Venus Science Priorities for Laboratory Measurements and Instrument Definition Workshop Report

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National Institute of Aerospace
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Executive Summary

Over 70 scientists, engineers, and students, including several international attendees, with ties and interests in Venus exploration met on April 7-8, 2015 at the NAI near NASA's Langley Research Center to discuss two important elements of Venus exploration: instruments and laboratory experiments. The objectives of this two day event were to (1) present, discuss, and document the *status of existing and developing instrument technologies that will enable future Venus missions*; and (2) present, discuss, and document the *status and needs of laboratory experiments and data that support and enhance fundamental Venus science as well as future mission preparation*. The workshop was intended to build on the Venus Exploration Targets (VET) Workshop held in May of 2014 at the Lunar and Planetary Institute near Houston, TX. That workshop focused on Venus exploration science targets and the measurements required to answer key science questions as set forth by both the Decadal Survey and VEXAG organizations.

This workshop was structured as a highly participative event where foundational information, such as the key elements of VEXAG's Venus Exploration Goals & Objectives and Technology documents were briefed, followed by presentations and discussions within discipline-based focus groups. These break-out groups (Orbit, Surface, and Atmosphere) convened several times in order to present key points and facilitate broader discussions with the full group. The intent for full group discussions was to pay particular attention to technologies and measurements that address cross-disciplinary science questions.

An important goal of the workshop was to engage and motivate students. Therefore the planning committee strongly emphasized student sponsorship and involvement, and student travel resources were generously provided by Northrop Grumman. Participating students, both

domestic and international, played active roles in the workshop by recording notes of break-out session discussions and by presenting and summarizing information during plenary sessions.

Other highlights of the workshop included a poster session on the first morning, where participants had the opportunity to browse dozens of posters and discuss specific technologies or results of recent experiments with peers. The posters were then left up for the duration of the workshop as well as for the 12th meeting of VEXAG (Venus Exploration Analysis Group) that was held immediately following this workshop. A public lecture was organized and two internationally-recognized speakers were invited to make presentations at the Virginia Air and Space Museum in Norfolk, VA. Dr. Jim Green, Director of Planetary Science at NASA HQ, and Dr. Hakan Svedham, Principal Investigator of the European Space Agency's Venus Express Mission offered perspectives on the search for life in the solar system and achievements of the Venus Express mission, respectively.

An important result of discussions during discipline-focused breakout sessions was the identification of resources (facilities and laboratories) that can be leveraged to increase the value of existing Venus mission data and/or maximize the return of future exploration. Moreover, the discussion groups identified technologies, instrumentation, and capabilities that require further development in order to fulfill the VEXAG Venus Exploration Goals and Objectives recommendations. Table A (below) provides a summary of the readiness or capability state of instruments, facilities, and infrastructure. More detailed information is available in *Tables 1-3* that follow the main workshop report.

Table A – Status Summary of Venus Technology and Supporting Infrastructure

Instrument	Surface	Atmosphere	Orbit
IR/NIR Spectrometer	Green	Green	Green
UV Spectrometer	Green	Green	Green
Raman spectrometer	Orange	Orange	
Laser-Induced Breakdown Spectrometer	Yellow		
LiDAR	Red		Orange
X-Ray and Alpha Particle spectrometer	Green	Green	
Gamma Ray / Neutron spectrometer	Green	Green	Green
Mass spectrometer	Green	Green	
Radar/SAR		Green	Green
Radio science	Green	Green	Green
Heat sensors	Green	Green	
X-ray diffraction	Yellow		
EM sounding / Ground penetrating radar	Yellow		
Imager / Microimager	Green		
Seismometer	Orange		
Penetrometer	Green		
Pressure sensor	Green	Green	

Facility	Surface	Atmosphere
Telescopic (Radar, UV, NIR)	Green	Green
Venus environment simulant	Green	Green
Mineral/chemical spectroscopy	Green	Green

Technology	Surface	Atmosphere	Orbit
Fixed wing aircraft (powered or unpowered)		Red	
Balloon	Orange	Green	
SMA linear actuators	Yellow	Yellow	Yellow
Rotational motors	Yellow	Yellow	Green
Hinge and ball joints	Orange	Yellow	Green
Communications	Green	Green	Green
Electronics	Orange	Green	Green
Wheels and chassis	Red		
Power generation	Yellow	Green	Green
Cooling	Green		

Status key:

Green	Mature and flight ready (or, operational)		Orange	In development
Yellow	Mature but requires modification for Venus (or, operational in limited capacity)		Red	Conceptual

Executive Summary - Enabling Capabilities

Common among all discussions was the need to obtain laboratory measurements and to test instrument behavior under conditions that closely mimic those of the Venus atmosphere (pressure, temperature, and composition), including those of the surface environment. NASA has facilities at GSFC, JPL, and GRC that have varying capabilities in this regard and are available for scientific and technological investigations.

Executive Summary - The Need for Reference Data

All three discipline groups (orbital, atmospheric, and surface) concluded that interpretations of existing and future chemical data are hampered by the lack of reference spectra under Venus conditions. While many remote observations of the Venusian atmosphere have been completed from Earth-based, orbital, and in-situ stations, these data are not well-calibrated with respect to the effects of pressure and temperature modifications on spectral peak locations, widths, and intensities. Moreover, the abundances of some major species (such as N_2 and CO) in the Venus atmosphere remain relatively unconstrained. At Venus surface pressures, the chemistry of supercritical CO_2-N_2 mixtures has not been extensively studied and there is no terrestrial analog from which to develop an intuition about its behavior on Venus. By the same token, even when Earth analogs exist (such as the H_2O-SO_2 system of the upper atmosphere) the complications of gas-aerosol interactions are still not well understood.

