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VENUS TECHNOLOGY PLAN

Report of the VEXAG Focus Group on

Technology and Laboratory Instrumentation

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1.0 EXECUTIVE SUMMARY

The planet Venus, with its unique environment, presents unusual challenges for planetary exploration. A number of scientifically important missions can be implemented with existing technology although some may involve engineering development. However, missions involving operations for extended periods in the atmosphere, at or near the surface of Venus are going to require significant investments in new technology but can leverage off commercial developments. A Venus exploration program should include a balanced investments in missions for the short term and technology investments enabling these more ambitious missions that can be conducted in the medium and long term.

2.0 BACKGROUND

This is the third in a series of three documents prepared under the auspices of the Venus Exploration Analysis Group (VEXAG) that are intended to provide NASA's Planetary Science Division with the analyses on which they can formulate a strategic direction for future Venus exploration. The Venus Goals, Objectives and Investigation (VGOI) document[1] establishes the scientific goals for Venus exploration and prioritizes the objectives and investigations needed to address those goals. The Venus Exploration Roadmap (VER) [2] translates these objectives into Mission Modes that can most effectively address the objectives and implement the investigations. The VER also reexamines the recommendations in the Planetary Science Decadal Survey[3] an assessment of the state of technical readiness for implementing missions using these different mission modes. The present document, the Venus Technology Roadmap (VTR), draws information from both of the prior documents but primarily the VER and performs a more detailed assessment of the technologies that NASA needs to invest in.

3.0 VENUS EXPLORATION CHALLENGES

While there is a long history of Venus exploration, there has been no dedicated US mission to Venus since Magellan ceased operations in September 1994.

3.1 Venus Environment

The Venus environment poses mission challenges like few other potential planetary destinations:

1) In orbit the thermal environment is challenging but less so than for Mercury
2) During planetary atmospheric entry, the velocity and thermal conditions are more severe than for entry at Earth or Mars (but less than Jupiter)
3) Once in the atmosphere, missions operating high in the atmosphere can experience a benign environment in terms of temperature and pressure but are exposed to sulfuric acid clouds
4) Landing on Venus is less challenging because of the dense atmosphere which eases both the initial parachute phase and terminal descent relative to Mars
5) Surface operations using conventional electronics and passive thermal control systems are limited to a few hours by the high temperatures. Long duration missions require components and packaging that will function in Venus ambient and/or have active thermal control systems.

3.2 Spaceflight Heritage and Mission Modes for the future

More than 30 spacecraft have flown to Venus since Mariner 2 flew by the planet 50 years ago. These missions have included flybys, orbiters, probes, short-lived landers and balloons. Most of the missions occurred in the first 25 years; only 2 missions to Venus have occurred since 1994, neither of which was done by the US.

The absence of recent activity has resulted in loss of some of the technical capabilities important in Venus exploration. Some capabilities are not easily reproduced. However, the early successes provided a proof of principle that orbiters, probes, short-lived landers and balloons could be successfully deployed at Venus.

Several assessments of Venus technology have been conducted in recent years. In 2006, NASA's Solar System Exploration Roadmap[4] included a Venus Mobile Explorer mission and an extensive discussion of the required technology for this mission. In 2007, an assessment of extreme environments technologies for planetary exploration was conducted under the leadership of JPL[5]. This was followed by a monograph focused specifically on Venus technologies[6]. In April 2009, the Science and Technology Definition Team for the Venus Flagship Mission[7] conducted an assessment of not only the new technology requirements for the Design Reference Mission (DRM) but also the mission and payload enhancements for what it referred to as extraordinary science return. Finally, in September 2009, a white paper [8]was submitted to the Planetary Science Decadal Survey by members of VEXAG on technologies for future Venus exploration. These are all important sources for the present document. However, the present document is guided by the specific recommendations of the Venus Roadmap team and the Venus Goals, Objectives and Investigations document.

The Road Map team has identified a number of Mission Modes generally involving different types of instrument carrying platforms that will be needed to conduct the comprehensive investigation of Venus described in the Roadmap. These Mission Modes differ in the level of technology that is needed. Later in this document we describe the technologies that are needed to enable each of the mission modes.

