Title of the white paper: VENUS SURFACE PLATFORMS

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Summary: Environmental conditions at the Venus surface are exceptionally challenging for assets that may be placed there due to the high temperature, pressure and reactive atmosphere. Despite these challenges, future Venus surface assets (landers, rovers, monitoring stations, or any other conceivable surface-based system - which are generically referred to as “surface platform” throughout this white paper) will be required because only in-situ operations can address some of the important science questions identified by the decadal survey report [1]. Given the importance of the science and realizing the technical challenges, NASA, and the Venus Exploration Analysis Group (VEXAG) embarked on a study to assess the relationship between potential science that can be accomplished with Venus surface platforms.

Specifically, a Venus Surface Platform Study was undertaken to evaluate the role of surface platforms in future Venus exploration. The 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 by this means. Major findings include:

- 1) Surface science is key to understanding Venus’ origin, history, climate, and interior;
- 2) Key data (like baseline mineralogy and morphology) can be acquired with a short-duration probe while other data (meteorology, seismology, and geological processes) need long temporal baselines provided by long-duration landers;
- 3) Ongoing technology development can already enable new classes of missions capable of addressing knowledge gaps;
- 4) Increased science can be realized by increasing surface missions’ capabilities in terms of a) surface operating life (time), b) mobility, c) sophistication and autonomous operations (smarts), and d) multiple copies at various locations making simultaneous measurements (multiple simultaneous measurements or “MSM”).

Increasing surface operating life and sophistication or “smarts” are the two capabilities expected to provide the greatest science return. This white paper is a short summary of the full report expected to be released in the Fall of 2020.

Challenge: The relative lack of knowledge of Venus’ surface and interior is a direct result of the challenging environment, which has temperatures hot enough to melt lead and even zinc (450°C), pressures equivalent to nearly a kilometer under Earth oceans’ surfaces (90 bars), and an aggressively reactive chemical atmosphere [2]. Remote sensing of the surface at visible to thermal wavelengths is limited in wavelength and spatial resolution due to high-pressure supercritical CO₂ atmosphere and light scattering by the thick layers of sulfuric acid clouds [3] – [8]. This has hampered the ability of orbiting missions to provide desired insights into surface features and processes, in particular mineralogy, and obscures valuable data needed to advance our understanding of the planet’s global climate, surface processes, and interior.

Over the period from 1970 to 1984, ten surface lander missions were successfully executed, yet the longest surviving asset (Venera 13) lasted only 127 minutes [2] before succumbing to the extreme temperature. While these and other landers provided valuable new data (and to date the only surface data), key measurements remain poorly constrained. In addition, the short life impacted the ability to understand any temporal processes, e.g., meteorology or seismicity, and therefore very little is correspondingly known about crust activity, the interior, and surface/atmosphere interactions.

Study Approach: The approach for this study was to engage experts in field related to Venus surface exploration and engage them to work together to address the following study purpose:

Assess the science achievable by various surface platform capabilities, the state of the technologies applicable to Venus surface exploration, and lay out a high level roadmap for the future exploration of the planet by this means. Invited scientists, technologists and mission planners systematically addressed relevant topics. Science areas were categorized into:

Interior: Geophysics, Geodynamics

Surface: Geology, Mineralogy, Petrology, and

Surface/Atmosphere Interactions: Mineralogy, Petrology, and Atmospheric Composition

In each of these three areas, a science sub-group was formed which formulated science objectives that centered on the science desired and surface platform capabilities necessary. For each area, the state-of-the-art understanding of what is presently known about Venus and the current capabilities, including information determined by other platforms such as orbiters, influenced the discussion on the potential role of landers in future exploration. Additionally, for each given science objective, the measurements, mission modes, technology needs, lander platform implementation, and technical methods to accomplish the objective were identified. These deliberations are summarized in Table 1.

In combination with the three science sub-groups, a technology sub-group was also formed. This sub-group explored specific capabilities and technologies required to carry out the science desired by the three science sub-groups. This group focused on Instrumentation, Avionics, Communications, Power, Mobility, and other technology driven topics. It was found that there was an interplay between lander capabilities/technologies and mission science return. The four key capability areas identified in this study to enable science are defined and described later in Table 2.