In order to leverage the value of existing data and to adequately prepare for future missions, it is critically important to support laboratory experiments that provide reference data at relevant Venus temperature, pressure, and compositional regimes. While these developments are in progress, observations from Earth-based telescopes can continue to provide increased constraints on the relative abundances of CO, CO_2 and SO_2.

Executive Summary - Mission Planning Considerations

In addition to the need for continued laboratory measurements to provide calibration data, there was significant discussion about mission design parameters. Previous missions to Venus that have included atmospheric penetrators and surface landers have revealed a planet with dynamic processes that develop over the course of years, days, and even hours. In order to provide a significant increase in understanding of the planet, future missions need to procure highly spatially and temporally resolved data. In the atmospheric regime this means aerial platforms are needed that are highly mobile in both lateral and vertical coverage, and capable of surviving for long durations in Venus' upper and middle atmospheres. On the surface, long-lived landers are needed to provide adequate sampling time for surface geochemical analysis, for observing changing weather patterns of the lower atmosphere, and for geophysical measurements. Technologies such as high-temperature electronics, thermal management systems, and sustainable power systems are required to enable extended surface life and mobility.

Executive Summary - Instrument Development and Adaptation

These mission parameters lead naturally to the concern about flight heritage for Venus instruments. Few scientific instruments with significant flight heritage are immediately useful in the Venus near-surface environment without significant modification. These modifications would include hardening to Venus surface temperatures, hardening against Venus' corrosive atmosphere, and modification for the greatest effective use of the limited time available for operation while exposed to these harsh conditions. Adaptations to common equipment, such as x-ray, gamma ray, Raman, UV, and LIBS spectrometers, are especially important in order to enable future in-situ investigations. The NASA Homesteader Program (and other similar technology-maturation programs) is providing valuable and needed resources to bridge this gap in instrument heritage, and should be strongly supported in the future.

1. Introduction

The last five decades of Venus exploration have yielded tremendous new insights into the composition, dynamics, and history of the planet. Yet the harsh environment of its atmosphere and surface continue to preclude the thorough probing of the deeper atmosphere and long-duration observations that are needed to develop a comprehensive picture of a terrestrial body that displays complex interactions among geological processes, surface topography and materials, atmospheric weather and chemistry, solar environment, and energy sources and sinks. Missions of exploration, most recently by the ESA's Venus Express orbiter, have continued to provide ground truth observations, but precise data on fundamental observables such as surface mineralogy and major chemical species abundance of the atmosphere continue to be elusive.

To take advantage of the volumes of data about the planet that have already been produced, as well as to prudently prepare for the next generation of Venus exploration missions, the conveners of the workshop solicited presentations and facilitated discussion with scientists, technologists, and engineers of the Venus community to provide updates on the status and development efforts of laboratory investigations and instrument development. Facilities now exist to partially or fully emulate the temperature, pressure, and compositional environment of Venus ranging from the upper atmosphere down to the surface, effectively enabling *in situ* experiments that have not yet been performed during spacecraft mission operations. These laboratory experiments can provide crucial information about the chemical processes and material evolution of atmospheric gases and surface minerals, physical properties of the complicated nature of supercritical systems, and spectral calibration data. Moreover, these facilities allow for the development and performance assessment of instruments to test performance and ensure their ability to withstand the harsh operating environment for extended durations.

This report is organized by logical operating regimes of actual or potential missions to Venus, classified as "orbital", "atmospheric", or "surface". While there is much cross-over between these environments (i.e., atmospheric composition detected by both lander and orbital platforms), the functional equipment requirements and Earth-based laboratory measurements necessary to support these investigations often have very different demands. The last section of this report provides a highlight of significant overlap between these mission regimes and illustrates opportunities for laboratory experiments that have the potential to simultaneously enhance multiple Venus science investigations.

We note that the information contained in this report is primarily derived from workshop presentations and discussions, and is based upon information volunteered by presenters and participants. It is therefore not a comprehensive survey of Venus science investigations. For specific requirements for future science operations (i.e., accuracy and precision of a particular spectrometer, or sensitivity of a pressure transducer) we refer the reader to current literature and other VEXAG documents including the *Venus Exploration Targets Workshop report* (http://www.lpi.usra.edu/vexag/).

2. Orbital

In this section, we combine observations that may be made from spacecraft orbiting Venus with those made from Earth-based observations as well as fly-by missions.

2.1 Surface Thermal Emissions

The atmosphere of Venus is largely transparent to (near) infrared radiation around 1 μm in wavelength. The NIMS and VIRTIS spectrometers aboard Galileo and Venus Express, respectively, took advantage of this spectral window to map thermal emissions of the surface. These mapping campaigns enabled several science goals: observing the thermal structure of the surface as it relates to topographic features, detecting time-varying thermal emissions due to surface processes, and obtaining compositional information about surface mineralogy. Furthermore, there is intense interest in the possibility of active volcanism and any associated transient thermal emissions.

Status: Although thermal cameras have a strong flight heritage, the interpretation of emission sources is complicated by the reliance upon modeling suggesting that emissions detected near 1 μm originate at the surface rather than in the atmosphere. For mineral analysis, Fourier Transform Infrared Spectroscopy (FTIR) is a well-developed process and spacecraft instruments have a long and robust flight heritage, and laboratory measurements are easily obtained using relatively inexpensive off-the-shelf technology. However, reflectance features of Venus materials can be masked by overlapping of the black body emissivity curve, which peaks in the IR region.