4.0 TECHNOLOGY PLAN OVERVIEW

A high level summary of the technologies needed for the Roadmap mission appears in Table 1. A more detailed description of the technologies needed for individual mission modes appears in sections 5, 6 and 7. The technologies are organized into three categories. Systems technologies apply at the scale of the spacecraft or, in the current parlance, Mission Mode. Some of these such as entry technologies are common to many mission modes, others are very specific. Subsystems technologies are generally components of these systems. While the subsystems, such as power, are needed for all of the mission modes, it is only in some of them that the technology is a challenge. We have devoted a separate section to science instruments which in many cases must be uniquely tailored to the conditions at Venus.

5.0 SYSTEM LEVEL CAPABILITIES

System level capabilities are typically at the level of the Mission Modes described in the Roadmap. It is important to recognize that these capabilities cannot be considered in isolation. These system level capabilities will generally feed down to one or more subsystem technologies described in Section 6.0

5.1 Entry

Entry technologies are needed for implementation of all the mission modes designated in Table 1 except for remote sensing from space. Although successful entry at Venus has been accomplished many times by Soviet, and later Russian landers, and by both a large probe and three smaller NASA probes, the technologies used in those NASA missions is no longer available. Several alternative approaches have been identified and some are under development:

1. *Heritage Carbon Phenolic*: This solution requires a descent into Venus at high entry angles to mitigate the cumulative heat load imposing high g loads on payloads[9]. Attempting to replicate the material used in previous Venus missions is one approach. Its advantage is that it has been proven to work. The shortcoming is that it would be extremely challenging to reproduce similar family of material as the manufacturing processes have atrophied and raw material no longer available and also expensive to qualify. Moreover this solution is prone to premature obsolescence.

Table 1: Framework for assessment of technologies for Venus Exploration

	Technology Area	Time Frame	Assessment
System Technologies	**Entry Descent and Landing**	N,M	Need new woven TPS or deployable technologies for entry at Venus since there is currently no technology that does the job. Descent and landing is much easier than for Mars and for airless bodies and is largely an engineering challenge
	Aerial Platforms	N,F	Technology for near term missions is mature. Near surface aerial capabiity would be one option for the "regional mobility platform" and does require substantial investment
	Landed Platforms	N,M,F	Three classes of landed platform will be needed of increasing technical challenge: short duration containing analytical instruments (current technology), long duration with geophysical sensors and long durations with a complex instrument suite and surface mobility
Subsystem Technologies	**Power**	M,F	Most compelling mid term need is for thermoelectric generators operating in a 460C environment. In the far term, the efficiency of Stirling would be highly desirable
	Thermal Control	M,F	Challenge is extending lifetime once on the surface. Prospects for extending life beyond several hours with passive cooling are low. Active cooling may be feasible for long life
	Extreme Environments	N,M,F	Advances in high temperature mechanisms would be enhancing for a first generation lander. High temperature electronics would be needed for the geophysical platform.
	Communications	N,M,F	Optical communications would be enhancing for an orbital radar mission. Proximity communications are needed to enhance data return from all in situ missions
	Guidance Navigation and Control	M,F	Miniaturized low power systems needed for localization and attitude knowledge on probes, aerial platforms, dropsondes and landers
Instruments	**Orbital Remote Sensing**	N	Technology for implementing these missions is hear today. Advances in radar and infrared techniques would be enhancidn
	Probe and Balloon	N,M,F	Instruments for middle atmosphere exist but should be miniaturized. Sensors for chemistry in the lower atmosphere need improvement
	Surface in situ	N,M,F	Need technologies in near term for "rapid petrology". In mid term need geophysical sensors that operate at Venus ambient. In far term need sensonrs for mobile laboratory

2. *3-D Woven Thermal Protection System*: The use of 3-D woven materials infused with resin to withstand a broad range of entry environment to result in mass efficient ablative TPS is currently under development by NASA's Space Technology Mission Directorate (STMD) and has the potential for infusion into missions in the next few years. The properties of this manufacturing technique permit the ablative TPS to be tailored to a preferred trajectory dictated by Venus missions and thereby reducing the entry environment (heat-flux, pressure and g-load). A currently funded development will result in demonstrating a small 1.5 m aero-shell scalable to much bigger aeroshell diameter. This development is considered to bring

the state of development of the larger aero-shell needed for a Venus lander to TRL 5/6 by the end of FY'16.

