heat flux, temperature probe
Geology and composition	What characterized Venus surface geology and history?	Single, multiple, stationary, short to moderate life	Imaging, chemical composition and age dating, physical measurements
	What is the spatial variation across the surface of Venus geology?	3+ landers (different altitudes and latitudes), stationary, short-lived preprogrammed mission, or long-lived or mobile system	Imaging, chemical composition and age dating, physical measurements
	What are of petrogenic elements, material properties, and surface structures?	Single, stationary, short-lived preprogrammed mission	Chemical composition and age dating, physical measurements
Climate, weather, and energy balance	What are the concentrations of atmospheric constituents, metrological conditions, and solar radiance?	Single, stationary, 3+ landers (different altitudes and latitudes), short life; preprogrammed mission	Meteorology, chemical composition, radiance
	What are the time variations in concentrations of atmospheric constituents, metrological conditions, and solar radiance?	Single, 3+ landers, stationary, long-lived mission up to one solar day	Meteorology, chemical composition, radiance
	What is the spatial variation of concentrations of atmospheric constituents, metrological conditions, and solar radiance?	Long-lived landers (different altitudes and latitudes): multiple stations, multiple short -life landers, and / or long-distance mobility	Meteorology, chemical composition, radiance

2.2 Interior

2.2.1 Science Questions

Major investigations related to a better understanding of the Venus interior (defined here to be a couple of meters or deeper below the surface) include investigation of seismic activity, interior structure and bulk composition, and interior heat loss. Venus has a similar size, mass, and location in the solar system to Earth, but our knowledge of its interior structure is limited to studies of the gravity field. For example, the bulk density and tidal Love number k_2 require the presence of a metallic core that is at least partially molten (Ref. 12), and regional gravity studies constrain the thickness of the crust and lithosphere (Ref. 13) and the locations of upwelling and downwelling flow in the mantle (Ref. 14). There is mounting evidence for currently active volcanism (Refs. 15 and 16), but the frequency and eruption volumes are not known. Venera 15 and 16 and Magellan data reveal abundant tectonic activity such as extensional rift structure, contractional structures such as ridge and mountain belts, and the highly deformed tessera. These features are indicative of a convecting mantle yet currently Venus does not have a magnetic field. Further, because Venus and Earth are similar in size and bulk density and likely similar in composition, one might expect them to have similar surface heat flows. However, Earth's interior heat is efficiently transported to the surface by plate tectonics, while Venus appears to have a thicker lithosphere, resulting in less efficient convective energy transport and a lower surface heat flow (Ref. 17). The details of the possible transition from an early mobile lithosphere on Venus to the present-day sluggish or stagnant lithosphere are poorly understood and were probably both spatially and temporally complex (Refs. 18 and 19).

Major science questions include:

- What is the physical structure and rheology of the deep interior?
- What is the physical structure, composition, and dynamics of the crust?
- What is the heat flux from the interior to the surface?
- What is the current level of endogenous activity on Venus?

2.2.2 Notional Mission Approach(es) to Address Science Questions on the Interior of Venus

While no in situ seismic data exists for Venus today, models suggest that perhaps a few tens of events of magnitude 5 or greater may occur over the course of a Venus day (1 solar day on Venus is 117 Earth days) (Ref. 20).

A long-lived surface lander that includes a seismometer and possibly a heat flow probe as part of the payload could make important contributions towards answering these questions.

A seismic system on a long-lived lander could both measure the level of seismic activity and use the measured seismic velocities to constrain the interior structure, such as the thickness and composition of the crust. One path toward seismology on Venus could be to start with a single station to assess the general level and amplitude of seismic activity as well as the level of wind noise, which could interfere with seismic measurements. Such a pathfinder experiment would also inform future missions to enhance and tune seismometers, power systems, and optimize other lander platform systems such as data transmission and storage. The InSight mission on Mars demonstrates the potential power of even a single, highly capable seismic station (Ref. 21). A long-lived surface platform, something like NASA's Seismic and Atmospheric Exploration of Venus (SAEVe) concept, Figure 2.4 (Ref. 22), could be used for such a mission. Combinations of two or more of those same platforms spaced an appropriate distance from each other would be able to determine the locations of seismic sources and probe the interior structure by measuring how seismic velocity varies with depth. Other geophysics measurements, such as heat flux and magnetic field measurements, would also be important. The Venus interior questions that such a mission approach would address include those shown in Table 2.1.

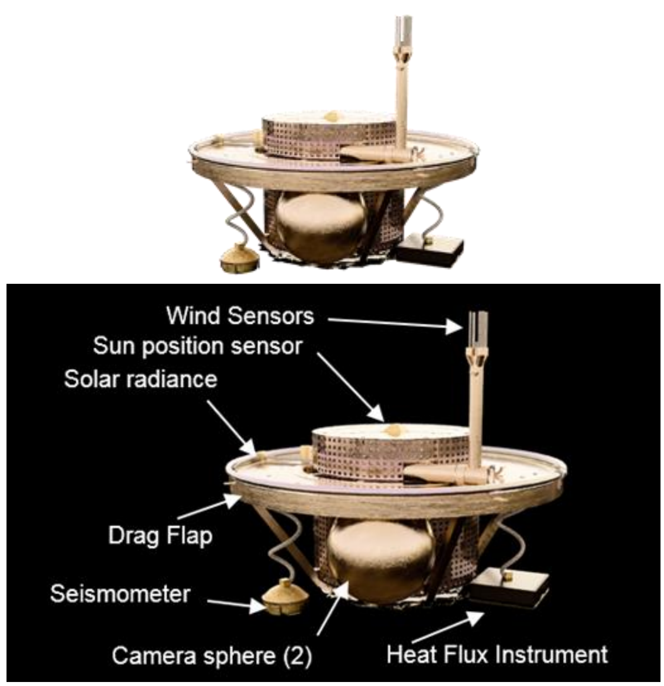

Figure 2.4. SAEVe lander concept (Ref. 22).

A key capability to address interior science is the ability to measure for longer times and with multiple landers. Mission duration should initially be for at least 30 Earth days with 120 days or more being the goal. For missions lasting up to a Venus solar day (117 Earth days), capabilities considered viable in the near-term are platforms like SAEVe. The addition of memory to platforms like SAEVe will enable capturing and transmitting all the data in the seismic waves making it a desired technology. Optimum distance between the surface platforms that support seismometers have been initially estimated to be between 300 to 800 km (Ref. 23). The more separation between platforms the deeper one can probe. It is estimated that depths up to 100 to 150 km can be probed assuming that the seismometer is sensitive to seismic periods between 10 and 100 seconds, while measurements at periods of 1 to 10 seconds could provide details on seismic source mechanisms. Networks of longer duration stations, even permanent platforms, can be envisioned in the future as other capabilities like permanent power solutions are developed and could continue to reveal more about the interior structure of Venus much as seismology has done on Earth.

2.2.3 Measurements

The key surface geophysics measurements for understanding the interior of Venus are seismology, heat flow, and magnetometry.

2.2.3.1 Seismology

One of the most direct methods to understand the interior of a planet is the use of seismology. The overall science objective is to determine the rate and nature of Venus seismic activity as well as using seismic measurements to understand the structure and composition of the Venus interior.

Seismic velocity is a function of temperature and composition; thus, it can be used to measure interior structure. For example, the thickness of the crust can be determined because the transition from the crust to the mantle is a major discontinuity in seismic velocity. Within the crust, it may also be able to distinguish composition (e.g., basalt, andesite, or granite) based on the seismic velocity (Ref. 24). The thickness of the lithosphere can be estimated from the velocity of Rayleigh waves (Ref. 25). At greater depths in the mantle, it may be possible to estimate temperature by looking for reflections from mineral phase transitions (e.g., olivine to spinel) in the upper mantle (Ref. 26).

Seismic measurements on the Venus surface have a specific set of challenges. The presence of the Venus wind will affect seismic measurements. While the velocities are not relatively large, the atmosphere is dense and will induce forces on the instrument. This can be addressed with simultaneous measurements of wind velocity and pressure in conjunction with the seismic measurements. Moreover, ambient seismic noise induced by the global wind field has the potential to be a useful seismic source, provided that it is measured simultaneously at two or more stations in a regional seismic network. Ambient noise seismology has become an extremely important technique in terrestrial seismology (Ref. 27).

The efficacy of a deployed seismometer can depend on the porosity and rigidity of the material at the landing site. Porous or loose material could result in poor coupling with the seismometer. If the seismology lander also includes a drill for a heat flow or geochemistry experiment, the drill could serve as an active seismic source for probing the structure of the shallow subsurface. A similar experiment was performed on Mars using the heat flow "mole" as a seismic source (Ref. 21). Adaptation of seismometer instruments (Figure 2.5) (Ref. 23) and tactics from NASA's Insight mission (Figure 2.6 and Figure 2.7) (Refs. 28 and 29) for Venus seismometry appears like a plausible solution.

2.2.3.2 Heat Flux

The flux of energy coming out of a planet's interior depends both on the pattern and vigor of convective flow in the mantle and on the distribution of radioactive heat-producing elements in both the crust and mantle. A broad range of evolutionary models have been proposed for Venus, involving a plate-tectonics-like mobile lithosphere, a stagnant lithosphere, transitions between these two states, and a possible catastrophic resurfacing event at some point in the last billion years (Ref. 30). Measuring the heat emitted through the crust can contribute to an understanding of the thermal state of the Venus interior. Currently our guides to understanding

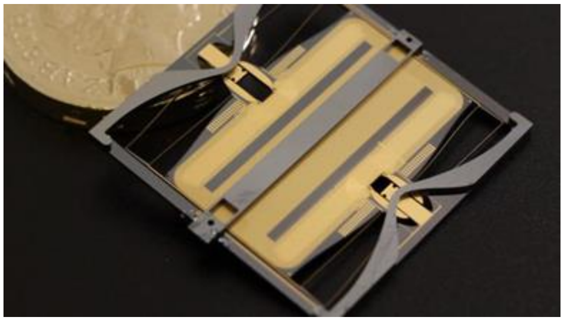

Figure 2.5. Insight seismometer 's Microelectromechanical systems (MEMS) sensor (Ref. 23).

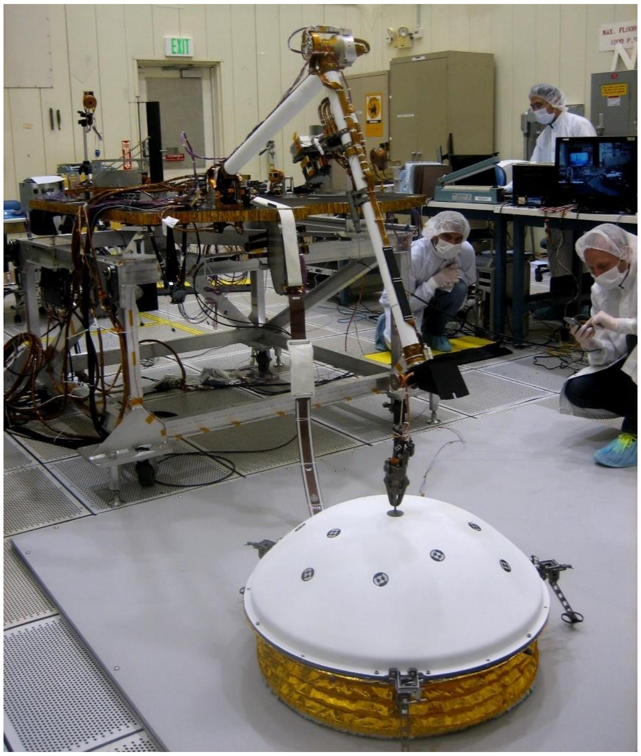

Figure 2.6. Insight Seismic Experiment for Interior Structure (SEIS) seismometer (Ref. 28).

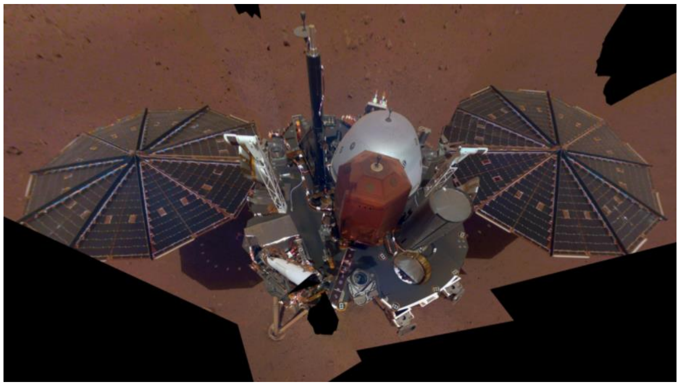

Figure 2.7. Image of NASA Insight Mission (Ref. 29).

these problems are gravity modeling, surface geology, and cratering record. Measuring heat flow directly would add critically important information on the current thermal budget of Venus, but implementation may be challenging. Heat flow is usually measured by drilling at least several meters into the surface and measuring the temperature gradient as a function of depth and the thermal conductivity. Near a planet's surface, the temperature varies over time due to the diurnal cycle in solar insolation, so these measurements must be made at sufficient depth to be below these diurnal temperature variations. On the Moon, this requires measurements at depths of 2 to 3 m below the surface (Ref. 31). On Venus, the likely lack of an impact gardened regolith results in a higher near-surface thermal conductivity. This, along with the long solar day, allows the diurnal thermal wave to reach depths of ~10 m on Venus. However, drilling to such great depths into Venus is a daunting task today for multiple reasons including the needed power and time to drill to the required depth as done previously on other planetary bodies.