Needs: The spectral character of minerals is modified by the high temperature of the Venus surface environment. Although ongoing laboratory investigations under high temperature continue to constrain the IR spectra of common surface materials, a comprehensive database is not yet available. Mineralogical information derived from orbital IR spectrometers may be enhanced by the continued production of laboratory reference spectra at high temperature (~470 C). Existing data would be further enhanced by a greater understanding of the weathering products that may be expected at the surface. Laboratory measurements of the reactions and rates of likely surface materials, and their associated 1um spectra, are needed in order to constrain orbital spectrometer results.

Emission spectra are also influenced by grain size and surface roughness. Some comparative morphology allows for the derivation of mineralogy, but reference data would help to constrain these comparisons further.

Furthermore, remote sensing of the surface of Venus is strongly dependent upon the ability to remove the effect of the intervening atmosphere. The scattering effect of the upper atmosphere clouds and lower atmosphere high-pressure gases is accounted for only in a first-order sense. Experimental constraint on this behavior, especially as it relates to the supercritical phase of CO_2 that may be characteristic of the near-surface, is necessary to fully deconvolve orbital spectral data.

2.2 Cloud dynamics

While readily observable, the dynamics and evolution of sulfuric acid clouds of the upper and middle atmospheres have not been thoroughly correlated with simultaneous measurements of the atmospheric concentration of SO and SO_2. There has also not yet been an extensive observation campaign of formation and dissipation of cloud structures as they relate to atmospheric chemistry. However, tracking of cloud tops has been successfully used to provide information about lateral motion due to atmospheric winds. LiDAR provides a method of profiling the cloud tops as well as determining cloud speed via Doppler shift from a non-nadir source.

Status: UV observations are well-suited for measuring the cloud tops, and recent advances in optical technology allows for the creation of smaller UV optics for Venus orbiters. While Earth-based observations are difficult due to atmospheric UV filtering, Earth-orbiting telescopes could make valuable contributions to cloud measurements albeit with some sacrifice of spatial resolution. It may also be possible to achieve some of these observation goals through the use of modern optics to do long-duration high altitude balloon observations from Earth.

Because the thick cloud layer on Venus provides a strong reflector, LiDAR measurements are expected to be robust to < 1 m/s. This technology is mature and requires only a power tradeoff analysis during mission design. These measurements can be made with either a directional solid state laser, such as those with flight heritage, or fiber optic guides that are under current development.

2.3 Upper atmosphere

2.3.1 Interactions with solar weather

Due to absence of an intrinsic Venusian magnetic field, the planet's upper atmosphere is strongly influenced by interactions with solar radiation. Fluorescent emissions have been detected from Earth-based observations and have been noted to correlate with solar coronal mass ejection impacts at Venus. Results from the Venus Express mission indicate that the upper atmosphere contains density heterogeneities, but little is known about their source or how they affect the atmospheric dynamics. Moreover, the SPICAV instrument detected that the mixing ratios of SO and SO_2 increase with height above the cloud layer, in contrast to predictions by existing models.

Status: UV telescopes, such as that carried on MAVEN, can be used to detect fluorescence of the upper atmosphere. From this solar-induced fluorescence, information about the physical properties of the thermosphere can be obtained. As noted in section 2.2, UV optics are a mature, flight-tested technology. In this case, mission design must take into consideration illumination angles and solar shading in order to take advantage of the instrument. IR telescopes are equally mature but higher resolution spectrometers would be able to better discriminate between SOx species.

2.3.2 Identification of major atomic species of the upper atmosphere

Using galactic cosmic rays (GCR) as an excitation source, a gamma ray spectrometer is capable of determining quantitative abundances of major elements. In the case of Venus, measurements from 60-70 km in altitude are likely to return weight percent abundances of C, O, N with a precision to +/- 1 wt %.

Status: Passive gamma ray spectrometers have a strong flight heritage and require little power and mass. Detection of minor species may require larger detectors and longer integration times, and conversely, cubesat-style missions may be enabled by current-generation small detectors.

2.3.3 Gas composition of upper atmosphere

Data from the Venus Express mission as well as Earth-based telescope observations indicate that the relative abundances of CO, CO_2, and SO_2 in Venus' atmosphere can vary measurably even on time scales as short as a few hours. The sources of these variations and their relationship to weather patterns are not yet clear.

Status: Earth-based observations from ALMA, CFHT, and IRTF observatories are capable of resolving major gas species of the Venus atmosphere. Moreover, Doppler velocimetry from these same facilities can provide constraints on wind speeds.

Needs: Temporal variations in Venus' atmosphere require long-duration and repeated observations. This requires an increase in observatory proposals, including those supported by the Solar System Observations program. Long duration balloon missions may also contribute to the temporal measurements required.

2.4 Middle and lower atmosphere

The remarkably high opacity of the Venus atmosphere presents substantial challenges to observation of the lower atmosphere and surface, but the presence of narrow spectral windows between the larger absorbance bands of CO_2 and H_2O in particular provides a means to probe specific depths of the atmosphere. These near-infrared bands, present between 0.8 – 3.0 µm, represent discrete emission locations ranging from the surface to the top of the upper cloud layer.

Status: Near-IR spectroscopic probing of the middle and lower Venus atmosphere has been very successful in the Galileo NIMS and Venus Express VIRITIS instrument campaigns, revealing cloud structure and motion, compositional information about major atmospheric constituents, and some limited insight into surface composition.