3. *Adaptable Deployable Entry and Placement Technology (ADEPT):* This approach involves reducing the ballistic coefficient of the payload by an umbrella-like deployment of a large area heat shield. The ADEPT Full Scale Demonstrator (FSD) Project is a STMD Game Changing funded new start project in FY14. The ADEPT FSD is focused on design, development, and integrated ground test of a 6m mechanically deployed decelerator capable of delivery of payloads up to 1000 kg while keeping peak deceleration loads below 30 g's. The ADEPT system decelerates much higher in the atmosphere and results in much lower peak heating. As such, no advanced thermal protection material development is needed and testing is well within range of existing facilities[10]

Table 2: Mission Modes and Applicable Technologies

		Mission Mode	Remote sensing from space		Deep Probes		Lander Short Duration		Lander Long Duration		Mobile* Platform Long Duration		Aerial Platform Mid Atmosphere		
			Orbiter	Multiple flybys	Single	Multiple	Smooth Terrain	Rough Terrain	Single	Network	Surface	Near Surface	Fixed altitude	Variable Altitude	Drop Sondes
Applicable Technologies	System Technologies	Entry			X	X	X	X	X	X	X	X	X	X	X
		Descent and Deployment			X	X	X	X	X	X	X	X	X	X	X
		Landing					X	X	X	X	X				
		Aerial Platforms										X	X	X	X
		Landers - Short Durations					X	X							
		Landers Long Duration - Geophysica							X	X					
		Mobile Platform - Surface or near surface									X	X			
	Subsysystem Technologies	Energy Storage- Batteries	X	X	X	X	X	X	X	X	X	X	X	X	X
		Energy Generation - Solar												X	
		Energy Generation - Radioisotope Power									X	X		X	
		Thermal Control - Passive					X	X						X	X
		Thermal Control - Active									X	X			
		High temperature mechanisms					X	X	X	X	X	X			
		High temperature electronics					X	X	X	X	X	X			
		Communications			X	X	X	X	X	X	X	X	X	X	X
		Guidance, Navigation and Control							X	X	X	X	X	X	X
	Insutrument	Remote Sensing - Active	X	X											
		Remote Sensing - Passive	X	X											
		Probe - Aerial Platform			X	X							X	X	X
		In Situ Surface - Short Duration					X	X							
		IN Situ Surface - Long Duration - Geophysical							X	X					
		In Situ Surface - Long Duration - Mobile Lab									X	X			

Very High. Ready for flight. Same as TRL 6

High. Limited development and testing still needed

Moderate. Major R&D effort needed.

Low. Major R&D effort needed with uncertainty about feasiblity.

5.2 Descent and Deployment

Descent/deployment capabilities are relevant to the same five Mission Modes as for entry. For probes and landers it is necessary to control the rate of descent and stabilize vehicle attitude during its passage to the surface through a progressively denser atmosphere.

For a probe mission, velocity must be controlled during descent to provide adequate time to sample the different regions of the atmosphere. This may require different sizes of parachute. There are material considerations for coping with the temperature and acidity of the atmosphere, but these are solvable. For a landed mission, the objective is usually to bring the vehicle to the surface as soon as possible to minimize the thermal input to the landing module. Maintaining attitude stability and minimizing jitter during descent is important to obtain images free of motion blur. These are engineering challenges with no new technology required.

For aerial platforms it is necessary to establish the conditions necessary for successful deployment of the aerial vehicle. For balloon deployment and inflation, experience indicates that descent velocities in the range of 10m/sec or less are required. These are readily achievable in the dense atmosphere of Venus. The needed descent velocity for airplane deployment is dependent on the design specifics of the aircraft but again the dense atmosphere is favorable. Demonstrations of the deployments of both balloons and airplanes in Venus-like conditions have been made.

Dropsondes deployed from an aerial platform can be used to sample the atmosphere in multiple locations. Deep dropsondes able to descend close to the surface can be used in conjunction with the platform that deploys them to relay large amounts of high resolution imaging data on potential landing sites but will require technology development in order to generate images in near surface conditions.

5.3 Landing

Landing on Venus is much more benign than landing on Mars. The VER calls for the capability of landing on the smooth terrains where many previous Venus landers have successfully deployed as well as much rougher terrain, the tesserae, which has not yet been explored. Technical approaches to landing on the tesserae range from landing systems that are resilient to any eventuality or “hazard avoidance” systems, similar to those developed for Mars, which would make last minute changes in the descent trajectory to avoid the extreme hazards. The difficulty for Venus is that there currently is no imaging data at a resolution relevant to the hazards of landing but there are technically feasible approaches, using deep dropsondes, that should be a necessary prerequisite to the design of a lander for the tesserae.