One alternative measurement concept that has seen some development is a contact type thermal plate (Figure 2.8). With good coupling, thermal control, and supporting measurements like surface skin temperature and accurate local diurnal data, the desired heat flux measurement might be feasible (Ref. 32). In principle, the measurement could be made in a short period of time. However, numerical climate simulations indicate that the surface temperature can vary by ~3 K over the diurnal cycle (Ref. 33), which will cause the heat flux into and out of the surface to vary with time. Even if thermal plate measurements were made over a full diurnal cycle, it has not yet been demonstrated that the measurements can be performed with sufficient accuracy to reliably remove the diurnal signal or to accurately measure the heat flow out of the Venus interior. As a first step toward measuring heat flux in situ, it would be useful to measure the temperature variation at the surface over the course of the solar day.

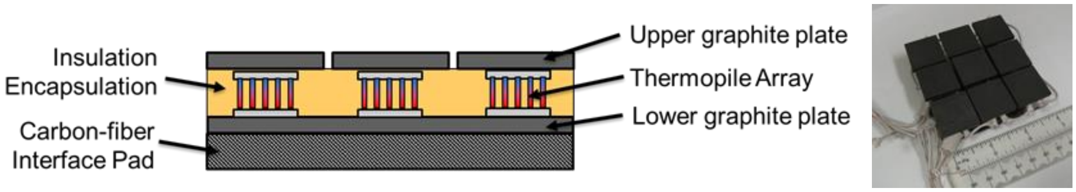

Figure 2.8. Contact type heat flux sensor and image of thermopile array (right) (Ref. 22).

2.2.3.3 Magnetometry and Electromagnetic (EM) Sounding

Venus does not currently have an active core geodynamo. Detecting crustal remanent magnetism would be a sign of a past geodynamo and would place strong constraints on the early evolution of Venus. Although remanent magnetism has not been detected by orbital observations, it is possible that small regions of remanent magnetism would not be detectable from orbit because attenuation is altitude-dependent. Measurements of the magnetic field on a Venus lander could therefore be useful, although such measurements would be more valuable if performed on an aerial platform that could survey an extended region (Ref. 34).

2.3 Surface

2.3.1 Science Questions

Our knowledge about the Venus surface environment, its centimeter to meter scale morphology, and the chemical composition of the surficial materials came from measurements made by the Soviet Venera and Vega landers 40 to 50 years ago. Those data have been compared to Earth analogues for clues onto processes and state of the surface on Venus Figure 2.9. These data, although fundamentally important, suffer from the low precision of the measurements and uncertainty in determination of the lander locations. So far, the geochemical aspect of the geologic history of Venus remains to be the most poorly investigated. This aspect includes chemical and mineralogical composition of the primary materials, degree of its alteration, and redeposition of the primary and altered materials by the surficial processes (e.g., wind transport). An extremely intriguing part of the geochemical evolution is the history of water on Venus. Recent modeling suggests that liquid water may have persisted on Venus for 2 to 3 Ga (Refs. 35 and 36). The record of this era may be presented in tessera, which is the stratigraphically oldest material unit on Venus.

Major surface science questions include:

- What are the chemical composition of the rocks on the Venus surface?
- What are material properties of rocks on the surface?
- What are the <1 km scale rock morphologies, structures and deposits on the surface and their relative ages?
- What are the dynamic processes that occur at the surface?

A long-lived surface lander that includes chemical and mineralogical instruments and cameras as part of the payload could make important contributions towards answering these questions.

2.3.2 Notional Mission Approach(es) to Addressing Science Questions About the Surface

A single lander mission of a conventional, complex surface platform that targets surface science with SOA instruments and techniques, like the Venus Flagship Mission concept (Ref. 6), will go a long way to addressing surface science questions. Mission objectives for such a platform would be to characterize morphology, phase and chemical composition mineralogy, structure of rocks on the surface, grain size distribution, and multiple physical properties of surface materials (e.g., conductivity). Such a conventional lander system could include remote sensing instruments, for example, LIBS, Raman, and

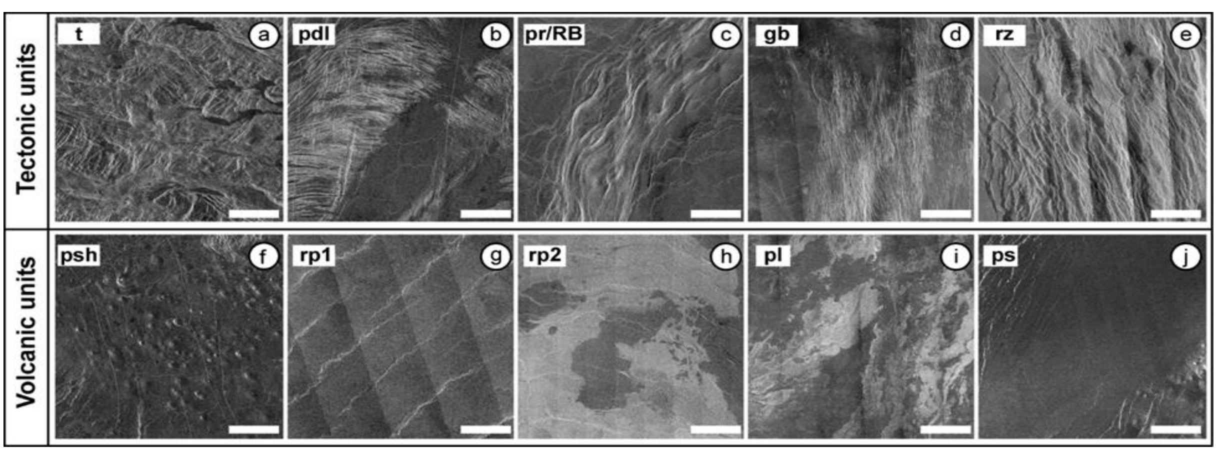

Figure 2.9. Representative Venus surface analogues from Earth units, Venera–D Joint Science Definition Team (JSDT) Report (Ref. 37).

gamma ray and neutron spectroscopy (GRNS) (Figure 2.10) (Ref. 38) as well as an imaging system for descent and surface images, including images to enable microscopic examination of the nearby rocks and soils. Such a lander would also include an interior chamber that can accept samples and have some form of thermal management to maintain interior conditions that would support instrument and sample needs. The vessel would contain complex measurement instruments, actuation mechanisms to acquire and process samples and perform physical analysis, structural measurements, and the ability to perform phase and chemical analysis of materials and rock samples (Ref. 39).

The lifetime of conventional lander systems (which is measured in hours) makes fully characterizing a given landing site a significant challenge. While conventional lander systems can perform a number of functions in preprogrammed mode, feedback between human operators and the lander system could provide improved science by allowing investigation of features of interest or repeating experiments as necessary to verify results. Thus, extending the life of complex lander systems and complementing them with a bidirectional communication system would significantly enhance the science gain from a single short-duration lander. Short-duration lander missions have been implemented in the past (Venera and Vega) and other missions with large, short-duration assets are in various stages of study or development (e.g., Venera–D and Venus Flagship Mission), therefore, the mission approach described in this section is reflected in those past and ongoing efforts. For example, the reports from the Venus Flagship Mission and Venera–D studies describe in some detail the science, measurements, and instruments required (Refs. 37 and 40). The instrument and measurements planned by the Venera–D mission are shown in Table 2.2. A similar list for the Venus Flagship Mission is shown in Figure 2.11 (Ref. 40).

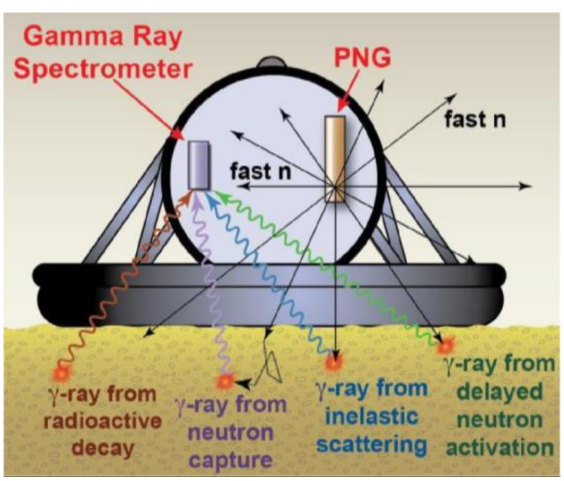

Figure 2.10. Measuring surface bulk elemental composition (Ref. 38).

A mission with multiple landers would represent a crucial step in expanding the understanding of surface materials. Each lander would have the capability to characterize a local environment as described previously. Comparisons of the data from these multiple sites would provide snapshots of both (plains and tesserae) geological features as well as specifics of a given site.

Long-duration missions (months) have the advantage of observing the variability of surface processes: weathering, winds, sediment movement, possible effects of volcanic eruptions, or on-going interface reactions between the atmosphere and surface (Ref. 41). The ability for a complex lander with a full set of characterization capabilities, or a simple lander for targeted measurements (e.g., imaging), to provide measurements over time notably adds to the baseline data provided by shorter term measurements.

Lander
Neutral Mass Spectrometer (NMS)
Tunable Laser Spectrometer (TLS)
Atmospheric Structure Suite [P, T, Radiometer] (AS)
Descent NIR Imager (DI)
Nephelometer (Neph)
Neutron Generator/Gamma Ray Spectrometer (GRS)
X-Ray Diffractometer (XRD)
Raman-LIBS Instrument (R-LIBS)
Panoramic Camera (PC)
X-ray Fluorescence Spectrometer (XFS)
Long-Lived In-Situ Solar System Explorer (LLISSE)

Figure 2.11. Summary of lander instruments and elements from 2020 Venus Flagship Mission (Ref. 40).

Table 2.2. Excerpt from Venera–D lander instrument summary (Ref. 37)

Instrument or Specific Subsystem	Description	Rough Characteristics/ Physical Properties (worst expected case shown)	Science Priority High (H), Med (M), and Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 or Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Main lander						
Instrument						
XRD/XRF	Elemental composition	275×162×190 mm, 30 W, 5 kg, <100 KB/sample	H	5	?	Gray shading signifies ingested sample. Sample volume required is 50 to 200 mg of <150 µm grain size
Mössbauer spectrometer	Backscattering Spectrum of Mössbauer radiation. Mineralogy of Fe-containing rocks, oxidation state of iron, analysis of rock-forming elements. Bulk chemical composition	40×40×100 mm. 0.5 kg, 3 W, 150 KB/sample	H	7	3	Detector cooling and integration time requirements may make this instrument infeasible for this lander concept. Gray shading signifies ingested sample required. Distance to sample as close as possible (in the range 1 to 2 cm, or closer), if possible, even mechanical contact (but not required) Pressure: high vacuum (10 to 6 mbar) to several bar, temperature: (a) operating: –100 °C to about 30 or 40 °C; (b) nonoperational: –100 °C to 70 or 90 °C. Sample volume required is TBD.
Camera system	Visible range color imaging system consisting of one landing, four to five panoramic and one close range cameras, mass memory/data compression unit (DCU) and cables. Five + two images, each image up to 2048×2048 px. Stereo imaging during the landing 30 to 45 grad, panoramic image of the surface at landing place	Camera heads 80×80×60 mm each, lens TBD at the Phase III, DCU 100×120×80 mm, camera heads 0.2 kg each, lens TBD at the Phase III, DCU 1.5 kg, 12 W 0.6 MB per image (compressed), i.e., 2.4 MB panorama, 0.6 MB closeup. Total estimate: decent phase 1…8 MB; landing phase 9.3 MB	H	4	2	Dependent on television systems for Russian lunar landing missions (Luna: 25…27), Exomars 2018 lander. Electronics temperature range up to 50 °C. At least three sessions, more is better, number of imaging sets is limited by data downlink capacity
CAP–GC-MS (gas chromatograph y-mass spectrometer)	GC-MS + Laser induced Mass-Spectrometry (LIMS) + chemical composition of the atmosphere, cloud aerosols, analysis of rock-forming elements, isotopic composition of noble gases and other elements	GC 260×180×130 mm, MS 250×150×110 mm, gas sampling 120×110×110 mm, used gas receiver-sphere diam. 150 mm, 10.5 kg, 60 W, 1 MB/measurement: 18 MB on descent, 3.5 MB on surface	H	3 to 7 2 to 7	5	Gray shading signifies ingested sample required. Sample volume is TBD. Measurements every 10 km on descent
Raman (potential integration with auxiliary LIDAR, laser induced breakdown	Remote time-resolved Raman and possibly integrated with LIDAR, LIBS, or other instrument	Nominally 300×300×250 mm, 80 W peak, 8 kg	H	5	3	Several Raman options exist—Some may require a sample to be brought in or up close to a window
Spectroscopy (LIBS), or other complementary instrument)	Mineralogy and possibly chemistry, atmospheric aerosols, molecular species (e.g., H_2SO_4, SO_2, H_2S, CO_2)	70 Mb/s Heat rejected 2 to 2.5 W				Time-resolved Raman instrument has been selected for Mars 2020 mission using University of Hawaii (UH) Raman instrument as prototype
METEO-lander-VD Fields Package	Meteorological instruments (T, P, dT, E, ω, H); measure the vertical structure of the atmosphere during landing and on the surface	(~1 L) max. ~2 W self-powered, ~1 kg, 0.1 KB/measurement, total 0.6 MB for descent and 0.65 MB for surface	H	2 to 7	3	