Needs: The near-IR spectral windows are now fairly well documented, with the caveat that lower atmospheric contribution to 1 µm emissivity is based upon modeling that needs to be verified with laboratory observations. This means that future spectrographic instruments can be specifically tuned to make detections within these windows. The need for new technology development is not anticipated to make these measurements from orbit.

2.5 Seismometry

The dense atmosphere of Venus results in strong coupling between surface and air. This may allow seismic ground motion to be transmitted through the atmosphere and into the ionosphere. If of sufficient energy, these waves can cause thermal emissions near 4.3 µm that may be detectable from an orbital platform. Other potential emissions around 4.72 µm (nightglow) have few alternative sources and may be even easier to detect. In addition, imaging may be able to detect the expanding pressure waves as they radiate outward from the seismic epicenter.

Status: Although some limited ability to detect seismic events from orbit has been demonstrated, this capability is largely hypothetical, especially in regard to the Venus environment. A recent Keck Institute workshop addressed this question specifically. (http://kiss.caltech.edu/workshops/venus2014/index.html)

Needs: Seismic detection from orbit makes use of IR spectrometers and imaging instrumentation that are already common payloads aboard planetary spacecraft. As with other time-dependent observations, detection of seismic events would require continuous monitoring and strategic mission planning. Moreover, the ability to reliably detect and resolve seismic events in this manner is largely hypothetical and thus requires further modeling and testing.

2.6 Topography

The 5 km^2/pixel resolution of topographic models derived from Magellan SAR has revealed a broad diversity of surface features that differ significantly from the airless surface of Mercury, the tectonics-dominated features of the Earth, and the aolian driven character of Mars. However, these static data are unable to resolve any potential modern-day surface deformation. Also, the resolution of existing topographic models is not sufficient to fully resolve small scale volcano-tectonic fabric that could provide clues to the age(s) of the surface. Topographic models at higher resolutions could also greatly assist in future mission planning especially for lander concepts.

Status: Orbital InSAR is flight-ready and does not require laboratory measurements for data enhancement.

Needs: Spurious effects from atmosphere can be mitigated via mission design for multiple passes over the same region.

2.7 Gravity

The gravitational potential field around bodies allows for probing of the interior composition. While the atmosphere of Venus precludes a low-altitude high-resolution (i.e. GRAIL) type of mission, a dual-spacecraft gravity instrument similar to the Earth-observing GRACE is reasonable. Thus, precise locating of an orbital spacecraft via 1 or 2-way radio tracking to Earth stations, optimally in concert with a gradiometer instrument, is required for a significant improvement in gravity observations. Magellan was not in a favorable alignment with Earth radio stations for much of the mission, so current gravity models of Venus have a relatively low resolution. Upgrades to tracking stations may allow for global resolution of ~ 160 km (compared to the Magellan-derived gravity models that reach only 315 km over poorly-resolved sections of the planet.

Status: Derivation of the gravity field of large bodies is in common use in planetary missions. This is due in large part to the pre-existing need for radio tracking for spacecraft tracking and control. These tracking data are enhanced with the inclusion of an ultrastable oscillator, which also has a long flight heritage.

Needs: The DSN stations have not yet completed upgrades to Ka-band telemetry. In contrast to S-band, Ka-band provides higher data rates and bandwidth as well as much more precise tracking. Optical communications may further enhance this capability by providing increased precision of Doppler tracking, especially between two or more subsatellites.

2.8 Aeronomy

The ionization of molecules and subsequent fractional loss to space of the upper atmosphere are often studied but poorly constrained. Much of the poor understanding of these processes and the physics that drives them are due to lack of a comprehensive database of atomic and molecular cross-sections. The degree to which these processes are influenced by isotopic content is also not well understood or measured.

Status: Databases of ionic cross-sections are now being assembled and made public. However, this is just the first step to determine the physics of ionization and loss. In order to better understand the orbital data that already exist, laboratory measurements of ionization and mobilization need to be completed.

Needs: Complete databases of ionic-cross sections must be generated for species applicable to the Venus environment. Additionally, in situ observations of solar weather during orbital operations are required in order to fully constrain ion mobilization.

2.9 Summary of Orbital and Remote Observations

Except for the south polar region scrutinized for over 6 years by the Venus Express polar orbiter, data obtained from previous orbiters as well as Earth-based observations have provided essentially static observations with only qualitative detections of temporally varying conditions. These dynamic processes (such as cloud formation/dissipation, winds, varying surface thermal emissivity, ionic loss to space, and evolving relative concentration of major atmospheric species) require extended and repeated observations. In some cases, these observations must be made from orbit to achieve the required precision and resolution. In other cases, increasing the cadence and duration of Earth-based telescope observation campaigns may provide sufficient data to address at least some of these questions.

Existing mission data may be significantly enhanced by the laboratory generation of quantitative data describing spectral behaviors of likely surface minerals and their weathering products as well as that of the dense lower atmosphere. These reference spectra can then be used to remove atmospheric effects and derive a better map of surface mineralogy.

3. Atmospheric

In this section, we discuss measurements that are made by spacecraft in direct contact with the Venus atmosphere, i.e. *in-situ* sampling. This may include spacecraft missions involving a primary orbital or lander mission but that also obtain data during an atmosphere grazing or terminal descent phase via an entry probe or lander, or via a long-duration flight within the atmosphere by an aircraft, balloon, or other mobile aerial platforms.