5.4 Aerial Platforms

The Roadmap finds that aerial platforms are “generally at an advanced state of readiness” although they may require improvements in instruments power, communications and support capabilities for specific mission architectures. Some of those needed improvements are identified here and elaborated upon in parts of section 6 .0 Subsystems and Section 7.0 Instruments.

The most mature aerial platform is the *superpressure balloon* designed for operation near 55 km. Two platforms of this type were successfully flown in 1984 by the Soviet Union and tracked by an international consortium, led by the Soviet Union and CNES, in which NASA participated. Over the last decade, work at NASA and to a lesser extent at ESA has focused on balloons with a larger payload capability with a potential life times of several months[11]. This technology is ready[12] to fly.

Approaches for accessing higher parts of the atmosphere focused on identifying the nature of the UV absorber were discussed at a workshop on high altitude include other types of balloon capable of excursions into other parts of the atmosphere, solar powered airplanes and hybrid blimps. These concepts have been reviewed in a paper given at the International Planetary Probe Workshop in June 2013[13]. Buoyant vehicles that could operate in the lower atmosphere are considered under *Section 5.7 Mobile Platform at or Near Surface.*

Subsystem developments that could enhance the performance of a balloon include wind assisted balloon navigation and autonomous on board landmark based navigation. They require advances in on-board guidance and control.

LANDER PLATFORMS

5.5 Landers – Short Duration

During the 1970s and 1980s, the Soviet Union successfully landed several vehicles that operated on the surface of Venus for periods of 1 to 2 hours and returned images as well as other scientific data. This was accomplished with insulated pressure 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 (PCM) to extend surface lifetime. Deployment of similar short duration missions using passive thermal control, which can survive on the surface of Venus for a period of hours, is viewed as an engineering development rather than a technology development.

Work in the last five years, has opened up the possibility of extending the lifetime of these landers by an order of magnitude - to 20 to 25 hours making it possible to carry out missions in which scientists have time to respond to the data and make decisions on limited follow up observations rather than the totally autonomous mission of 2 to 3 hours duration. These technologies include the use of the phase change materials (PSMs) employing the liquid vapor transition in water and ammonia[14]

La**nders – Long Duration – Geophysical**

The VER calls for a vehicle capable of operation on the surface with a lifetime of one Venusian year and capable of accommodating seismology, Geodesy, temperature, pressure, wind and EM sounding experiments (Investigation D2) and also calls for a network of such vehicles (Investigation D3). Given progress in the development of high temperature electronics, a vehicle with these capabilities may be feasible in the future without the need for active cooling of part of the vehicle to temperatures near Earth ambient. However, given the limitations of high temperature electronics, by contemporary standards this will be a rudimentary observational station with the ability to transmit a stream of low rate data but not much else.

Power for such a vehicle could be provided by a radioisotope power using a thermoelectric transducer exploiting the Peltier effect. There are thermoelectric materials couples that are capable of operating under conditions where the cold junction of the devices is at Venus surface ambient.

The scope of the science that can be implemented with sensors operating at Venus ambient is still not well understood and depends on the performance of specific sensors in the Venus environment.. This topic is examined in Section 7.4

5.6 Mobile Platform – Surface or near surface

The VER calls for a mobile platform that would operate on the surface or in the lower atmosphere with a mobility range of 10s to 100s of kilometers that would analyze surface compositional variations on a regional scale. This would include conducting geochemistry and mineralogy measurements at multiple sites, remote sensing from low altitudes (<1km) and panoramic and high-resolution imaging correlated with composition.

Unlike the geophysical landers discussed above, these systems must include payload compartments maintaining temperatures at near Earth ambient for imaging instruments. Achieving high fidelity, visible imaging and remote sensing infrared measurements often requires cooling of sensors to well below Earth ambient. Operation of those sensors at Venus surface temperatures would require sensors unlike any available today and may be limited by fundamental physics. Other instruments may be operable in the range 150 to 200^{o}C. Both a power system and a cooling system that can operate at Venus temperatures will need to be developed.