Science Questions: Table 1 addresses the science questions associated with the Venus surface as compiled by the science groups from the current Decadal Survey report [1], VEXAG guiding documents describing Venus science goals and objectives and technology needs [3],[9] and the group discussions. Important questions relate to local composition and chemistry, climate and weather, and interior dynamics and structure. These questions are core to understanding Venus, to better understanding terrestrial planets in general, and perhaps the exoplanets that are being regularly discovered. In some cases, the questions can be answered using heritage lander technology with upgraded instrumentation, e.g., “What are rock-forming elements, material properties and surface structures?” However, several science questions will require advances in capability to obtain the needed measurements, and these, in particular, drove key focus areas of this study. For example, longer durations, better autonomous decisions, multiple measurements at various locations, or surface mobility will enable answering questions like “What is the physical structure and rheology of the deep interior?” or “What are spatial and time variations of concentrations of atmospheric constituents, meteorological conditions and solar radiance?” and other questions as found in Table 1. Addressing these and other questions will require advances in technologies to enable or enhance one or more of the capabilities mentioned. Table 1 also includes known technology/capability drivers for the science as well as development needs to achieve the desired capability.

Given the limited number and duration of previous Venus surface missions to date and the fact that the last one was several decades ago, even small incremental advances in capabilities will help future missions capture much needed new data and help address more of the questions described in Table 1.

Table 1. Science Questions and associated Missions, Technologies, and Development Needs

	Science	Minimum Mission Needs	Technologies	Development Needs
Local composition, Surface/atmosphere, Geology	What are rock-forming elements, material properties, mineralogy and surface structures.	Single, Stationary, Short life, Preprogrammed Mission (or a.k.a. state-of-art platforms “SOAP”)	Improved instrumentation suit, as describe in recent flagship mission studies like Venera-D [10] or Venus Flagship Mission Study [11], Solar flux measurement; Adaptation of multiple technologies for Venus applications; Surface conductivity measurements; Magnetometer; Densitometer and other material characterization instruments	Viable with updates to current instrument capabilities
	What characterized Venus surface geology and history?	SOAP	Advancements in lander survivability and instrumentation; surface and descent imaging;	Viable with updates to current instrument capabilities
	What is the spatial variation across the surface of Venus geology?	Multiple SOAP at different altitudes & latitudes, or Long-lived mobile system	Improved instrumentation suit, as describe in recent flagship mission studies like Venera-D or Venus Flagship Mission Study, Solar flux measurement; Adaptation of multiple technologies for Venus applications; Surface conductivity measurements; Magnetometer; Densitometer and other material characterization instruments and/or hundreds of kilometers mobility	Viable with updates to current instrument capabilities and/or development of high-temperature technology and mobility
	What are the concentrations of atmospheric constituents, meteorological conditions; solar radiance (Single or multiple points)	Single or Multiple SOAP (if multiple, at different altitudes & latitudes)	Improved mass spectrometer/gas measurements; Solar flux measurement; Sample capture systems	Viable with updates to current instrument capabilities
Climate, Weather, Energy Balance	What are the time variations in concentrations of atmospheric constituents, meteorological conditions, solar radiance	Single to 3+ platforms at different altitudes & latitudes), Stationary, Long-lived platforms	High-temperature technologies to realize long life, gas measurements; Solar flux and metrological measurements	Development of high-temperature technologies needed
	What are the spatial and time variations of concentrations of atmospheric constituents, meteorological conditions; solar radiance	Long-lived multiple platforms or mobility	High-temperature technologies including instrumentation and/or actuation, power, cooling, and autonomous systems for mobility	Development of high-temperature technologies, and/or mobility and autonomy needed
Interior Diversity and Structure	What is the physical structure and rheology of the deep interior?	Long-lived, Single or Multiple, Stationary	Background seismic noise; High-temperature technologies including seismometer, magnetometer, pressure sensor;	Development of high-temperature technologies
	What is the physical structure, composition, and dynamics of the crust?	Long-lived, Single or Multiple, Stationary or Mobile	Background seismic noise; High-temperature technologies including seismometer, magnetometer, sampling; mobility (power, cooling, autonomy)	Development of high-temperature technologies, mobility, and autonomy needed
	What is the heat flux from the interior to the surface?	Single, Multiple, Stationary,	Heat flux sensor; graduated temperature probe, Planar heat flow; temperature depth profile	Development of heat flux sensor; deep drill

Key science questions were discussed by each respective science sub-group in this Study. Examples of questions/comments from the VEXAG Venus Scientific Goals, Objectives, and Investigations that relate to the science and study subgroups are:

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” (VEXAG GOI - III.A.GA).

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 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). The suite of needed instruments to fully address surface geology question can be found in recent studies e.g. Venera-D [10], the Venus Flagship Mission concept [11].