3.1 N_2 content

Although nitrogen is the second most abundant component of the Venus atmosphere, its concentration relative to CO_2 is known only to within an error of 45%. As a major component, the presence of nitrogen can have a measureable effect upon the thermal structure and heat transport behavior of the atmosphere. In particular, the behavior of nitrogen as a component of a near-surface supercritical CO_2 mixture is not well understood.

Status: Current equipment is capable of measuring N_2, with some practical limitations. The molar mass of N_2 is close enough to CO to make separation via mass spectrometer difficult. In the upper atmosphere, gamma ray spectroscopy may provide more precise measurements, and near the surface, a Raman spectrometer may also be capable of measuring absolute concentrations of N_2 and the ratio of N_2/CO_2.

Needs: As with most chemical sampling methods, there are multiple approaches to detection which may include solid state electronic gas sensors or several spectroscopic techniques. All of these technologies are mature for deployment in atmospheric conditions. Effective analysis of the absolute or relative abundances of N_2 vs. CO_2 in the Venus environment requires the identification of the most practical and efficient detection tool.

3.2 Near-surface CO_2

At mid and high altitudes, the chemical behavior of CO_2 can be modeled using a straightforward approach. However, under the high pressure and temperature of the near-surface environment, CO_2 exists in a supercritical phase. The effect of this state upon spectroscopic measurements is to flatten and broaden peaks. Constraining this behavior is critical to efforts to characterize emissions from the surface. In particular, narrow windows of 0.05 um in width that lie within the larger 0.8-1.2-um spectral band are often assumed to be free of influence from CO_2 absorption, but this has yet to be fully tested in a laboratory setting.

Status: Facilities currently exist to measure some limited set of a simulated Venus atmosphere, and work is underway to fully simulate and measure a Venus atmosphere with all major components equilibrated at high temperature and pressure. The insights gained from these synthetic experiments are likely to inform and direct future instrument development and guide the process of testing for future surface or near-surface deployment.

3.3 Aerosols/Clouds

Radiative transfer models of Venus' atmospheric thermodynamics are dependent upon the behavior of energy absorption, reflection, scattering, and re-radiation of the sulfuric acid aerosols that dominate the cloud layer. Recent results from Venus Express are suggestive of the presence of at least one other aerosol species, but identification of this and other possible components has not yet been accomplished.

Status: A pyrolizer-mass spectrometer combination has been successfully used aboard the Huygens probe to identify components of the Titan atmosphere. Development of a flight-capable nephelometer for Venus like environments, ideal for measuring the characteristics of suspended particles, is not yet complete. Raman spectrometers are flight ready and would likely be capable of determining aerosol composition, although all instruments intended to operate in the Venus atmosphere must be designed and tested for the harsh environment.

3.4 Upper atmosphere SO_2 chemistry

Above the cloud layer, the photochemistry of SO_2 is not well constrained, especially in regards to its interaction with water vapor. These dynamics are challenging even for Earth studies, but are nonetheless critical for understanding the state of the UV portion of the upper atmosphere. In addition, the identity of a UV-absorbing material has still proven elusive.

Status: Preliminary modeling of UV-driven SO_2 chemistry has been completed.

Needs: Laboratory studies, especially those that include the effects of gas-aerosol interactions are needed to verify and supplement the photochemical models. These experiments may also provide a path for understanding the nature of the UV-absorbing material. From a mission perspective, *in-situ* analysis of aerosol dynamics will require long-duration aerial platform support.

3.5 Seismic

As is the case with detection of seismic events from orbit, the coupling of the thick atmosphere to ground motion makes atmospheric measurements plausible. In this case, hypothetical observations of such events would be via infrasonic microphones or sensitive pressure transducers. In this scenario, instruments would be suspended from the atmospheric platform and corrections would need to be made for motion through clouds or background pressure gradients.

Status: The possibility of atmospheric detection of seismic events was extensively studied during a recent Keck Institute for Space Studies workshop (http://kiss.caltech.edu/workshops/venus2014/index.html) and found to be plausible, if untested. This type of detection, similar to a lander, requires a long mission life aboard a stable atmospheric platform. However, even given the harsh environment, the density of the Venus atmosphere makes this technique even more viable than in the Earth's atmosphere. Moreover, these same instruments might be used for detection of thunder, if present.

Needs: While the actual detection of seismic events via infrasonics is plausible, further modeling is required to determine the scientific usefulness of such detections. It is not known if this method could recover substantial information on the interior structure of the planet. The development and testing of a robust atmospheric microphone also requires at least minimal attention.

3.6 Atmospheric circulation and weather patterns

Wind velocity observations by Pioneer Venus and Venera probes, as well as cloud tracking by Venus Express, revealed that the atmospheric circulation has a zonal structure and is in a state of superrotation for all but the lowest altitudes. Moreover, Venus Express revealed that the velocity of the cloud tops increased globally during the duration of the orbital mission. In order to develop a comprehensive model of Venus' atmospheric circulation, long-term *in situ* observations need to be collected from mobile platforms. The precise location and tracking of these platforms, in concert with weather instrument payloads, could allow for significantly increased understanding of the whole-planet circulation state and the mechanisms that drive the observed changes.

Status: Glider and blimp-type platforms are currently being designed, and a prototype volume-controlled balloon with programmable buoyancy has been constructed. No long-lived, mobile atmospheric platform has yet been deployed in a planetary mission.