The mobility range for such a vehicle is a lesser challenge although still formidable. Concepts for floating platforms capable of traversing all terrain types have been devised, however, the near surface conditions on Venus are not known. Wheeled or legged vehicles require many more mechanisms that would be vulnerable to the conditions near the surface and Issues of long term exposure to the corrosive conditions of the near surface would need to be explored. Attaining the 10 to 100 km range called for would be challenging.

6.0 SUBSYSTEM LEVEL TECHNOLOGIES

This section focuses on those subsystem elements that are critical to the implementation of the systems solutions discussed above.

POWER

6.1 Energy Storage – Batteries

Of the Mission Modes described in Table 1, many can be implemented successfully with existing technology; orbiter missions, balloon missions as well as probe and lander missions. Long duration landers are one area where technology development may be needed. If long duration landers can be implemented with sufficiently low power consumption, then batteries may be a reasonable option; this trade needs to be examined. Secondary batteries may also be required to handle peak loads in conjunction with a radioisotope power system.

6.2 Energy Generation – Solar

Remote Sensing from space with orbital missions or flyby missions can be implemented with existing capabilities. Solar power is not needed for short duration probes or landers. For landers deployed on the surface, the amount of solar energy reaching the surface is limited and the challenges of developing efficient energy converters to operate at these temperatures is so formidable that solar energy is not a practical solution. Solar cells that operate at higher temperatures generally do so at the expense of only sensing blue and ultraviolet radiation and very little of this penetrates to the surface of Venus.

Where advances in solar power technology can play a role and technology developments are needed is in the development of aerial platforms for operation in the mid-atmosphere.

- The airplane approach requires efficient, lightweight and acid resistant panels that clad – on both sides – the deployable wings of an airplane.
- Long duration balloons are less demanding since the power demands are two orders of magnitude lower and no gains in specific power are needed.

6.3 Energy Generation – Radioisotope Power

Radioisotope power can play an important part in the in situ exploration of Venus. Near the surface there is very little solar power for a long duration mission. Floating platforms may benefit from radioisotope power on the night side of Venus although trades with battery options are needed and as they approach the polar vortex radioisotope power can extend operations.

1) *Advanced Radioisotope Stirling Generator (ASRG):* The ASRG, currently under development, uses highly efficient Stirling engines coupled with linear alternators to convert radioisotope heat to electrical energy. This technology could be implemented on an aerial platform at Venus provided it uses a low ballistic coefficient entry system, such as ADEPT, to mitigate the g loads on entry.
2) *ASRG for High G:* For other entry systems, the ASRG would need to be ruggedized so that it could tolerate and operate through the entry phase. The feasibility of this has not been assessed.
3) *ASRG for high temperature*: For operation near the Venus surface a version of the ASRG capable of operating with its cold end near Venus surface temperatures of approaching 500C is needed. Research has been performed on this very challenging development but is no longer being conducted. Because this device will require high temperature electronics we have classified its technology readiness as Low.
4) *High Temperature Thermoelectric Converter:* This is an alternative to the ASRG for operation near the Venus surface. We consider its readiness to be moderate because it does not require high temperature electronics. However, the efficiency of this device will be much lower than the ASRG and it is unlikely that it would be practical for use with active cooling (see next section).

THERMAL CONTROL

6.4 Thermal control- passive

Passive thermal control was used on each of the Venera landers that operated for up to 2 hours on the surface of Venus. The elements are insulating materials to prevent heat leaking into the lander and thermal capacity and phase change materials to absorb the heat entering the lander to mitigate the temperature rise. Minimizing the heat leaks due to windows and cabling is an important part of the design process.

1) Large Landers: The readiness of this technology is very high, for lifetimes of 2 to 3 hours. As noted in Section 5.3, liquid vapor Phase Change Materials may extend this by a factor of 10 but the technology is immature. Techniques use either a water or ammonia as the phase change material and it may be coupled with a lithium getter to avoid the need to vent to the atmosphere.
2) Microprobes/Dropsondes: The major impact of technology could be in the extending the performance of these devices. At present, it is not clear how small a device could be built that would survive and operated to the surface using conventional silicon technology. A key application of deep dropsondes would be to image potential landing sites and state of the practice silicon imagers generate unacceptable levels of dark current at temperatures much above 30C.