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 could enable the study of supercritical carbon dioxide.” (II.B.IN)

The four capabilities/technology areas identified in this study to enable enhanced science are defined in detail in Table 2, where critical surface platform capabilities identified and explored in this Study include: a) surface operating life, b) “smarts” (employing complex electronics/processing, situational awareness, autonomous decision making, complex instruments /measurement capabilities), c) “mobility”, and/or d) multiple simultaneous measurements (MSM). These capabilities are expected to be key to going beyond basic incremental measurement advancements and achieving major and even breakthrough advancements in science.

Table 2. Capability Definition (for purposes of this study) and Discussion

Capability	Definition	Range	Comments / Discussion
“Time” or operating life of the platform on the surface	The capability for a surface platform to continue to operate nominally on the surface for longer and longer periods of time	From current state-of-the-art (few hours) to many months	The relationship between new science and “time” is not expected to be a smooth proportion but rather step based. As an example, the marginal science expected by a lander surviving 48 hours is not expected to yield twice the science as a lander that operates 24 hours. However significant new science is expected (e.g., climate/meteorology for a lander that would survive 60 days). Extending time to 120 days could yield significant science on geologic/seismic activity and insight into the interior, assuming the capability in “smarts” exists to capture the measurement.
“Mobility” or the ability to acquire measurements from different locations	Ability to acquire science data at different locations via in-situ motion	One single local point (e.g. fixed sample ingestion of a state-of-art lander) to the ability to acquire measurements with the same platform at locations 100’s - 1000’s of km apart	Mobility spans from one <i>fixed location</i> , to selectable location within a mobile “arms” reach to <i>short distance (many meters)</i> roving or hopping to <i>long distance (100’s to 1000’s of km)</i> roving, hopping, flying, or floating. Short distance mobility is not likely to yield the science return as on Mars, for example. Therefore, after achieving ability to make measurements within an arms-reach at a fixed location, the next step change in science will likely be achieved with long distance capability, enough to reach a diverse geologic region.
“Smarts” or the sophistication/degree of autonomy of the platform	Ability to assess surroundings, perform complex processing, quickly transfer large quantities of data, and make correct decisions. Ability to	Ranging from the ability to execute pre-programmed set of tasks with no local feedback or informed decision making to the ability to autonomously assess	This capability is perhaps the most subjective construct yet is a critical capability in achieving increased science by future surface platforms. Smarts can dramatically increase its science return as reflected in the history of Mars landers [12]. The Venus surface’s environmental challenges demand that new type of sensors and electronics be matured to achieve the smarts needed.

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Capability	Definition	Range	Comments / Discussion
	make precise landings is an example where Smarts capability would be applied.	local area, make informed decisions on the next course of action, request human informed course of action as when needed, quickly process data and transfer the desirable data to the Earth.	Developments are ongoing to improve the various aspects that can increase smarts of future Venus platforms.
Multiple Simultaneous Measurements “MSM” /copies of platforms	Ability to acquire simultaneous or near simultaneous measurements from multiple locations with similar but distinct platforms (e.g. meteorology or seismic stations)	Single platform at one imprecisely placed location to many platforms precisely located around Venus	The key aspect of this capability is the acquisition of data at nearly the same time leveraging the fact the multiple copies of the same platform are relatively low-cost/risk and, for some science can not only be an alternative to mobility, but will be required for certain science, e.g. collecting simultaneous seismic data from multiple locations to understand the interior structure of Venus [8].

Science and Driving Capabilities: The driving capabilities for the respective science and science questions were explored with the science subgroups as well as the technology subgroup. Table 3 addresses the relationship between science questions and the core capabilities defined and discussed in Table 2, namely Time, Smarts, Mobility and MSM. An “H” in a field signifies that the capability is highly impactful in realizing that aspect of the science. A “S” in a field signifies somewhat impactful. A blank in a field implies the capability is not expected to yield significant additional science return. All four of the key capabilities identified in the study are expected to make significant positive contributions to surface related science.

Table 3. Relationship between science areas and the respective questions in that area to the set of core capabilities identified, namely Time, Smarts, Mobility and MSM. “H” in a field signifies that the capability is highly impactful in realizing that aspect of the science. A “S” in a field signifies somewhat impactful.

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
Age	S	H	S	S
Geologic Record (Layers, craters, ...)	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

Time and MSM are the most significant capabilities to address the science questions related to the Venus interior. The measurements to address structure, dynamics, and heat escape data are relatively simple and don’t require large volumes of data. Mobility provides some enhancements to science, but its relative impact is expected to be less significant. Further discussion of these

relationships is provided in the full Study report.