Table 2.2. Excerpt from Venera–D lander instrument summary (Ref. 37)

Instrument or Specific Subsystem	Description	Rough Characteristics/ Physical Properties (worst expected case shown)	Science Priority High (H), Med (M), and Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 or Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Main lander						
Instrument						
Gamma and NS	Active gamma-ray and NS, subsurface elemental composition	6.7 kg, 9.5 dm^3, 5/19 W	H	6 to 7	1 to 2	Consists of two pieces to be separated but both located near vessel bottom
Multichannel diode laser spectrometer with gas sampling system	Multichannel Laser Absorption Spectrometer (MLAS) and AGS system. In situ vertical profiles of sulphureous and minor gases and isotopic ratios in the Dense Venusian atmosphere down to the surface level. SO_2, CO_2, CO, H_2O, OCS; 13c/12c, 16o/17o/18o, D/H, 34s/33s/32s	100×120×450 mm, 6.3 kg MLAS unit; 90×120×400 mm, 3.6 kg AGS unit, 25 W average (5 W standby to 48 W peak); 20 Kb/min for active phase; total 5 MB for descent and 11 MB for surface	H	4 to 7 for functional blocks and subsystems	<5 yr	
IR radiometer and UV-VIS spectrometer	Measurements of upward and downward radiative fluxes in transparency windows. Active part of descent trajectory. Integrated with this is a UV-VIS spectrometer operating from 0.23 to 0.66 μm, 0.3 nm resolution 0.23 to 0.32 μm, broad ~1.0 nm resolution longward		H	3	6 to 8	UV-VIS will need a small window, and accommodation of external gas chamber comparable to that used on VEGA Descent Lander

2.3.3 Measurements

2.3.3.1 Imaging (Including Microscopy)

Imaging of the local geomorphology is a first step towards understanding Venus surface geology. Six panoramic landing site images returned from Venera 9, 10, 13, and 14 (Figure 2.12) show that the surface is accessible to optical imaging despite the atmospheric filtering of a significant amount of sunlight through substantial mid-altitude (48 to 65 km) cloud cover and low-altitude hazes. These images, created by a scanning video camera well before the era of digital imaging, hold tantalizing clues to microphysical and chemical (e.g., rock oxidation to ferric oxide) processes that shape the surface but are limited in scope and resolution. Lessons learned from the Venera imagers drive hypothesis testing and measurement goals. Descent and surface imaging are required for optical images of the surface, which are integral to the interpretation of radar characteristics at similar scales. Descent and surface panoramas with a resolution of mm/pixel at 1 m, and multispectral surface panoramas of, for example, five channels from 0.5 to 1.1 μm, are needed to understand both surface morphological features and their optical properties that inform about phase composition. These data would help to identify rock types, layering and fine-grained materials, and mineralogy of rocks and fine-grained materials. Landing site images, of individual basalt flows can reveal flow texture and

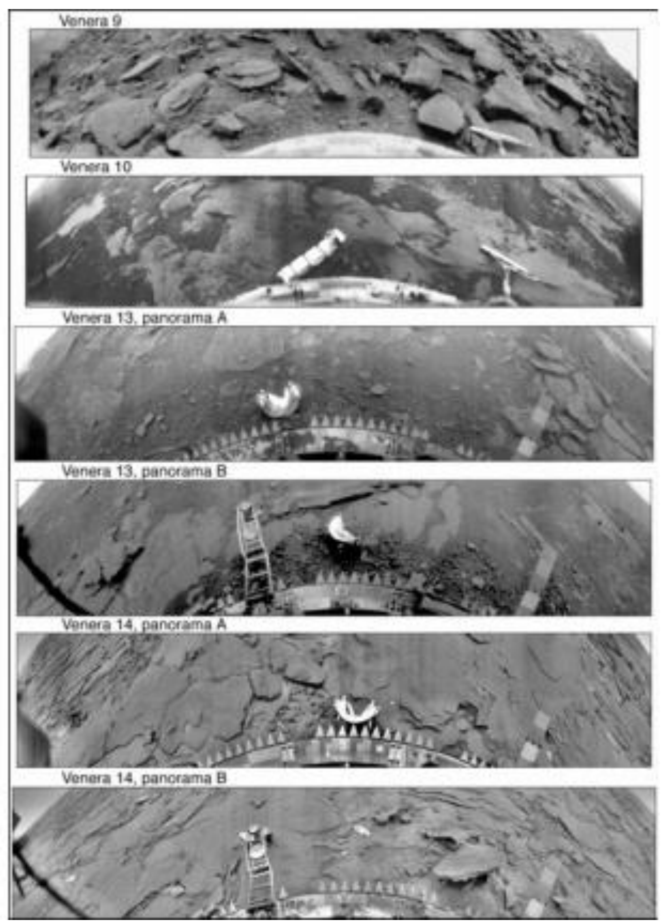

Figure 2.12. Images of various locations on the Venus surface (Ref. 42).

directional clues, xenoliths, meteorites, organized fractures, faults, layering, caves, and collapse pits, in addition to a multitude of fine-scale features like ripples, microdunes, and scour marks. The grain size distribution of rock fragments and fine-grained materials can be determined with a microscope with submillimeter capabilities.

Comparisons of these types of data at multiple landing sites can inform about the diversity and the variability of surface morphology and geology including the tesserae and associated high-reflectivity materials. For example, the Venera cameras revealed that although all four of these spacecrafts landed in areas regarded as "plains," each locale was distinctly unique. The images represent a kind of continuum, from a subrounded boulder field with angular rubble and a large amount of unconsolidated material (Venera 9), to a nearly continuous sheet of smooth rock with little to no visible regolith (Venera 14) (Ref. 43).

Extended-duration operations also have notable advantages. The Venera missions were short-lived and thus do not have time-elapsed images. Nonetheless, the particles that were transported onto the lander structures is visible evidence for the active transport of sediment as seen in the images that were obtained (e.g., Venera 13 and 14) (Ref. 44). Low-lying areas, especially in the Venera 9 and 10 images, are filled with what appear to be unconsolidated grains while smooth flat surfaces are free of an obvious dust layer. Organized textures of ripples and layering in the rocks further suggest that an aeolian deposition process was important in recent past, or possibly an ongoing phenomenon (Ref. 45). Analytic models of sediment transport at the surface of Venus, due to the dense atmosphere and ~1-m/s wind, conclude that rolling and saltation of relatively large grains is entirely plausible, along with lifting and suspension of very fine dust (Ref. 46). This means that long-term observations of the landing environment, with repeated images of the same targets, in concert with wind measurements, would be valuable contributions toward understanding one of Venus's major geologic processes.

2.3.3.2 Compositional Measurements

Chemical composition of samples at the various locations of the Venera and Vega missions are consistent with basaltic composition (Refs. 44 and 47) with the exception of Venera 8 data. Both x-ray fluorescence (XRF) and gamma-ray spectrometry were used to constrain concentration of major rock-forming and radioactive elements (K, U, and Th), respectively (Refs. 42 and 48). However, instrumental errors were insufficient to assess this (Refs. 44 and 47). Improved measurements of the concentrations of major petrogenic elements (Si, O, Mg, Fe, Al, Na, K, Ti, S, Cl, P, etc.) and trace elements (Ni, Co, Sr, Rb, U, Th, etc.) would further constrain origins and origin of surface materials.

Soviet landers did not constrain mineralogy. In future missions, identification and quantification of crystalline and amorphous phases could be done with x-ray diffraction (XRD), Raman spectrometry, and reflection spectrometry in the visible and near-IR (VNIR) ranges (<1.1 μm). XRD, VNIR, GRNS, and Mössbauer spectroscopy would enable understanding of this and could be accomplished with sample retrieval and processing inside of a lander (e.g., (XRF, XRD) and Mössbauer), or by interrogating samples exterior to the lander (Raman, LIBS, VNIR, and GRNS) (see Figure 2.13 for example).

Compositional measurements can constrain the secondary mineralogy of gas-solid type weathering. A drill sample at multiple depths can allow comparison of the mineralogy of the surface rocks and regolith to that of rocks deeper in the core. As has been done on Mars (Ref. 49), a Raman/LIBS system offers the capability to repeatedly ablate a rock surface with the laser to expose deeper surface layers inside a rock and evaluate the change in composition with depth. Surface composition information will offer insights into the potential of gas-solid type buffering of atmospheric gases, and the gas reactants and products of gas-solid type weathering reactions. See Section 2.4 on surface-atmosphere interfaces for additional details. These may reflect current atmospheric chemistry or record evidence of past climates.

Identical measurements by multiple landers or the use of mobile systems will allow geology across the planet to be compared,

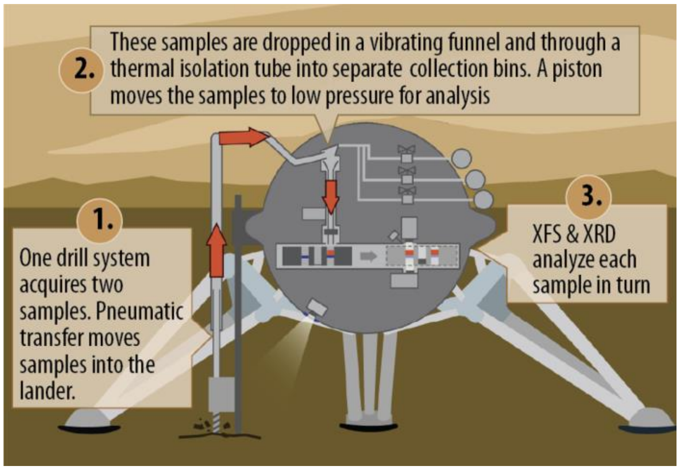

Figure 2.13. Venus Flagship mission concept (Ref. 7).

enabling a better understanding of the origins of the plains and tesserae. It is understood that there were notable changes in the Venus geology in its past. While compositional measurements at a single location can provide some clues as to these cataclysmic events, comparative data across the planet will allow for a much deeper understanding. Time-varying measurements, particularly of in situ exposed pristine samples or from samples brought into the lander, may provide additional data about reaction rates and potential rind characteristics.

2.3.3.3 Physical and Electrical Measurements

The mechanical properties and strength of the materials at the Venus surface are additional components for understanding Venus surface materials. Properties such as compressive strength, porosity, density, tensile strength, and deformation provide clues on the processes that formed and altered the rocks, rock fragments, and fine-grained materials. Performing these measurements with a penetrometer or densitometer, or even a drill mounted on an arm, can interrogate the structural properties of local rock or regolith, as was done on Venera 13, for example (Figure 2.14) (Ref. 42). Measurement of the electrical conductivity (as done at Venera 13 and 14 and Vega 2 sites) of surface materials could further constrain phase composition. Comparative measurements of physical and electrical parameters at multiple locations on Venus would improve understanding of planet scale processes that alter Venus rocks.

2.4 Surface-Atmosphere Interfaces

2.4.1 Science Questions

Investigation of atmospheric dynamics and composition at the surface addresses questions of how solar energy drives atmospheric circulation, cloud formation, and chemical cycles that define the current climate on the terrestrial planets. This interface affects surface composition via chemical weathering reactions that change the composition of the rocks and the atmosphere through both trapping and releasing gases at the atmosphere-surface interface.

These measurements are significant, in part since there is strong reason to believe that the surface and near-surface atmospheric conditions are dynamic and could be a significant key to processes, reactions, and chemical cycles controlling the chemistry of the lower, middle, and upper atmosphere of Venus (Ref. 50), (Figure 2.15). The study of the surface-atmosphere interface ranges from the planet-wide to regional or local scale that impact specific mineralogies and surface rocks.

Figure 2.14. Venera 13 image of penetrometer (Ref. 42).