6.5 Thermal Control - active

Following an assessment of the technology, the Extreme Environments Report of 2007 identified thermal control goals. These were updated in the Venus Flagship Mission report. There has been only limited progress towards these goals and the progress is not repeated here. A scalable and efficient powered refrigeration/cooling system to maintain temperatures at operational levels for the payload and the subsystems for extended periods of time (e.g. months)[15] is required. The current state of development is low.

EXTREME ENVIRONMENTS TECHNOLOGIES

6.6 High temperature electronics

There are several technical approaches to exploring the surface or near surface areas of Venus:

1) *Medium Temperature Semiconductor Based Electronics:* Medium temperature (200-300^{o}C) electronics not only are technically less difficult than electronics that operates at Venus temperature but also have terrestrial commercial applications. A broad set of component options, including microprocessor and memory devices exist. For *Venus surface missions*, medium temperature electronics could be used along with a Stirling-based power system/cooler The use of medium temperature electronics with cooling systems would significantly reduce the delta-T required, and hence reduce the amount of power required to achieve long-duration surface missions as compared to systems cooled to Earth ambient temperatures. These electronics could be used for aerial platforms operating in the middle atmosphere (below the cloud layer) missions, where temperatures reach values higher than can be tolerated by conventional silicon electronics. In this case, no cooling systems would be needed.

2) *High Temperature – Semiconductor based electronics.* Two material systems - Silicon Carbide and Gallium Nitride - are being developed in research efforts spearheaded at NASA Glenn Research Center. In Silicon Carbide electronics*, b*asic electronic components have been demonstrated in silicon carbide electronics with long term operation (thousand of hours at 500^{o}C). The level of complexity that is possible is closer to the early formation of silicon electronics e.g. Mercury era electronics. Memory is very limited and has relatively high power consumption. In *Gallium Nitride Electronics*, High Electron Mobility Transistor (HEMT) devices with pinch off less than 2V have been demonstrated at 500^{o}C More advanced circuits are under development that have increased complexity. Substrates, passive components and integration techniques as well as packaging require development. This technology is still at a very low level of maturity with only very small devices practical and

3) *High Temperature – Digital Vacuum Electronics:* Recent efforts in this area have exploited the properties of Carbon NanoTube electron sources which operate as field emitters without the need for a heated cathode. This field is immature but shows a great deal of potential for low-powered high-temperature memory and logic devices because, unlike semiconductors, there are no temperature dependent leakage currents to deal with[16].

6.7 High temperature mechanisms

1) *High temperature mechanisms for surface missions:* These will require development. Motors exist today that have operated for long periods at Venus surface temperatures. However feedback systems require development of high-temperature encoder systems. Many of the required mechanism components, materials, lubricants, etc. have been developed for operation at Venus temperatures. Significant materials development, along with and testing and qualification for the Venus environment is still required, especially at the system level.

2) Sample acquisition: Sample handling and caching techniques need to be tested with the mechanisms and instruments for the Venus surface environment. This includes the algorithms for control and various faults conditions.

6.8 Communications

As with Mars, we need to consider communications for the "Trunk Line" between Venus and Earth and proximity communications between assets that are well positioned to do the science and those assets, typically orbiters, that have the powerful trunk line communications capabilities

1) *Communications for orbiters*: Communications systems exist today for Venus orbiters. However, optical communications for Venus to Earth communications would enhance high data rate for the missions. A technology demonstration mission is planned that would demonstrate optical communications on a planetary mission. This is particularly relevant to the radar missions.
2) *Proximity Communications- probes, sondes and aerial platforms:* Communications systems also exist for atmospheric, or short duration surface, missions supported by a relay orbiter. Application of the Mars relay link communication protocols would enable better asset leveraging. For in situ atmospheric missions with direct to earth communications, the development of phased array antennas would greatly enhance data return.
3) *Communications on the Surface:* Surface to orbit or Earth communications systems for long duration surface missions will require significant research and development. Close proximity (2m, wired or wireless) high-temperature communication systems have been demonstrated for 24 days. Lifetimes need to be extended for long duration applications.

6.9 Guidance, Navigation and Control

Guidance, Navigation and Control (GN&C) for the orbital spacecraft envisaged here present no unusual requirement. For the in situ elements, we define GN&C to be the motion planning, sensing and vehicle control to achieve desired maneuvers in order to accomplish a specific goal. A recent assessment of GN&C technologies covers in situ missions at Mars, Venus and Titan[17]. Here, we focus specifically on the state of technology for Venus missions.