Needs: All atmospheric platforms, with the exception of descender-type craft, require further maturation and durability testing for the Venus environment. Long lived power systems and mass reduction of instruments and vehicle systems are highly desired in order to maximize lifetimes. Laboratory tests and materials for such platforms will be required.

3.7 Summary

Miniaturization and increased sensitivity of heritage instruments such as mass spectrometers will unlock new opportunities for long-duration Venus exploration. In addition, a new generation of mature optical instruments are able to conduct an increasing portion of chemical analysis with the benefit of fewer moving parts and lower power requirements than traditional approaches. In all cases (even of those with flight heritage) instruments must be tested against the expected harsh conditions of the Venus atmosphere, especially those that are likely to be encountered near the surface. Calibration of all of these instruments with a Venus reference atmosphere chemistry and physical environment provides further value and resiliency to future missions.

Further studies are needed to address the long-standing question of UV interactions with upper atmosphere aerosols, particularly SO_2. There is also significant potential for Earth-based investigations to determine the source of Venus' pervasive UV absorbing material.

The weather and circulation patterns of Venus' middle and upper atmosphere remain perplexing questions and are difficult to fully investigate without observation platforms that have a high longevity and mobility. Technology under current development could allow instruments to be carried on balloon or aircraft platforms that could profile these phenomena at a wide range of vertical and lateral locations.

4. Surface

Although it is possible to derive some data about Venus' surface and interior from remote sensing, in situ instruments at the surface can provide a level of detail that cannot be surpassed by orbital or atmospheric instrumentation. The fact that the surface of Venus is one of the most harsh and challenging environments of the terrestrial bodies means that significant engineering and mission design considerations have to be addressed in order to provide robust science observations.

4.1 Heat flow

Models of the interior dynamics of Venus, its convective state, the source of surface tectonic features, and the energy transferred to the atmosphere are all dependent upon constraining the surface heat flow. Moreover, the contribution of radiogenic heat from isotopic decay of potassium and thorium, especially in the upper crust, must also be determined in order to derive the heat budget for the planet.

Status: Penetrating heat flux detectors are impractical given the hardness of surface materials and the unlikelihood that both time and power can be expended for a drilling apparatus. Thus, a flux plate instrument deployed by armature to be in contact with the surface is the most reasonable approach. Radioisotope measurements have been made by gamma ray spectrometers aboard the Venera landers, but the precision of these data is not sufficient for present-day heat flux modeling.

Needs: Surface-deployed heat flux sensors require high heat tolerance and thermochemically resistant insulation. Gamma ray spectrometers must have higher precision than those aboard the Venera landers as well as have the capability of collecting a representative average of multiple surface rock samples.

4.2 Seismology

Passive seismic sensing is one of the most valuable methods of determining the internal structure of a terrestrial body. Thus far, the only non-Earth ground-coupled seismic stations to be deployed were during the Apollo lunar missions. As with the upcoming InSIGHT mission to Mars, wind noise is a large consideration. Unlike Mars however, the thick Venus atmosphere can be used to some advantage, since near-surface winds may couple to the ground and provide a seismic source. A recent Keck Institute for Space Studies workshop (http://kiss.caltech.edu/workshops/venus2014/index.html) completed a detailed analysis of this prospect as well as the duration and sensitivity needed for detection of tectonically-originated seismic activity.

Status: A mechanical leaf-spring seismometer had been partially developed but is no longer being actively supported. High temperature electronics that are now in development may provide a path to accelerometer-based sensors and communications needed for deployment to the Venus surface.

Needs: Detection of seismic activity, especially activity of tectonic origin, requires strong ground coupling with the seismometer as well as long lifetimes in the harsh Venus surface environment. A surface weather station is also needed in order to correlate detected signals with ambient wind activity and pressure changes. All of these are ultimately dependent upon the development of a high-temperature, solid state accelerometer with the required sensitivity needed to detect expected signals. It should also be noted that a long lived seismic station on the surface of Venus requires significant technology development beyond the sensing instrument itself. Power, communications and other systems for the supporting platform will require development and testing.

4.3 Deep crust structure

While seismology is the definitive investigation for determination of deep interior structure, electromagnetic sounding can provide insights into the structure of the upper crust, possibly including the extent of a thermal lithosphere and compositional stratification. This method of induction sounding has a relatively large depth of penetration, but due to the long wavelengths involved, requires substantial antenna loops for transmission and reception.

Status: EM sounding has not yet been deployed on planetary missions, but the technology has matured to near flight readiness. The requirements for this instrument are unlikely to change with future component development and miniaturization, due to intrinsic need for large antenna loops and a high power transmitter.

Needs: Deep structure sounding requires a long surface operational time (from several days to several months). Since this is an active instrument, it also requires a strong power source.

4.4 Shallow surface structure

Ground penetrating radar (GPR), a shallow sounding method, can resolve sharp contrasts in dielectric properties. On Venus, the dehydrated nature of near-surface materials would facilitate penetration of signal. However, the effective depth may still be limited by a relatively high iron content of the mafic rocks.

Status: GPR is a mature technology and is widely used on Earth, especially in arid environments. If the relatively high power requirements are satisfied, it could be readily integrated in surface operations.

Needs: Like deep sounding, GPR has relatively high power demands albeit for much smaller amounts of time.

4.4 Geodesy

The determination of geodetic parameters, which can provide information on planetary structure parameters such as core state and size, is not strictly a surface investigation. However, measurement of geodetic parameters requires precise tracking of features on the body's surface. Given the difficulty in observing Venus' surface from orbit, it is prudent to use landers to augment these measurements.