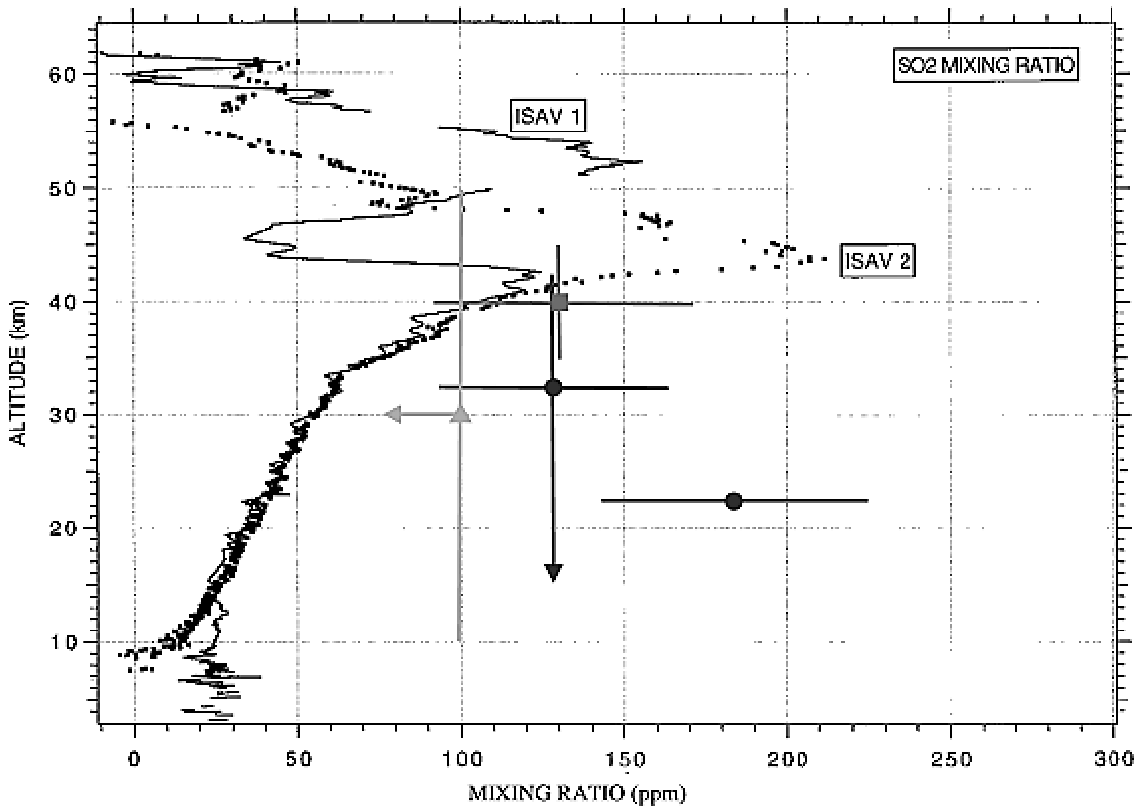

Figure 2.15. SO_2 mixing ratio from Vega, Pioneer Venus, and Venera measurements (Ref. 50).

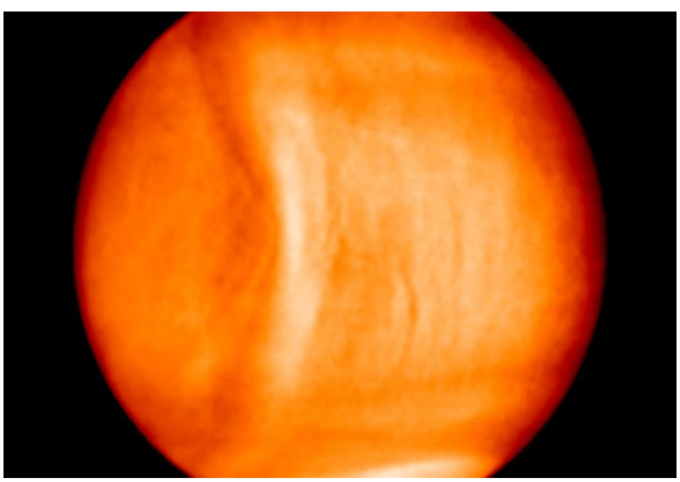

Figure 2.16. Venus gravity wave observed by Akatsuki (Ref. 51).

At the macroscale, for example, observations of planetary scale gravity waves (Figure 2.16) from Akatsuki (Ref. 51) bring into question the stability of the Venus atmosphere, its impact on our understanding of the exchange of momentum between the surface and the atmosphere, and the way in which the atmosphere evolves diurnally over long time scales (defining the climate) (Refs. 52 to 54). Thus, to begin to understand the energy and momentum vectors that allow this motion, the temperature and species profiles need to be mapped from the surface into the upper atmosphere. In particular, mapping of the atmospheric conditions at the surface level requires an in situ element that can trace changes in the atmospheric behavior and the energy budget as a function of local time for extended periods. This includes pressure and temperature measurements to inform about near surface heat fluxes due to local circulations such as slope or katabatic winds. Near surface wind speed and direction for extended duration provides the first indication of the sense of possible momentum exchange between the atmosphere and the surface at locations on Venus. For a global measure, such measurements need to be made at several latitudes for an estimate of the net exchange. Radiance measurements will provide insight into where and how energy is deposited into the Venus system and how that may drive processes such as superrotation.

Related to atmospheric characterization of chemical species, the Decadal Survey in planetary science identifies as a high priority a mission to "understand the physics and chemistry of Venus's atmosphere, especially the abundance of its trace gases" (Ref. 3, p. 127). Currently, scientists do not know "the …compositions of species in Venus's atmosphere, especially…nitrogen-, hydrogen-, carbon- and sulfur-bearing species" (Ref. 3, p. 118). NO may indicate lightning (Ref. 55 and 56) but further study is needed to confirm these hypotheses. A mission, like Venus In Situ Explorer (VISE), that "focuses on the detailed characterization of the surface, deep atmosphere and their interaction" (Ref. 3, p. 129) is targeted by the Decadal Survey. Answering gaps in atmospheric science requires "in situ measurements, such as can be performed during atmospheric transit by Landers like VISE, using balloons, and/or dropsondes/probes" (Ref. 3, p. 133). Further, VEXAG Exploration Investigations III.B.3-4 includes determination of "the abundances and altitude profiles of reactive atmospheric species (OCS,...SO2,…HCl, HF)…H2O" and as well as CO (Ref. 4, p. 5). Such data provide information about atmospheric chemical processes and surface-atmosphere interactions.

Major science questions include:

- What are the concentrations of atmospheric constituents, metrological conditions, and solar radiance in the subcloud and near surface atmosphere?
- What are the temporal and spatial (altitudinal, latitudinal, and local) variations in concentrations of atmospheric constituents, metrological conditions, and solar radiance?
- What chemical weathering processes are currently active on the surface as evidenced by the near-surface gases and rock composition?

These questions involve gas, winds, chemical reactions, and momentum exchange. A better understanding of the surface-atmosphere interactions of Venus will undoubtedly help answer some of these important questions and are also relevant to the surface questions in Section 2.3.1.

2.4.2 Notional Mission Approach(es) to Addressing Science Questions About the Surface-Atmosphere Interface

A surface platform is critical for surface-atmosphere interaction studies since in situ measurements are necessary and the interactions are time dependent. Remote sensing techniques have limited efficacy at the Venus surface due to thick cloud layers and the dense CO_2 rich atmosphere. Measurements from previous descent and landed platforms provided important scientific insight on composition and basic physical characteristics but these only provided a brief snapshot of the atmospheric conditions and interactions. For weathering and other reaction-related measurements, time is essential and ideally taken at more than one location.

New measurements by a complex lander with a limited duration of operation (e.g., the recently studied Venus Flagship Mission (Ref. 40) or the recent Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission selected under the NASA Discovery program (Ref. 57)) making a range of meteorological and composition measurements to understand local conditions would continue to make new important contributions to Venus surface-atmosphere interaction science. However, significant gains in scientific insight can be made by missions with extended duration missions (Ref. 22). Further, data from multiple locations around the planet could provide system-level knowledge and minimize the potential of local features confounding broader processes.

2.4.3 Measurements

The following surface-atmosphere measurements are needed to address the science questions.

2.4.3.1 Meteorological Data

Meteorology measurements are desired both during descent and on the surface (Figure 2.17). Required measurements include temperature, pressure, wind speed and direction, and solar radiance. Measurements during decent can provide a vertical profile of atmospheric conditions from the upper atmosphere to the surface. A lander mission on the surface taking meteorological measurements is, in effect, a weather station monitoring surface atmospheric conditions to then influence climate and weather models and understand solar energy deposition. This atmospheric data is also needed to understand the equilibrium between surface and atmosphere, constrain surface-atmosphere interactions and determine surface dynamics and variability. Further, surface atmospheric data, such as wind velocity and direction, provide information on momentum exchange between the surface and atmosphere and a better understanding of their interaction. While multiple landers provide more science, data from a single lander operational for a limited duration would still improve upon the very limited data available from previous Venus missions and orbiter observations.

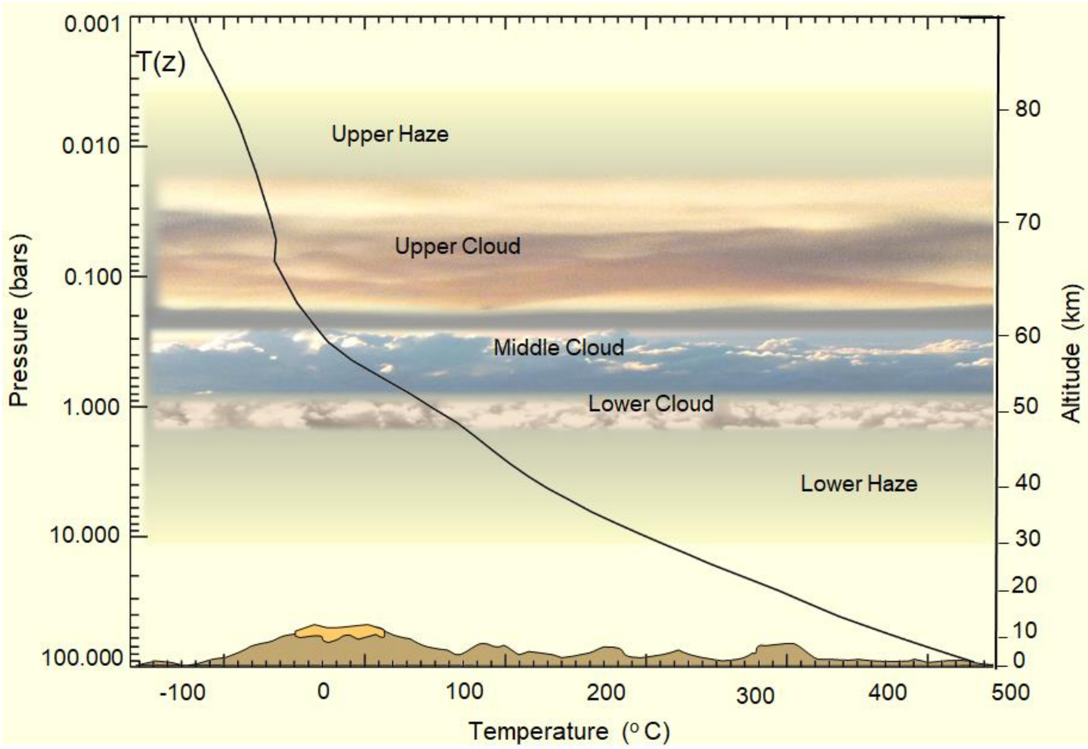

Figure 2.17. Venus temperature and pressure profile versus altitude (Ref. 37).

Extended duration operations in particular would address important science questions as to whether Venus surface atmospherics is unchanging or relatively dynamic over time. Understanding of surface-atmospheric dynamics would answer the basic question about Venus having a stagnant and unchanging surface due perhaps to the supercritical nature of the atmosphere to the surface. Changes in meteorological conditions might be correlated with other events observed on the surface, for example, transition from day to night, the possible presence of volcanic activity, or even variations from year to year. Such results can only be obtained through surface monitoring with extended operation.

A complete understanding of the climate cannot be based on measurements at a single location. The effect of different altitudes, latitudes, or even geologic features can impact meteorological measurements. Therefore, measurements in locations around the planet and with different surface features would be a specific interest. For example, differences between meteorological conditions in the plains versus tesserae would be indicative of how the surface-atmosphere interfaces are affected by the terrain. Such comparison of meteorological data at different locations would ideally be done simultaneously to allow a better framework for understanding that data.

2.4.3.2 Chemical Species Measurements

In conjunction with the meteorological data, a wide ranged characterization of the chemical composition of the lower atmosphere both during descent and on the surface is needed. This includes concentration of major gases (CO_2, N_2) and trace chemically active gases (SO_2, COS, H_2O, CO, H_2S, etc.), concentrations and isotopic composition of noble gases (He, Ne, Ar, Xe, and Kr), as well as the deuterium to hydrogen (D/H) ratio in H_2O gases and water history (Figure 2.18) (Ref. 58). Further, the atmosphere on and near the surface of Venus is predominately supercritical CO_2; this has not been fully explored and may produce anomalies not seen in other planetary environments, for example, localized stratification of the chemical species (Ref. 59).

As with meteorology, extended duration chemical species measurements simultaneously at multiple locations would provide more complete understanding of surface-atmosphere dynamics. Further, depending on the lander location, changes in the concentration of trace gases such as H_2O, SO_2, Sn, H_2S, CO, HF, HCl, can provide indications on whether Venus is volcanically active, and the localized increase of NO may be indicative of lightning. In addition, adding mobility to chemical species measurements may allow the possibility of "sniffing" a region to monitor variations in chemical species; such an approach has been used on Mars to attempt to discern the source of a given chemical species (Ref. 60). On Venus, it can be used to verify variances in the chemical species concentration across the distance traveled by the mobile system and locate sources of atmospheric gases, whether they be from volcanic vents or particularly robust areas of chemical activity.

In addition to the evaluation of the chemistry and mineralogy of surface rocks (Section 2.3.3.2), long lived landers can directly monitor weathering reactions using sensors composed of known materials. Changes in the composition of these materials, particularly with simultaneous measurement of the atmosphere, can help constrain the style and rate of weathering reactions over the months'-long duration of the mission.