1) *Aerial platforms – velocity and attitude*: Knowledge of the velocity and attitude of the platform is important for certain scientific objectives as well as for enabling high-gain communications. Recently, developments of navigation systems for Micro Aerial Vehicles (MAVs) which use only a downward-looking camera and an Inertial Measurement Unit (IMU) to achieve real-time and onboard autonomous navigation is applicable. These systems have comparatively modest processing requirements[18]. Aerial missions with high data return requirements, or precise pointing are needed to achieve science objectives. A specific requirement is low power infrared cameras for locating surface features. These features can be used not only to localize the platform but also compute its attitude.
2) *Aerial Platforms – global localization*: Venus missions which need very precise knowledge must couple the capabilities described above with referencing to a global map of Venus. Since the global map is based on radar data and the platform will most probably use infrared imaging for localization, it will be necessary to extract features from the images in order to correct for the distinctive nature of the sensor signatures[19].
3) *Mobile platforms on Surface or in lower atmosphere*: Advanced GN&C technologies would be useful for precision landing although there is no explicit requirement for precision landing in the

missions in the Roadmap. Attitude knowledge will be needed for high gain communications from the mobile vehicle

7.0 INSTRUMENTS

This section is structured in five sections: remote sensing instruments that can be deployed on an orbiter, instruments that can be implemented on a probe or balloon and would primarily sense the atmosphere; and three categories of landed instruments. The focus group has only spent limited time evaluating the status of these technologies and so this part of the probe is quite brief.

7.1 Remote Sensing – Active

Because of the dense atmosphere of Venus, techniques that are useful to study the surface of airless bodies and Mars such as visual imaging, gamma ray detection and most applications of infrared sensing are not useful. However, radar which has been used on both NASA (Magellan) and Venera spacecraft is an effective tool for characterizing the surface. A variety of techniques have been used for characterizing the atmosphere as exemplified by Venus Express. Some early work exploring specific orbital penetrating instruments other than radar is ongoing.

7.2 In Situ – Probe and aerial platform

Many instruments needed for a variety of atmospheric probes, higher altitude aerial platforms that maintain internal temperatures well below Venus surface ambient are relatively mature. Many of the advancements needed are better described as achievable engineering challenges specific to missions or measurements rather than significant technology advancements.

7.3 In situ – Short duration landed missions

A primary focus of these missions is to carry out elemental, mineralogical and petrologic analysis on the surface of Venus. With such limited lifetimes on the surface, time is of the essence so the speed with which these measurements can be conducted is vital. Technical developments in the following instruments can have a major impact.

1) **X ray diffraction Fluorescence**: This technique measures the composition of elements and minerals in a powdered sample placed in the instrument by irradiating it with an X ray beam. **The Chemistry and Mineralogy (**CheMin) instrument on the Curiosity rover employs this technique and worked successfully but took 27 hours of integration time to analyze the mineralogy of a sample, [20]. The STDT for the Venus Flagship Mission recognized that speed of operation would be critical for a short lifetime Venus mission and identified the use of a high flux X ray source based on a carbon nanotube X ray emitter as a technology solution.
2) **Laser Induced Breakdown (LIBS/Raman).** For the Venus SAGE New Frontiers mission, a team at Los Alamos National Laboratory studied another type of instrument, which is also placed inside the lander and also measures both elemental composition and minerals. [21] A similar LIBS instrument but without the Raman mode has been successfully deployed by the Curiosity rover on Mars. They key difference is that this instrument samples remotely by sensing a beam through the window of the pressure vessel to the Venus surface and does not required bringing a sample inside the pressure vessel. The LIBS mode is degraded by the Venus environment but the Raman mode is not affected significantly. The instrument also ablates material which may help in investigating the depth of surface weathering.

3) **Fine Scale Elemental and Mineralogical Analysis**: Neither of the above instrumental approaches has the ability to identify the nature of individual mineral grains in a rock or a soils sampel as they are viewed microscopically. As the Mars 2020 Science Definition Team [22]looked at the requirements for that mission they recognized the importance for geologic objectives of fine scale imaging, fine scale elemental analysis and fine scale mineralogy. We can anticipate that similar requirements are ultimately going to be important on Venus. While these goals seems quite practical for samples brought into the pressurized chamber, the ability to do this measurements in situ, where they will be most interesting will be technologically challenging.