Needs: In order to make the best of use lander-based tracking, it is necessary to maintain operation and communications for a long mission duration. Since landers can act as "control points" for highly accurate surface tracking, more than one continuously functioning lander is preferable. However, even a single platform tracked for a full Venus day could contribute to more precise rotational parameters.

4.5 Elemental abundance

4.5.1 X-ray spectrometers such as the XRF and APXS are capable of resolving elemental concentrations in a fluoresced material. This requires the instrument to provide an x-ray and/or alpha particle source. Two modes of operation have been used in prior planetary missions. In an internal mode, samples are retrieved from the surface and delivered into a shielded test container. In external modes, the samples are either observed at a small distance from the instrument, or they are retrieved and brought to close proximity of a window transparent to x-rays, behind which sits the protected source and spectrometer.

Status: XRF instruments have been successfully operated on the surfaces of Venus (Venera 13) and Mars (MSL). However, the use of external x-ray spectrometers is limited by the inability of current detectors to isolate the signal of interest against the Venus background.

Needs: Mission design must take into consideration the risk/benefit of mechanical delivery into the protected environment of the lander versus the loss of signal when using external observation. Signal processing and detector advances may improve the viability of stand-off XRS, but through-window operation in a thick atmosphere needs further testing and validation.

4.5.2 Gamma ray and neutron spectrometers have the ability to rapidly acquire elemental spectra (especially with regard to radioactive elements) with high precision for volatiles like Cl and S. However, the cost of this precision is the careful construction of the sampling vessel and relatively high power requirements (as compared to XRS).

Status: GRNS have decades of successful flight heritage, but little history in environments as challenging as that of Venus.

Needs: Successful operation on the Venus surface requires significant modeling of neutron generation modes and expected performance of the instrument. A lander would also be required to supply the neutron source, active cooling, a protected sampling chamber, and a sample delivery mechanism.

4.5.3 Laser-Induced Breakdown Spectroscopy is a standoff technique that makes use of a pulsed laser to vaporize rock samples and in concert with a spectrometer, is able to determine elemental composition from the resulting plasma spectra. This instrument is unique in that it is capable of detecting compositional changes in the target material with (very shallow) depth, as the target is ablated by the plasma discharge.

Status: LIBS has had broad success in use aboard the ChemCAM instrument on the Mars Curiosity rover. Even in the thin Martian atmosphere however, corrections are required for the ambient environment.

Needs: The effect of the Venus atmosphere would likely be a significant challenge. Laboratory work is needed to constrain the effects of atmospheric composition, turbulence, and the largely untested effect of supercritical gases. Moreover, there is a concern about how distance, angle of incidence, and material porosity may affect signal fidelity and the ability even to ionize the target.

4.6 Mineralogy

There are a number of approaches to mineral identification that are both appropriate for Venus and that have a significant planetary mission history. The main challenge is, as with other instruments, resistance to the extreme environment and calibration for the unique atmospheric effects.

4.6.1 X-ray diffraction is often considered the gold standard for mineral identification. It also requires what are arguably the most demanding conditions for sample preparation and testing. Signal aquisition can take hours and samples must be delivered into a protected chamber and sorted in order to select those appropriate for diffraction analysis.

Status: XRD has recently been employed on the CheMIN instrument aboard the Mars Curiosity rover. This suitcase-sized device has been used to analyze soil which is delivered and seived by robotic arm.

Needs: This instrument would require significant adaptation to operate on the Venus surface. At a minimum, it would require a mechanical sample delivery system and a protected test chamber. For practical mineral analysis, it would require new development of sensitive sensors and a powerful x-ray source.

4.6.2 Raman spectroscopy makes use of the re-emission of light from irradiation of a laser source. This method can be used either in a stand-off mode through telescoping observation, or proximity mode which maintains very small distances between the laser, sample, and spectrometer. The acquisition of a spectral signal is rapid, and the laser-spectrometer system is mechanically simple and compact.

Status: A number of Raman spectrometers are in development for planetary missions, with the closest to launch being integrated with the ESA's EXOMars mission. A coupled Raman-LIBS system is in development for the Mars 2020 SuperCam instrument. Existing databases are only sufficient for identification of mineral species up to 85% accuracy, and in some cases significantly less.

Needs: For instrument development, most of the components are already well-suited for a planetary mission and only integration and testing remain prior to deployment. However, extensive work remains to be performed in order to calibrate expected data and any actual data from the surface from Venus. First, the thermal environment causes changes in the signature spectrum of typical rocks and minerals. Some work has already been done to obtain new reference spectra for near/infrared under ~500 C, and this work needs to be extended to Raman spectra. Second, the effects of the atmosphere, especially for standoff Raman, are not well understood and reference spectra need to be generated for these regimes. Specifically, the effect of turbulence in supercritical phases and the pressure/temperature induced broadening and shifting of spectral peaks needs to be quantified in order to obtain a clean target signal.

4.6.3 Visible and near-IR emissivity provide a passive, low-power method of remote detection of major mineral compositions. This instrument has a low mass, low power requirement, and does not require special considerations for sample preparation. On the surface, spectral contributions of the middle and upper atmosphere are removed, but there remains a significant concern that the dense lower atmosphere may still limit the useful width of spectral windows.

Status: The process of VNIR spectral analysis is well understood and frequently used in planetary missions. Like other spectral techniques however, the extreme conditions of the Venus surface environment modify the characteristic spectra. Laboratory investigations continue to be made to obtain a reference database of mineral spectra under ~500° C. Moreover research suggests that emissivity of high temperature surfaces may significantly affect reflectance peaks.