2.4.3.3 Radiance Measurements

Measurement of radiance over a broad range of wavelengths is needed to improve the understanding of the heat balance between the surface and atmosphere. This includes measurements both upward and downward from the ground to track incident and reflected radiant flux, respectively. The net result reflects the rate of solar driven energy deposited at various altitudes and also provides input on the current rate of heat flux at the Venus surface (refer to (Figure 2.19) (Ref. 61). These measurements would take place both during descent and on the ground. A single measurement would be valuable, and periodic measurements over an extended time would determine if the energy loss is variable and dependent on other factors such as meteorological effects. Measurements across the planetary surface would provide information on whether energy loss across the surface of Venus is uniform, or if there are differences between the plains, tesserae, and crustal features. Further, measurement of multiple specific wavelengths, for example, in the IR spectrum, may be of interest in understanding the energy distribution of incident and reflected radiant flux further characterizing the surface-atmosphere interactions and provide insight into composition and possibly reactions.

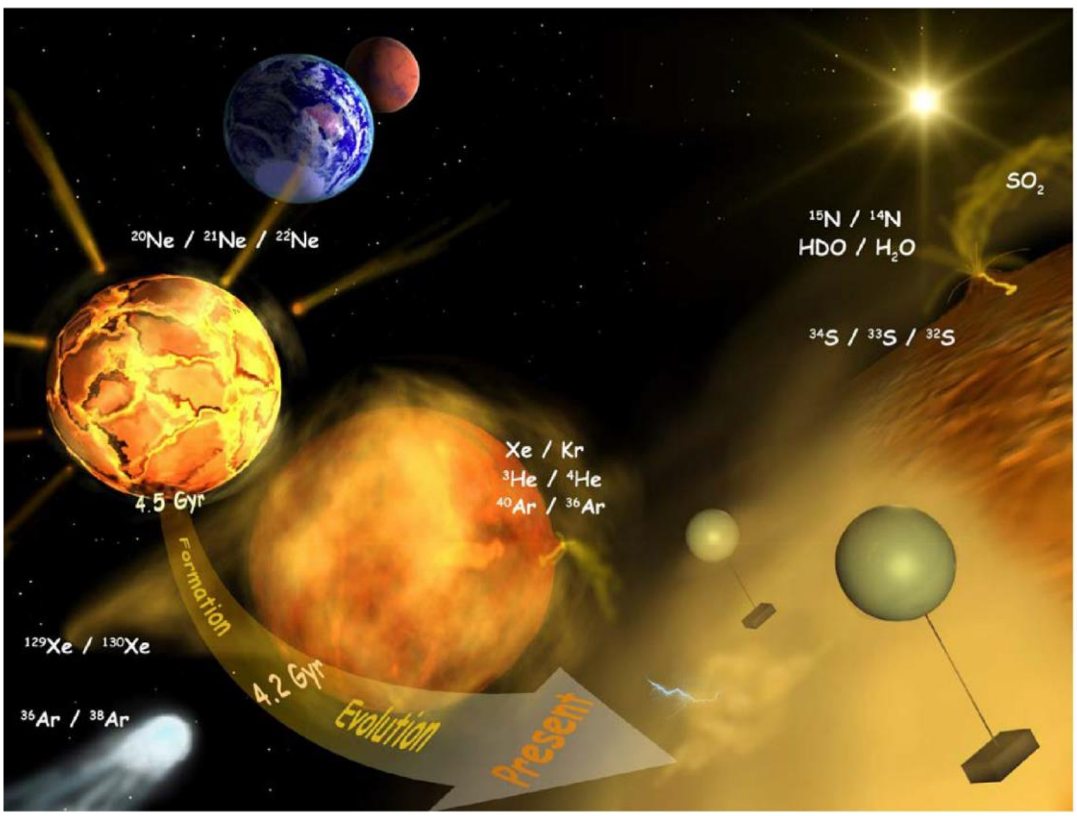

Figure 2.18. Importance of isotopic ratios to origins (Ref. 58).

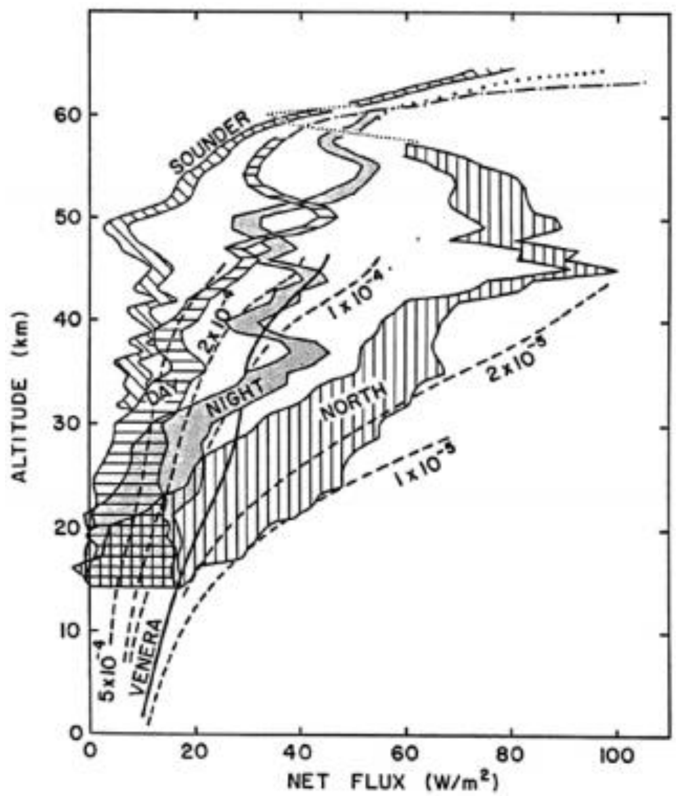

Figure 2.19. Derived net thermal fluxes in the Venus atmosphere (Ref. 61).

3.0 Science and Driving Capabilities

In discussions during the face-to-face meetings, a set of driving capabilities were identified based on the various science questions and mission approaches. In this process, four capabilities rose to a relatively greater level of impact across the three science areas. The four most notable surface platform capabilities and their definition for purposes of this study are:

- Time: defined here as the duration of the nominal surface operations. This ranges from the relatively short durations (minutes to hours) of previous Venus missions to operation for months or years.
- Mobility: defined here as the ability to interact with the environment across locations. This can range from something as simple as taking two different samples by stationary lander with a mobile arm to traversing the surface for 100s of meters with a roving platform to access a targeted location, to traversing long distances, 100s or even 1,000s of km, with more capable rovers or possibly using some form of aerial capability to reach the next landed site.
- Smarts: defined here as a relatively high degree of sophistication and/or autonomous operations for Venus surface platforms. This is a subjective construct that includes the ability to assess and monitor the relevant local environment and use that to make informed decisions, adapt to changing situations, provide onboard analysis and processing, and/or the capability to carry out complex operations.
- MSM: this is defined here as multiple copies of a lander platform implemented at various locations across the planet making simultaneous similar measurements.

Table 3.1 captures the relationship between science questions and the set of the four key capabilities identified, namely, time, smarts, mobility, and MSM. An “H” in a field signifies that the capability is highly impactful in understanding that aspect of the science. An “S” in a field signifies it is somewhat impactful. It should be noted that different science investigations are dependent on different types of capabilities. In general, the capability for time and MSM have a notable impact across the range of investigations across all three of the science areas of interior, surface geology, and surface-atmosphere interactions. However, for some specific investigations, such as surface composition science questions, smarts and mobility may have a greater impact. Appendix B includes notes and data from discussions of the organizing committee and science and technology subgroups. These conversations led to mapping science impacts to an expanding set of surface platform capabilities.

Table 3.1. Relationships Between Science Questions and Set of
Key Capabilities Identified, Namely, Time, Smarts, Mobility and MSM (Multiple Simultaneous Measurements)

Science field	Capability			
Interior	**Time**	**Smarts**	**Mobility**	**MSM**
Structure	H			H
Composition	H	S	S	H
Dynamics	H			H
Heat flux	S			S
Surface				
Composition		S	S	S
Dynamics (eruptions, flows, …)	H	S	H	
Diversity (spatial)	H	S	H	S
Morphology	H	H	S	H
Stratigraphy	H	H	H	H
Surface-atmosphere interactions				
Gas Composition	H	H		H
Winds/physical processes	H			H
Reactions/chemical processes	H	H		H
Momentum exchange	H		S	H

3.1 Rationale for Table 3.1 Mapping

3.1.1 Interior

Major investigations related to better understanding the Venus interior include investigation of seismic activity, interior structure, bulk composition, dynamics, and interior heat escape. In particular:

- Structure, dynamics, and composition: the seismicity and dynamics of the interior are measured with seismometers and will generally also rely on naturally occurring events of yet unknown frequency. Because of this, these science objectives will require long-duration operations on the order of several months. Time is an essential capability for much of the science questions related to the interior. In addition, multiple sites are needed to correlate seismic activity to a location, gain insight into structural boundaries, and to determine bulk composition, making MSM a highly impactful capability. Seismic measurements can be done with relatively simple instruments and onboard data capture assuming that the data will be transmitted to an orbiter or ground-based assets that have the additional processing capability to interpret the data. The measurements supporting interior structure dynamics would need to be taken with a stationary and stable platform, thus, mobility is not a required or beneficial capability for this set of science objectives. However, more sophisticated instrumentation and onboard processing could enhance interior composition science; therefore, smarts is assessed to be somewhat impactful for interior composition questions.
- Heat flux: local measurements of interior heat escape can be made in a relatively short time (minutes to hours), essentially once the local conditions are isothermal, so technically a heat flux measurement is feasible for a short-duration (hours) mission. However, in addition to waiting for the instrument system and environment to become isothermal, enough time must be allowed to either drill and acquire the actual measurements or use proposed contact type heat flux instruments and determine the thermal variability due to other sources such as the diurnal cycle, for example, day to night transitions. Heat flux will depend on local crustal conditions, and comparison between multiple locations will strengthen the measurements.

3.1.2 Surface

Major investigations related to better understanding of the Venus surface include investigation of the history of water on Venus including characterization of tesserae and plains, and the mineralogy, meteorology, and the physical and chemical state of primary and secondary surfaces. There is also a set of science objectives that are considered more "complex" for remote robotic techniques such as interrogating the geologic record and determining age.

- Composition: Phase mineralogy and elemental composition measurements will need to examine both primary and secondary materials and, to understand spatial diversity, will need to be taken at multiple locations. Various remote and contact type instruments can be utilized to determine composition. These measurements can be made with short-duration missions. Longer life, more sophisticated instruments, sample processing, ability to select desired samples, and increasing the number of samples and source locations will all enhance science. Therefore, the capabilities of smarts, mobility, and MSM are determined to be somewhat impactful to surface composition science objectives.
- Dynamic phenomena (eruptions, flows, …): Many geologic phenomena such as volcanic (e.g., Figure 3.1) (Ref. 62) and seismic events require time variant measurements using various techniques and instruments when the location and/or timing of those measurements is not readily predicable in short time scales. While individual measurements can generally be made quickly, sustained operations are required to wait for events and potentially move to relevant site(s), thus, both time and mobility are determined to be highly impactful for this set of science objectives. The smarts capability is considered somewhat impactful because more sophisticated situational awareness, instruments, and techniques are expected to enhance the amount and quality of data.

  Diversity (spatial): Some characterization of geological spatial diversity could possibly be made at a single local site if it happens to be just the right spot. Science can be advanced with smarts that enable determining the diverse features desired in that location and then interrogating the different areas with instruments or tools on a mobile arm or by targeting with remote sensors. Characterization of spatial diversity can also be somewhat addressed by placing multiple

Figure 3.1. Heiturpottur Volcanic Vent in Iceland, 2014 (Ref. 62).

  platforms (performing MSM) into areas that are known or suspected of having the desired geologic diversity. Both these capabilities, smarts and MSM, have been chosen to be somewhat impactful for this area of science.
- Morphology: Images at the surface and during descent are uniquely capable to assess submeter scale morphology that cannot be measured from orbit due to the Venus atmosphere. Images from a short-term lander at any site are critical to advancing our understanding of surface morphology. Images at multiple sites, especially those less interpretable from orbital radar (e.g., tesserae) would be even more impactful. Smarts will enable the acquisition, storage, and triage of images that can maximize data collection from short-term observations during descent or on the surface.
- Stratigraphy: The examination of geologic contacts at the lander scale would advance our understanding of the details of major geologic events. As has been done at Mars, mobility, smarts, and time would allow us to land in one geologic unit and approach and explore the boundary with another geologic unit. MSM can enhance the capability to sample a variety of key contacts

The most impactful capabilities for this science area are time and mobility. Time is needed to enable access to the interrogation and processing of the various locations and targets. Mobility is needed to take the platform into the required locations. From images (Ref. 16) and coarse remote sensing data (Ref. 15), Venus is expected to be geologically similar across large areas of the planet. Depending on where one lands, relatively long distances may need to be traversed to get to the next geologically diverse area. This suggests that short-distance rovers may not be the most productive tool to characterize the geologic diversity of Venus. Perhaps an aerial vehicle like a vertically controlled balloon that can drop onto a location, perform its science objectives, and then ascend to touch down at some other distance location may be a better form of mobility, at least as far as spatial characterization of geologic properties goes. The ability to target sites and perform the most impactful measurements at those sites puts Smarts in the somewhat impactful category. The ability to acquire measurements at diverse locations around the planet helps achieve a larger scale of diversity and therefore makes MSM somewhat impactful for this set of investigations as well.