Many surface/atmosphere interaction processes are relatively slow processes, so it is not unexpected that time would be a significant enhancing or enabling capability. Taking measurements at multiple locations, as done on Earth, is a proven approach to better understanding of weather and climate and its potential effects on the surface. More discussion on the relationships can be found in the study report.

Along with the key/critical capabilities described in Table 2, other capabilities were identified and discussed as well. While these may not yield the same level of impact they still need to be considered as future surface platforms are planned. Some of these include the ability to collect samples at depth (to reach pristine/un-weathered material), the ability to access and navigate difficult terrain (tesserae, mountains) and the ability of platforms to interact and work together (swarm).

Underlying Technology Needs: To realize the driving capabilities of Time, Smarts, Mobility and MSM, continued advances in underlying technologies are required. Table 4 summarizes some of the links between the capabilities and underlying critical technologies. This table utilizes the same approach to describe impact as was used in Table 3 above. Since MSM, by our definition, implies copies of similar platforms it is not viewed as a new technology driver and therefore not considered further here. It should be noted the advancements in technologies can be co-dependent, i.e, one technology may reduce the need/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 need to be developed together. For example, a cooling system that would support a Venus surface platform is of no value if there is not a power system that can support the load for extended periods of time. Further discussion of the technology state-of-art and possible future advances can be found in the VEXAG Technology Plan [9].

Table 4. Relationship Between Technologies and the Capabilities Enabled.

Critical Underlying / Supporting Technology	Capability		
	Time	Smarts	Mobility
Power (Low – 10's of watts or less)	H	H	
Power (High - 100's of watts)			H
Cooling [Will also need Power (High)]	S	H	S
High Temp Electronics / Memory / Power Processing	H	H	H
Mechanisms (Drills, Wheels, ...)			H
Autonomous Ops, Nav		H	H
State-of-art Instruments		H	

Results: The final report for this study is still in preparation. Nonetheless, major high level finding of this report include the working versions of the tables and Figure 1 above, and more detailed table(s) linking the underlying technologies to the driving capabilities. Technologies such as power, mechanisms, high-temperature electronics, cooling/thermal control, and others. Overarching high level findings of this study include:

- 1) Surface science is key to understanding Venus origin, history, climate, and interior.
- 2) Key data (like mineralogy and morphology) can be acquired with short-duration surface platforms but other data (meteorology, seismology, and geological processes) need long temporal baselines provided by long-duration landers. Extension of surface life by any amount will enhance science return even for today's "short" lived missions.

- 3) Current technology developments can already enable new classes of missions capable of addressing major knowledge gaps in the decades-old Venus surface data.
 - 4) Increased science can be realized by increasing surface missions' capabilities in
 - a) Time (aka operational life on surface)
 - b) Mobility
 - c) Smarts (sophistication and autonomous operations)
 - d) MSM (multiple copies at various locations making simultaneous measurements)
- As Table 3 indicates, Time is the most impactful capability followed by MSM.

Recommendations are discussed in the full study report but include continuing the development of critical technologies that enable the capabilities (Time, Smarts, Mobility and MSM) needed to address the science that is possible with in-situ surface platforms.

References: [1]. Visions and Voyages for Planetary Science in the Decade 2013–2022, National Research Council, 2011, [2] Venus Flagship Mission Study, Report of the Venus Science and Definition Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, April 2009, [3] Venus GOI: Scientific Goals, Objectives, and Investigations for Venus Exploration”, Revised, 219 https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_GOI_Current.pdf , [4] S. E. Smrekar, et al., Science, 328, p. 605-608, 2010. [5] E. V. Shalygin et al. Geophys. Res. Lett., 42, 4762–4769, doi:10.1002/2015GL064088. [6] T. Kremic et al., <https://www.lpi.usra.edu/vexag/reports/SAEVe-6-25-2018.pdf> , [7] J. Peralta, et al. Nature Astronomy 1, Article number: 0187 (2017), [8] T. Kremic et al. Planetary and Space Science 190 (2020) 104961, [9] Venus Technology Plan, https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_Techplan_Current.pdf , [10] Venera-D Study Report; <https://www.lpi.usra.edu/vexag/reports/Venera-DPhaseIIFinalReport.pdf> https://www.nasa.gov/mission_pages/mars/missions/index-past.html , [11] Venus Flagship Mission Concept Summary; <https://science.nasa.gov/solar-system/documents> , [12] https://www.nasa.gov/mission_pages/mars/missions/index-past.html