7.4 In Situ – Long Duration – Geophysical

Because of the severe environment, implementing geophysical measurements on the surface of Venus is a formidable challenge. It is important to be able to take advantage of the Venus environment where possible to deal with this challenge. One example is heat flow measurements. On the Earth, Moon and Mars, geophysicists have to take account of diurnal or seasonal variations in making the measurement and it requires measures in a bore hole acquired over an extended period of time. On the Venus surface, where there is little diurnal and seasonal temperature variation, a heat flux measurement can be implemented with a flux plate and from a short duration lander.

Seismic experiments is an example where measurements must be made over a long time baseline. Some work is being funded by NASA on a device that could operate on the Venus surface. However, other options, unique to Venus, may exist as identified in a workshop organized by the Keck Institute for Space Studies in 2010. It was pointed out by Lognonne[23] that because of the high density of the Venus atmosphere, coupling of seismic signals into atmospheric acoustic waves is 60 times more efficient than on the earth and they become amplified as they rise in the atmosphere and could be detected in the atmosphere as well as from orbit. This may be a powerful complement to surface seismometry. Very high temperature electronics and sensors along with instrument thermal control systems may still be needed solutions for some measurements.

7.5 In Situ – Long Duration – Mobile Laboratory

Most concepts for a long duration surface laboratory have assumed that much of the instrument would be contained in a protected volume whose temperature is controlled to near Earth ambient and where instruments developed to operate in the laboratory or in Mars like conditions could function. However, this may be unattainable. Therefore, it is important to understand what can be done with sensors that are operating at Venus ambient. The challenges for long duration geophysics missions all still apply but are even more difficult with more complex instruments. Significant thermal control achievements enabling mature sensors to be used or high temperature electronics systems, sensors, memory, etc. specific to those instruments may be needed.

8.0 FINDINGS

The following findings are preliminary. They will be updated after the Technology Forum on November 19, 2013.

1. **Entry Technology:** The thermal protection system (TPS) technology for missions involving entry into the Venus atmosphere has not been used for many decades and as a result has been lost. Two attractive options for replacing the prior technology, 3D Woven TPS and ADEPT technology, are currently under development under the sponsorship of the Space Technology Missions Directorate (STMD) with the goal of reaching TRL 5/6. These developments will not only enable

the next generation of Venus entry missions but also promise to be a stable and enduring solution and one that is not prone to premature obsolescence.

2. **Testing Facilities:** Testing facilities are important to the development of advanced TPS materials such as 3D Woven TPS and also for investigating and validating the performance of new technologies for operating deep in the Venus atmosphere. A number of facilities capable of high temperature and high pressure operations have been developed and these need to be equipped with diagnostics equipment. Larger facilities may be needed as we progress in technology development of long duration operations on the Venus surface.
3. **Landers – Short Duration:** The technology for missions with lifetimes of 2 to 3 hours called for in the VER is available now. Technologies with the promise of extending lifetimes by a factor of 10 are looking increasingly promising. Maturation of these technologies could greatly increase the capabilities of Venus surface missions and enable the operations team to respond to information from the lander while it is still operating.
4. **Landers – Long Duration**: Advances in high temperature electronics may enable long duration missions on the surface of Venus operating for periods of up to a year where the sensors and all other components operate at Venus ambient. However, the types of measurement that can be made from these vehicles will be limited.
5. **Aerial Platforms:** After more than a decade of development, the technology for deploying balloon payloads approaching 100Kg with floating lifetimes in excess of 30 days near 55 km altitude is approaching maturity. Vehicles for operation at higher and lower elevations in the atmosphere and with the ability to modify altitude are much less mature and need development. A buoyant vehicle, operating close to the Venus surface, is one option for the Regional Mobility Mission Mode called for in the VER but requires major development.
6. **In Situ Instruments:** Since the last Venus technology assessment performed in support of the Planetary Science Decadal Survey in 2011, there has been significant progress in instruments for surface geology and geochemistry. The utility of Laser Induced Breakdown Spectroscopy (LIBS) in conjunction with remote Raman spectroscopy has been demonstrated. Advances in other instruments for “rapid petrology” also appear possible spurred in part by developments underway for investigating the surface of Mars At this stage, the best approach for pursuing the scientific objectives defined by the GOI team are not clear and a workshop focused on this topic is desirable.

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