3.1.3 Surface-Atmosphere Interactions

Investigation of atmospheric dynamics and composition at the surface addresses questions of how solar energy drives atmospheric circulation, cloud formation, and chemical reactions that define the current climate on Venus. This area also captures the pathways and rates of physical and chemical weathering processes.

- Gas and surface composition and gas-gas and gas-solid type reactions: near surface gas composition can be determined today with short-duration platforms and SOA instruments. We do not yet understand how much gas composition changes over time or as a function of altitude, latitude, or local environment. Because near-surface gas composition may vary, the ability to make time variant gas measurements is important. These measurements can inform models for gas-gas and gas-solid interactions and constrain deep atmospheric circulations. Multiple coupled measurements of gas and surface compositions over various locations are desired.

  While gas compositions can be measured with SOA instruments, the ability to detect and react to a possible event that may result in changes to the local atmospheric composition requires a higher level of capability and the monitoring of the local environment over time. These capabilities will allow more rapid informed decisions than what is available today. Smarts and time are considered impactful capabilities for these science areas.

  In summary, time, MSM, and smarts are the capabilities expected to have the highest potential impact on science related to gas composition, most notably the variations over time (dynamics) and location.

- Winds and physical processes: winds and other physical processes (e.g., saltation) can have significant impact on surface features, especially over time. The formation of dunes, and aeolian erosion exemplify physical processes at the atmosphere-surface interface. Monitoring of wind speed and direction (Figure 3.2), together with surface changes can provide insight into current, past, and potential future modification and transport of surface materials. Time and MSM are two capabilities expected to be highly impactful for this area of science. Unlike composition- and reaction-related questions, major episodic events are not expected to drive measurements requirements for the winds and physical weathering processes so a higher level of smarts than normal is desired but not expected to be a major contributor here (Ref. 63).
- Momentum exchange: the Venus atmosphere is uniquely dense among the terrestrial planets in our solar system. Data from Venus Express, Magellan, and ground-based observations have confirmed the variability of the Venus spin rate, on the order of several minutes per Venus day over the period the observations were collected. It is widely accepted that there is an exchange of momentum occurring between the dense Venus atmosphere and the planet body and that is contributing to the changes in spin rate. A better understanding of this exchange will help constrain the planet's moment of inertia, which in turn will provide insight into the yet illusive interior structure. Data on the variability of the deep Venus winds and directions are key data to get at the question of momentum exchange. Therefore, the capability of time is required to make the needed measurements. Measurements at multiple locations are required to capture the breadth of the needed data and to account for local effects. Mobility is expected to be somewhat impactful as it may again help accurately account for local effects on the exchange of moment.

3.2 Capability Synergies

It is expected that coupling of capabilities will yield synergistic results. For example, combining the capabilities of time and smarts will allow not only long-term measurements but do so in a way that is most effective and efficient. One can imagine a long-lived platform (time) with smarts so that it can intelligently select samples to acquire or target. Combining the capabilities on the platform will yield better interrogation of the geologic record and perhaps better science from the local morphology. An attempt was made to summarize three dimensions of the capabilities and reflect their synergistic nature in Figure 3.3. This graphic assumes mobility and MSM are along the same dimension to make it more readable. It also notes that MSM is a capability to be at simultaneous locations rather than an inherent feature of a platform like the other three constructs.

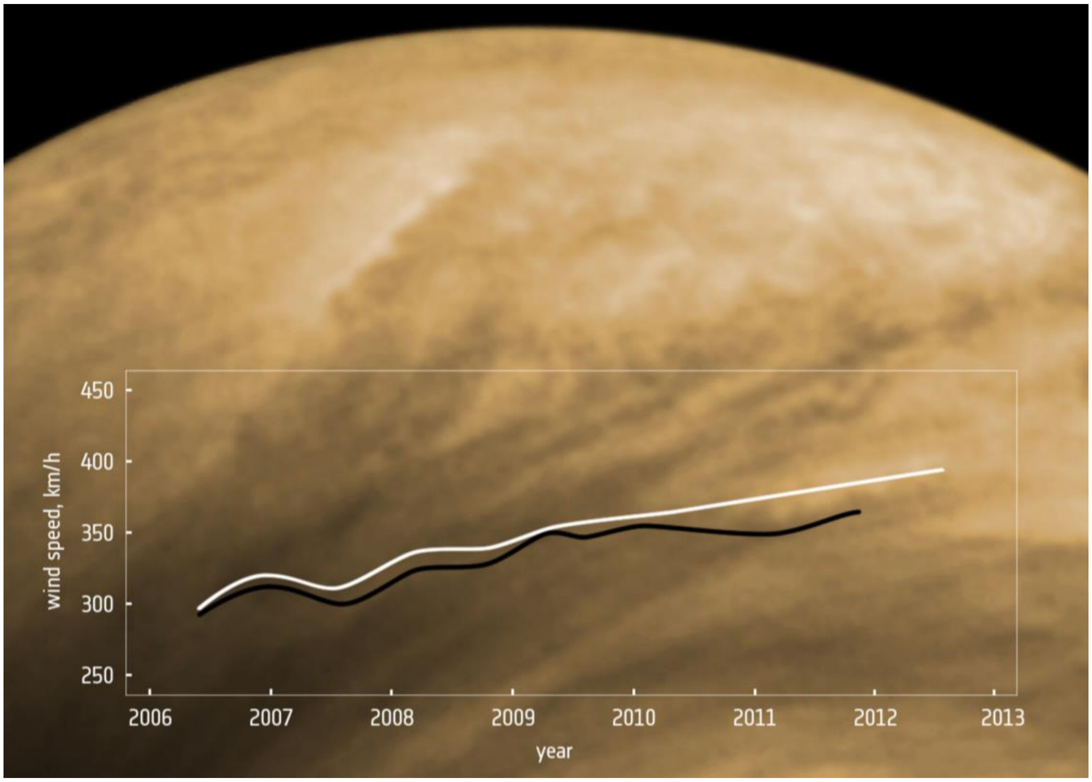

Figure 3.2. Increasing wind speeds at Venus (Ref. 63).

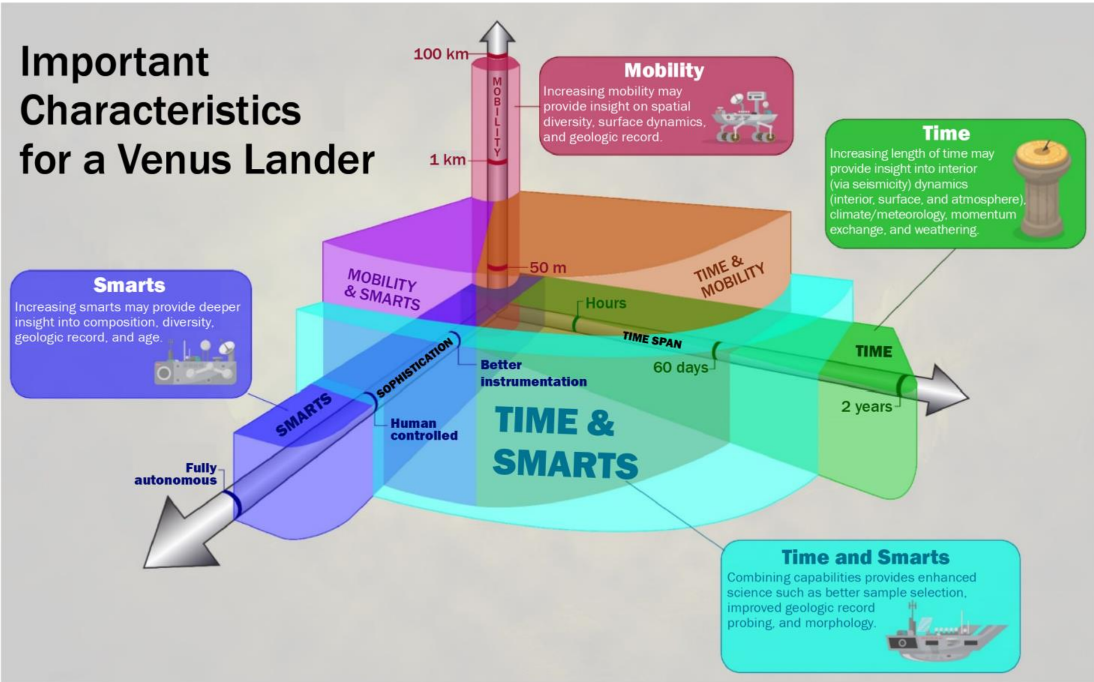

Figure 3.3. Driving synergistic capabilities of Venus surface platforms.

4.0 Underlying Technology to Enable Capabilities

To realize the driving capabilities of time, smarts, mobility and MSM, continued advances in enabling and underlying technologies are required. Table 4.1 describes some of the technologies to enable these capabilities. Table 4.2 summarizes some of the links between the capabilities and technologies that enable them, such as power, cooling, etc.

Through science subgroup discussions, the capabilities noted in Section 3.0 were identified. With further exploration, particularly by the capabilities/technology subgroup, technologies required to enable the capabilities and obtain the needed measurements were determined. A summary of the key technologies underpinning the capabilities is provided in Table 4.1.

It should be noted that the advancements in technologies can be codependent. As an example, one technology may reduce the need or urgency for another, such as increased high-temperature electronics will reduce the need for cooling technologies. On the other hand, technologies like cooling and power will need to be developed together, that is, a cooling system that would work for vessels on the Venus surface is of no value if there is not a power system that can support the energy demand. Table 4.2 maps the technologies from Table 4.1 to the capabilities the specific technology is expected to enhance or enable. As noted earlier, MSM is the capability of being in multiple locations at the same time rather than an inherent capability of a platform, therefore, the mapping of technologies to MSM is not applicable or provided in Table 4.2.

Table 4.1. Technologies That Enable Capabilities Such as Time, Smarts, and Mobility

Technology	Description
Power (low)	Power systems appropriate for operating instruments and communication (low is soft term—notionally up to 25 W or so).
Power (high)	Power systems appropriate for providing cooling for a thermally managed enclosure or mobility for a platform (>25 W).
Cooling	Cooling technology to environmentally manage an enclosed environment such that components and technologies can be used that cannot otherwise tolerate high temperatures. Note, cooling technology will also require an appropriately sized power system, in other words, needs development of power (high) at the same time.
High-temperature electronics/memory/power processing	Electronic systems that can operate in situ in the Venus environment for extended periods of time without needing cooling, pressure vessels, or other overheads.
Mechanisms (drills, mobility, …)	Actuation capabilities to enable mechanical operations on the Venus surface.
Autonomous operations and navigation	Integrated intelligence into the lander system to allow independent operations and decision-making.
SOA instruments	SOA instruments designed for Venus applications that can provide the necessary data for scientific investigations.

Table 4.2. Relationship Between Technologies and Capabilities Enabled

Critical underlying and supporting technology	Capability		
	Time	Smarts	Mobility
Power (low—25 watts or less)	H	H	
Power (high—25 to 100s of watts)			H
Cooling (will also need power (high))	S	H	S
High-temperature electronics/memory/power processing	H	H	H
Mechanisms (drills, wheels, …)	S		H
Autonomous operations and navigation		H	H
SOA instruments		H	

4.1 Rationale for Table 4.2 Mapping

In Section 3.1, we discussed rationale for the mapping of capabilities to science impacts. Here, we discuss rationale for mapping of underlying and enabling technologies to the capabilities of time, smarts, and mobility. As noted previously, the capability of MSM is not a technology of a platform per se, therefore, mapping to the MSM capability is not applicable in this approach.

- Power (low): one of the principle challenges facing Venus surface exploration is platform power. The harsh environment, isothermal conditions, and limited solar energy eliminate or at least make the application of much of our SOA lander power options very difficult. In addition to noting the challenges, one must also note that platform capabilities themselves will drive the power demands. For example, a stationary meteorology suite can operate for long time periods with a power source as simple as a high-temperature battery, as is planned by the ongoing Long-Lived In-Situ Solar System Explorer (LLISSE) project (Ref. 64). From LLISSE, we find that a power source that can deliver 7 to 10 W for short time periods to support the transmission of the data to an orbiter could support missions lasting months. Whether it is battery powered or powered by some other source, power is a critical technology and impactful to the life of any surface platform, especially on Venus. Platform smarts will require power. Even if the smarts are enabled by more complex electronics, memory, and sensors, some amount of power is required and on Venus this is expected to be presently limited. Therefore, both time and smarts are enabled or significantly enhanced by a Venus surface power system producing up to 25 W.

  Power (high): an example of a capability that will likely require a higher level of delivered power source is mobility. Mobility includes the power needed to move a rover around the surface or manipulate an arm and drill through a rocky surface. The physical movement of mass requires a more capable power system than moving electrons between chips or reading a sensor value. The capability of high power is expected to significantly impact the mobility capability.

  Having a power system on the surface of Venus capable of providing many 10s or even 100s of watts will not only enable mobility, but may offer other benefits as well such as direct-to-Earth (DTE) communications or to power a cooling system for sensitive instruments or detectors. While a large amount of power is significant for the mobility capability, there are other desired results even though it is not directly captured in Table 4.2.
- Cooling: one of the characteristics that makes the Venus surface so challenging for lander platforms is the high temperature. A cooling system could provide a more amenable environment for complex and sensitive components like electronics, detectors, instruments, and so on. Those components are the building blocks for smarts thus cooling is expected be highly impactful for the capability of smarts. Cooling may be able to extend surface operating time, but high-temperature electronics and systems more directly address the time capability. Given progress in that area, cooling is determined to be somewhat impactful to time. Likewise, for mobility, high-temperature mechanisms and ample power are expected to address most of the mobility capability needs but cooling of, for example, navigation sensors or imaging system detectors may enhance mobility thus cooling is expected to be somewhat impactful to the mobility capability.
- High-temperature electronics/memory/power processing: the ability to operate a landed platform on Venus without temperature control is pivotal for extended surface operations. High-temperature electronics, memory, and power processing, as well as sensors that operate in Venus conditions without cooling or active thermal control will significantly impact the capability of time. These same technologies will drive arms to acquire samples, maneuver instruments, and/or provide the means to control rovers or other mechanisms thus these technologies are highly impactful for mobility as well. Advancing the complexity and capability of these technologies will also significantly impact the smarts the lander platform has, especially when long-duration science is required. Therefore, the category of high-temperature electronics is deemed to be highly impactful for time, smarts, and mobility.
- Mechanisms: having more capable mechanisms for Venus surface applications is not expected to provide more smarts nor directly enable long operations of something other than a mobile platform. The one exception is if wind is used as a power source, as it requires high-temperature, long-duration mechanisms, which could provide a consistent low amount of power. Therefore, mechanisms are somewhat related to

time. High-temperature or corrosion-resistant mechanisms will highly impact the capability of mobility, enhancing platform range or mechanism lifetime but have only limited impact on the other capabilities.

- Autonomous operations and navigation: the ability to understand its environment and make informed decisions is not expected to significantly impact time for a lander platform. However, a major purpose of autonomous operations is to allow for greater mobility, and it is enabled or enhanced by onboard sensing and processing tools. Thus, autonomous operations and navigation is expected to significantly impact mobility and smarts but have limited impact on time.

SOA instruments: SOA instruments are not expected to enable or enhance a mission's life. An ultralow-power instrument may have some impact on demand of a battery on a surface platform while that instrument is operating but the total impact relative to ongoing surface platform operations and the power required to beam data to an orbit is very small. A low-power SOA instrument is not expected to make much of an impact on total energy need and has minimal impact to the capability of time.

Depending on the specific SOA instrument(s) in question, there could be significant impact on overall platform smarts. As an example, an imaging system that would capture images only when the field changes in some scientifically meaningful way could greatly impact science return and may enable better onboard decision making, which is one measure of smarts. In some respects, SOA instruments will not only contribute to smarts but also can benefit from it. For example, better high-temperature processing technology would serve the platform and could also enhance instruments as well if they chose to embed that technology into an instrument. SOA instruments are not expected to significantly impact mobility. Perhaps instruments with a lower volume or mass may improve mobility for a surface platform, but this is viewed as a secondary effect rather than directly enhancing the mobility capability. Therefore, SOA instruments are expected to be highly impactful for smarts but minimal for time and mobility.

5.0 Technology and Infrastructure Development Needs

The VEXAG Technology Plan (Ref. 2) provides a comprehensive overview of the status of Venus technology across platforms, identifies areas of technology development, and what might be accomplished if investments are made in various development efforts. From both that document and considerations within this Platform Study, areas for technology development were identified. Following is a summary of a series of specific technologies meeting the capability needs identified in Table 4.2. This list provides options for how capabilities, for example, power (low), might be achieved. This list of options is not exhaustive but illustrates examples of investments that would support a path to maturity technologies that have the highest potential to impact key surface platform capabilities.

5.1 Power (Low): Operation of Instruments and Communication: <25 W

Candidate systems that may provide power to a surface platform needing a few 10s of watts or less include:

- High-temperature batteries: complete technology maturation of current batteries and improve specific energy
- Efficient solar panels and improved high-density power sources: develop technology to enable long-duration operations in Venus surface conditions and then improve efficiency and life
- Wind power generation: which would require development of windmills, materials, turbines, converters, etc.; many of the technology needs for wind generated power are addressed in Section 5.5; more characterization of surface winds at Venus will be needed to assess overall power that may be generated with this technique
- Alternate methods of power generation: such as small high-temperature radioisotope power systems (RPSs); refer to Section 5.2 for discussion of technology investment needs for either dynamic or static RPSs

Investments in high-temperature batteries; solar arrays, generators, and rotating mechanisms; small RPSs; and other advanced power generation approaches as well as power management and distribution systems would move this technology area forward. It is anticipated and desired that these power systems will operate for months or longer on the Venus surface.

5.2 Power (High): Cooling or Mobility to an Enclosed Vessel: 25 to >100 W

- RPS-based, or new advanced systems with power levels of 25 W to several hundred watts will be required to meet desired capabilities. For cooling of vessel interiors to standard spacecraft temperatures, power systems in the 100s of watts may be required. The combustion of lithium with the Venus atmosphere has been studied as an approach that could generate power on the kW level. While this could greatly aid in operating cooling systems, the drawback is that such a system would operate for limited time (days) before expending its fuel (Ref. 65). It should be noted that some missions may place other demands on the power system like requiring that the power system be portable (ability to be carried around on a rover) or generate no dynamic noise for seismic investigations. This may further limit the power solution space or require investment in more than one power technology.

Investments in high-temperature RPSs or new novel power systems that can supply hundreds of watts for months or longer are required for cooling and or non-wind-driven mobility. For power systems that may support mobile platforms, volume and weight will be important characteristics along with resistance to reactive atmospheres. Investments in RPS power technology at Venus temperatures will require material and system-level work. Prior work has identified potential material solutions and system concepts, but actual hardware needs to be developed and tested. For dynamic systems, mechanisms, coatings, seals, and lubricants will need to be developed and, for all applications, high-temperature electronics for power management and distribution will also be required.

5.3 Cooling: Environmentally Manage an Enclosed Environment

- Active cooling systems, with significant power demand, can extend short-duration missions and would enable more sophisticated and complex instrumentation to be operational for long-duration missions and/or mobile platforms.

Investments in high-temperature and Venus chemistry resistant materials, working fluid(s), seals, coatings, and lubricants, as well as system designs and eventually hardware development and testing, will be required. As noted previously, a complementary power system will need to be developed along with the cooling system if it is intended to be used for something other than a short battery-powered mission.

5.4 High-Temperature Electronics/Memory: Venus Environment In Situ Operations for Extended Periods of Time

- High-temperature electronics are expected to significantly impact all the key capabilities noted in this report. Currently, high-temperature electronics are approximately at the level of 1980s electronics. These systems do not have internal memory at this time, thereby, limiting mission operational parameters.
- Increasing the complexity and capability of high-temperature electronics would be enabling and/or enhancing to future missions.
- Availability of low power memory with increased storage is needed for some mission scenarios and would be beneficial for all long-duration surface missions.

Investments to further develop high-temperature electronics (integrated circuits and passive components), memory, and processors will be required. Different device architectures may also help increase impact and robustness of the electronics in various applications. High-temperature electronics are expected to be one of the most impactful technologies for future Venus surface platform capabilities and recommended for continued investment.

5.5 Mechanisms (Drills, Wheels, Arms, Tools, …)

- Supporting mobility (transiting across the Venus surface), drilling and digging technology developments (investments) are required including high-temperature electric motors, wheels, bearings, gears, lubricants, and other components to support a mobile surface platform or robotic arms and mechanisms to dig or drill. These developments would focus on identifying the right materials to withstand the temperature, pressure, and reactive chemistry (Ref. 66) as well as meeting performance requirements (distance, traction, maneuverability, durability, and so on). It should be noted that a high-temperature drill is beneficial for both short- and long-term missions, as drill mechanisms are located outside of any passive thermal control systems. Honeybee Robotics has developed a drill that has operated at Venus temperatures in high-pressure CO_2 but has yet to operate in the full Venus chemical environment (Refs. 67 and 68). As noted earlier, the complementary developments would be required in suitable power, electronics, and autonomous navigation systems. It is not expected that an involved material identification and selection process is required for every component. Rather it is expected that a catalog be built over time of suitable materials with a range of properties suitable for various components and applications.

Investments in remote sensing and/or optical systems suitable for the environment, including precision placement or pointing of instruments or tools, would be required, along with the mechanisms technologies noted previously. If the application is something other than a short-duration temperature-controlled lander or one with active cooling, the sensing systems would need to be suitable for high-temperature Venus conditions.

5.6 Autonomous Operations and Navigation

- Mobility and science needs:
  - The ability to identify where landers are on the surface and what direction they are pointed will require investments in high-temperature sensors and electronic processing/memory. Orientation is an interesting challenge on the surface of Venus, but solutions have been identified to provide that information and will need to be verified.
  - Specific entry and landing systems to enable deployment to various Venus terrains at increasing location accuracy will be important for surface exploration. Venus/surface platform specific entry system designs utilizing "Heatshield for Extreme Entry Environment Technology" (HEEET) (Ref. 69), or other thermal protection systems like Adaptable Deployable Entry and Placement Technology (ADEPT) (Ref. 70), will be required. It should be noted that ADEPT is a critical technology for MSM, as it may greatly reduce cost for multiple small payload entries.
- Vehicle system operations and navigation development:
  - For most mobile platforms and related decisions, the technologies required include situational awareness (via the remote sensors and processing/memory capability), locomotion technologies (high-temperature motors, mechanisms, and the components to support motion, and capable power systems (>100 W). Depending on the science payload, there may also be a need for cooling. Clearly a number of significant technology investments will be required to enable mobile surface platforms with autonomous navigation and operations.
  - Both stationary and mobile platforms can benefit from autonomy developments including autonomous decision making for image targeting and sample handling for drill location, selection, and sample acquisition (Ref. 71).
  - While not addressed here, one approach to mobility is to use floating carriers, which have their own technology needs. Interested parties are referred to the Aerial Platforms for the Scientific Exploration of Venus study (Ref. 72).

Investments supporting real-time situational awareness (various sensors and electronics, memory, and processors for decision making), hazard avoidance, and target locating and interrogating techniques will be needed to realize autonomous navigation and operations. If the application is something for other than supporting a landing or a platform with active cooling, all the systems would need to be suitable for Venus surface conditions.

5.7 State-of-the-Art Instruments

There are a host of instruments that have applicability to Venus. However, there are challenges to using many of the SOA instruments on Venus, due to the harsh environment. There are two approaches to solve this challenge, 1) controlling the environment or 2) designing the instruments to work in Venus ambient conditions.

The first approach can be done with a pressure vessel and thermally controlling the vessel interior with a passive approach for short time periods or with powered active systems for longer duration missions. Passive approaches have already been executed at Venus successfully several times for time periods on the order of 1 to 2 hours and this general approach is deemed viable going forward. For long-duration missions (days or longer) a power system of 100s of watts and an active cooling system will be required. Therefore, investments in power and thermal management/cooling technologies are required to achieve long duration use of SOA new instruments on surface platforms at Venus.

The second approach is to develop instruments that function in the ambient Venus surface environment. To enable this, continued investments in materials and high-temperature electronics are required.

Following are examples of instruments that are candidates for Venus surface platforms organized by duration and the approach taken:

- Short-duration missions (1st Approach, Passive): A primary focus of short-duration missions is to perform elemental, mineralogical, and petrologic analysis on the surface of Venus to identify presence and abundance. With limited lifetimes on the surface, time is of the essence so the speed with which these measurements can be conducted is vital. Descent images should connect the orbital radar images with the landed images, capture morphologic features, and provide ground truth for the orbital radar images.

  Candidate instruments may include:

  - XRD/XRF
  - LIBS/Raman
  - Various versions of mass spectrometers

  This list is by no means exhaustive. The choice of instruments on any mission is driven by the science goals of the mission. Additional instrument candidates can be found in recent studies that include Venus landers such as the pre-decadal Venus Flagship Mission report (Ref. 6) and Venera–D JSDT study, (refer to Table 2.2 (Ref. 37). The time needed to capture the required measurement will vary by instrument and some measurements benefit greatly if the measurement can extend for hours versus seconds or minutes. It should also be noted that some measurements require acquisition and/or processing of a sample before a measurement can be made. In those cases, supporting capture and processing mechanisms must be developed and tested along with the instrument proper.
- Long-duration missions (2nd Approach): Potential instruments and sensors for long-duration missions could include: temperature, pressure, solar radiance, wind speed and direction, chemical sensors, seismometers, and more. Unless the platform has long-duration active power and cooling systems, the instruments and sensors need to be high-temperature compatible and robust against the reactive Venus surface environment. In general, there is an overall need to increase the complexity and capabilities of instrumentation operating in situ at Venus temperatures and pressures. This includes supporting technology (electronics, actuation, sample handling, etc.) for such instrumentation.

  Improved surface images are needed to help determine the local and regional geologic history, see individual grains and their variation with a microscopic camera, measure composition from spectral reflectance and emissivity, and evaluate the texture of surface materials to constrain the weathering environment. It may be noted that there have been preliminary efforts to develop cameras which could operate at Venus temperatures, without the need for cooling (Ref. 73).
- Extended duration and temperature-controlled platforms (1st Approach, Active): Extended rover missions where complex instruments are housed in temperature-controlled chambers, the core instrument needs are similar to that of the short-duration missions. However, the interfaces to these instruments, such as sample processing from the surface, will need to be long-term compatible to the Venus environment. Autonomy and/or human in the loop operations would also be a component of such missions. The technology investments described early would enable either or both approaches.

Finally, while not a technology per se, investments are also required in terrestrial laboratories and facilities to develop instruments and test them in relevant environments. These facilities could also serve to support laboratory experiments or to test Venus system models and theories in addition to being tools to mature technologies and demonstrate surface platform capabilities.

This section presented a short summary of surface platform technologies and investments that are required to achieve the key capabilities identified in this study. VEXAG produced and maintains a set of relevant documents among which is a Technology Plan (Ref. 2) and Roadmap (Ref. 1). These provide a more comprehensive review of technology needs not only for landers but other platforms as well.

6.0 The Potential of Future Venus Surface Platforms

During the 1970s and 1980s, the Soviet Union successfully landed several probes (Venera 8, 9, 10, 13, 14, as well as Vega 1 and 2) that operated on the surface of Venus for periods up to 2 hours and returned images as well as other scientific data. This was accomplished with thermally insulated vehicles that maintained imaging sensors, communications systems, computers, and energy storage systems at temperatures below 100 °C. The vehicles consisted of insulated pressure vessels, which also contained solid-liquid phase-change material to extend surface lifetime. These missions are the established paradigm for Venus surface exploration.

As found in this study, advances in multiple fields suggest there is growing potential to expand the science that future surface platforms can return. Improvements can be made in harsh environment capabilities through investing in the underlying technologies. The technologies will change how future surface platforms look and operate and they may be much different than expected just a few years ago. With technology investments in the areas noted, the key capabilities of time, smarts, and mobility can be realized and duplication of the MSM capability will also be achieved. These capabilities will pave the way for addressing the critical science questions regarding the interior, surface, and surface-atmosphere interactions.

7.0 Summary of Overall Findings

Overarching high-level findings of this study include:

1. Answering decadal science questions related to Venus interior, surface, and surface-atmosphere interactions are key to understanding Venus origin, history, climate, and structure; Venus surface related science will also inform our understanding of the Earth system, terrestrial planets in our solar system, and planets around other stars.
2. Critical measurements including surface chemistry, mineralogy and morphology can uniquely be acquired with short-duration surface platforms.
3. Other important measurements and data (like climate and meteorology, seismology, and geological processes) require longer duration surface missions.
4. Longer duration missions, mobility on the surface, increased surface platform sophistication, and simultaneous presence at multiple locations are needed to address many science questions.

This study identified four key capabilities that will positively impact science returned by future Venus surface platforms. These are time, smarts, mobility, and MSM. The mapping of capability to science impact is reflected in Table 3.1. These capabilities promise to enable new science and combining these capabilities increases science return even more through synergism, Figure 3.3. The capabilities will be realized through specific technology developments. The mapping of capability to the underlying technology needed is shown in Table 4.2. Investments in the underlying technologies will realize the key capabilities, which will enable new measurements that will help answer the important outstanding science questions.

Appendix A.—Study Team Membership

A brief overview of the study organizational structure was presented in Section 1.1. Table A.1 describes in more detail the study team membership and their roles. The study team consisted of experts from multiple centers and institutions with expertise across a broad range of fields. Subteams were formed associated with the various areas of science investigations (interior, surface geology, and surface-atmosphere interactions), as well as capabilities/technology.

Table A.1. Organizing Committee Membership and Roles

Name (alphabetical)	Affiliation	Role
Mike Amato	NASA Goddard Space Flight Center (GFSC)	Co-Chair
Jeff Balcerski	Ohio Aerospace Institute (OAI)	Organizing Committee
Noam Izenberg	Johns Hopkins Applied Physics Lab (APL)	Organizing Committee
Natasha Johnson	GSFC	Organizing Committee
Tibor Kremic	NASA Glenn Research Center (GRC)	Co-Chair
Thomas Thompson	Jet Propulsion Laboratory (JPL)	Organizing Committee
Carol Tolbert	GRC	Organizing Committee
Subgroups		
Interior: geophysics and geodynamics		
Walter Kiefer	Lunar and Planetary Institute (LPI/USRA)	Lead
Jeffrey Balcerski	OAI	Subgroup Member
Robbie Herrick	University of Alaska Fairbanks	Subgroup Member
Sue Smrekar	JPL	Subgroup Member
Surface geology		
Martha Gilmore	Wesleyan University	Lead
Lynn Carter	University of Arizona	Subgroup Member
Darby Dyar	Mt. Holyoke College	Subgroup Member
Richard Ghail	Imperial College, UK	Subgroup Member
Tracy Gregg	University at Buffalo College	Subgroup Member
Misha Ivanov	Vernadsky Institute	Subgroup Member
Surface-atmosphere interactions: composition, chemistry, and geochemistry		
Natasha Johnson	GSFC	Lead
Joern Helbert	DLR Institute of Planetary Research	Subgroup Member
Sebastian Lebonnois	Laboratoire de Météorologie Dynamique	Subgroup Member
Sara Port	GRC	Subgroup Member
Misha Zolotov	Arizona State University	Subgroup Member
Capabilities/technology		
Jonathan Sauder	JPL	Lead
Alan Cassell	NASA Ames Research center (ARC)	Subgroup Member
James Cutts	JPL	Subgroup Member
Jeffrey Hall	JPL	Subgroup Member
Gary Hunter	GRC	Subgroup Member
Geoffrey Landis	GRC	Subgroup Member
Fredrick Rehnmark	Honeybee Robotics	Subgroup Member
Thomas Spilker	Orbital Assembly Corporation	Subgroup Member

Appendix B.—Overview of Science, Capabilities, and Technologies for Expanded Venus Surface Exploration

Sections 3.0 and 4.0 discuss "Science and Driving Capabilities" and "Underlying Technology to Enable Capabilities," respectively. Table B.1 expands upon that discussion bringing together in one table the broad range of science goals and corresponding needed capabilities and enabling technologies.

Table B.1. Overview of Science Goals, Needed Capabilities, and Enabling Technologies

Capability	What new science/measurements would this capability enable			
	Surface interface, composition, and chemistry and geochemistry	Venus interior, heat flow, geodynamics, and seismic activity	Geology	Enabling technology
Time				
2 to 5 hours	Most surface interface measurements are enabled by this	Maybe shorter times could do this, but certainly at this time frame with a lander, could use multiple techniques (ground penetrating radar (GPR), EM sounding, and active seismic) to get local vertical profile to at least 10s of meters of near-surface stratigraphy	Evaluate geochemistry and mineralogical of single key site	Within range of current mission proposals
1 to 5 Earth days	May be able to find variability; opportunity for human interaction; also note that time on surface and depth are connected	Should be able to get feel for overall planetary seismicity level, maybe even basic vertical structure; probably enough time for a heat flow pad to equilibrate	Evaluate geochemical and mineralogical diversity as you could achieve several locations and calibrations	Need either active cooling system, with lots of stored power (possibly combustion), or high-temperature electronics with some stored power; rubidium/strontium spectroscopy takes many hours; longer duration enables multiple measurements
~30 Earth days	May be able to find variability	Could definitely lock down heat flow, probably enough large quakes to get global internal structure	One image per day for 30 days would start to identify evidence of active erosion and movement of sediment on Venus	Enabled by large solar panels (Venus peak solar day), RPS and/or improved high-specific energy batteries
117 Earth days (diurnal cycle)	More likely to be able to find variability in diurnal cycle, plus you can see variability in wind, and possible in very near surface atmosphere	Somewhere between this and above would be enough to likely evaluate where major centers of seismicity are for the planet; probably some significant geodesy things can be done to get moment of inertia; probably interesting to measure whether surface atmospheric pressure varies over course of a day	One image per day for 120 days would help to see if there is evidence of active erosion and movement of sediment on Venus; allows you to observe differences in the weather (for example, does dust blow in the morning/evening)	Enabled by Venus capable wind power, battery, or radioisotope thermal generator (RTG)
134+ days (multiple diurnal cycles)	Composition for multiple diurnal cycles, could find variability in the surface processes, which would provide interesting results		Determine if Venus volcanically active with long-term chemical species measurements on the surface	Enabled by Venus capable wind power or RTG

Table B.1. Overview of Science Goals, Needed Capabilities, and Enabling Technologies

Capability	What new science/measurements would this capability enable			
	Surface interface, composition, and chemistry and geochemistry	Venus interior, heat flow, geodynamics, and seismic activity	Geology	Enabling technology
Distance between measurements				
Point measurement: 0 m				Within range of current mission proposals
1 to 2 m	Would tell you if something is homogenous	Can use lateral reach. To separate vertical profiles (use GPR and active seismic from side reflections)	Enables picking rock or dust; ensuring you get a rock, and not dust; picking a suitable target is important; centimeters (versus a meter) may be adequate to select a desired sample	Utilizes sample arm; within range of near future mission proposals
10s of meters	Not as helpful; could be beneficial if in obstructed wind area	Even better for moveout, can nail down local vertical profile, even identify local horizontal discontinuities	Very dependent on landing location; current landing sites show small changes in variability; provides protection where you land in a "bad" place, like a patch of sand	Sojourner-style rover, with limited mobility in an area
1 to 20 km	Really depends on where you are, and what the geology sees	Good for regional refraction seismology, could get Mohorovičić discontinuity depth, other key crustal interfaces	Traveling more than 1 km would get you beyond the horizon; 10 to 20 km with images at 0.5 km steps would be fantastic; answers questions like "What is the geomorphology of the local surface?"; likely to find something interesting (for example calderas); can start to locate yourself relative to orbital data	Opportunity- or Curiosity-style rover for a long-lived mission; Venus Mobile Explorer (VME) for a short-lived mission.
100s of kilometers	Guaranteed to be at different geologic areas; also beneficial for wind measurements, likely to find more variability and something different; in the landing site, will be similar	Great for seismic and, infrasound networks	Ability to get outside of landing ellipse; for example, land in a safe place, but go to an interesting place; could land near a tesserae on the plains, then travel into the tesserae and explore both the tesserae and transition elevation change; note: making a traverse from the air enables additional context images, gives you the best of both worlds	Balloon mobility for a long-lived mission or multiple probes
Depth				
Surface		Most geophysical instruments could be deployed right at the surface		Penetrometer as on Venera
Surface abrasion (1 to 2 mm)	Depends on the thickness of a surface layer on Venus (debate between millimeters to centimeters); goal is to obtain nonweathered material.			Simple scraping tool

Table B.1. Overview of Science Goals, Needed Capabilities, and Enabling Technologies

Capability	What new science/measurements would this capability enable			
	Surface interface, composition, and chemistry and geochemistry	Venus interior, heat flow, geodynamics, and seismic activity	Geology	Enabling technology
1 to 10 cm	May be required to get to nonweathered material	Either drill or scoop could be used as source with local geophones to get seismic reflection profile around landers	Better access to fresh primary materials if depth of weathering may be quite deep, as in meters to 10s of meters	Drill (current capabilities of Honeybee Robotics drill)
10 cm to 1 m			May allow access below regolith	Scoop for digging (like Insight); possible future capabilities for Honeybee Robotics drill
10s of meters		Great for heat flow; could be used as active source for VSP (vertical seismic profile)	May allow sampling of horizontal contacts between units	Deep drill; requires multiple interlocking sections/bits
Terrain accessed				
Flat plains				Safe, current mission goals
Rocky plains (0.2- to 0.75-m boulders)				Like Venera 9
Rough terrain (tessera, slopes, cliffs, valleys)				Autonomous hazard navigation
Autonomy				
Preprogrammed mission		Much of geophysics may be addressed with preprogrammed missions		Within range of current mission proposals
Preprogrammed with response to environment	Humans in the loop and good autonomy may be same thing	Guide placement of geophysical instruments	Land in targeted location	Within range of future mission proposals
Humans in the loop each day	Improved science benefit from cycles of experiments	Improved science benefit from cycles of experiments	Ideal scenario, is where you inspect the images, and state we want to go there, and get there, without worrying about how to do it	Longer duration mission; probably requires a Venus communications platform
Humans in the loop every 2 hours	Verify targeted experiments in case of unexpected result	Verify targeted experiments in case of unexpected result	Initial arrival is more important for higher frequency humans in the loop; during first day, let humans jump in loop, then let it carry out tasks	Requires advanced Venus telecommunications infrastructure
Points/network				
Points/network				Mostly relate to cost instead of technology
Single lander			Essential to coordinate data with existing data set	
Coordinated lander and orbiter/aerial	Geologic context and infrared measurements (IR) are important aspects to correlate		Provides context for lander data at a resolution that can bridge the gap to orbiter resolution	

Table B.1. Overview of Science Goals, Needed Capabilities, and Enabling Technologies

Capability	What new science/measurements would this capability enable			
	Surface interface, composition, and chemistry and geochemistry	Venus interior, heat flow, geodynamics, and seismic activity	Geology	Enabling technology
Two landers		Much better than one for seismology, infrasound		
Network of landers (3+)		Best for seismology, infrasound	As you increase the network size, the benefit goes up by more than the number of parts; Three landers three years apart is less valuable than a coordinated set of measurements	
Coordinated network of lander/aerial/ orbiter				

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