Needs: In order to derive robust surface mineralogy from existing orbital or future surface operations, a robust catalog of laboratory derived spectra under Venus surface conditions needs to be completed. Moreover, reference data for atmospheric contributions would significantly enhance these efforts.

4.6.4 Penetrometers are capable of detecting some limited structural characteristics of the surface material. This can include dominant grain size in unconsolidated sediment, or strength and cohesion of solid rock. On the Venera landers, single-use penetrometers were deployed, which provided some information about the regolith, but with results that may not be representative of the overall landing site. The cost of a penetrometer instrument is mainly in the mass that is needed to drop the arm (with gravity assistance) or drive the arm (if multiple sampling is required).

Status: These instruments are simple mechanical systems and require no additional further technology development.

4.6.5 Visible and near-infrared cameras are critical tools in understanding the geologic context for other collected data. With the addition of a micro-imager, remote analysis of grain-sized features is possible, which can substantially enhance understanding of flow characteristics, grain transport, weathering, and other dynamic processes.

Status: Robust optical electronic and mechanical components are currently available, and techniques that assist with auto-focusing are in a mature state of development.

Needs: While a panoramic camera would likely operate from within the protected environment of a lander, the microimager requires remote deployment with a robotic armature or alternatively, retrieval of a sample that is brought close to the imager window. In either case, robust mechanical actuators that can operate in the unprotected Venus environment are required. The motor and linear actuator components for such a system have been developed but not yet integrated into a robotics package or tested under simulated Venus surface conditions.

4.6.6 Meteorology of the near-surface environment has only been explored in a very rough sense, due to the extremely limited lifetime of descent and lander vehicles. This instrument suite includes sensors for 3-D wind velocity, pressure, air and ground temperatures, hydrogen and sulfur humidity, UV radiation, and suspended particulates.

Status: These instruments have been deployed on the surface of Mars, but no space-qualified, Venus-appropriate weather instruments currently exist. Due to the dramatically different environments, flight heritage may not represent a significant advantage.

Needs: In order to provide a deeper understanding of the Venusian weather, long-lived instruments capable of withstanding the extreme surface conditions (particularly the high temperature of 470° C) need to be further developed and tested. It may be possible to derive instruments through heritage with the REMS aboard Mars Science Laboratory.

5. Summary

Even with the volumes of data that have been returned from Earth-based, orbital, atmospheric, and surface observations of Venus, there remains a significant lack of understanding about fundamental processes and components of the planet. In order to address outstanding science questions about the history and current state of the planet, we require much more precise constraints on the chemical composition of the atmosphere and surface. Perhaps more critically, we require long-duration observations of the planet in order to start to constrain possible dynamic processes that may be responsible for often-perplexing data such as thermal and chemical changes on the surface or atmosphere during the space of only a few years.

Many instruments that could be included in future missions have a strong flight heritage, either from previous Venus missions or those to other planets. This is especially true of orbital spacecraft. However, operations within the atmosphere or on the surface for the duration that is required to obtain data with substantially enhanced scientific value, require considerable engineering and mission design considerations that are unique from most previous planetary missions. Continued development of miniaturized sensors and detectors with smaller power and mass requirements directly address these concerns, as does the further development of electronics capable of operating in at the extreme temperature and pressure conditions of the Venus surface.

Earth-based observations and laboratory investigations are also valuable and indeed critical for enhancing the value of existing Venus mission data as well as planning for future exploration. Long-duration telescoping observations, either from the ground, high-altitude, or orbit, are capable of addressing the outstanding questions like the changing SO_2 content of Venus' upper atmosphere and the dynamics of cloud formation and dissipation. Furthermore, laboratory analyses of mineralogical reflectance and emission spectra in the UV, visible, and infrared bands can leverage the orbital spectral data that has already been collected and substantially enhance and refine expectations for surface investigations. Indeed these are necessary and critical for future exploration of Venus and for addressing long-standing and yet-unresolved questions about the present and past conditions of the planet.

6. Appendix

The following tables present quick references to the state and application of existing and planned capabilities to Venus exploration. A ***Status*** of "mature" indicates that the technology or capability has been applied previously to Venus (or other planetary operations) but does not necessarily indicate that it is ready for operation in a specific environment. The ***Needs*** column provides a brief description of what may be required to mature the specific item to mission readiness. Specific technologies that provide platform capabilities are not included (i.e., high temperature electronics/mechanics or atmospheric balloons) except where they are directly required for instrument operation.

Table 1. Applications of Instruments and Technologies

Instrument / Technology	Surface Platform			Atmospheric Platform			Orbital Platform		
	Use	Status	Needs	Use	Status	Needs	Use	Status	Needs
IR/NIR Spectrometer	Mineral identification		High P-T reference spectra	Mineral identification, thermal emissions		High P-T reference spectra, atmospheric reference spectra	Surface thermal emissions, atmospheric chemistry, cloud structure, seismic airglow		Atmospheric reference spectra
UV Spectrometer				SO_2 photochemistry		N/A	Cloud structure, thermosphere fluorescence		N/A
Raman spectrometer	Mineral/molecular identification		High P-T reference spectra	Chemical species identification		Atmospheric reference spectra	N/A		N/A
Laser-Induced Breakdown Spectrometer	Atomic species identification		High P-T operations						
LiDAR	Ranging, morphology changes		Propagation analysis				Cloud structure		TRL
X-Ray and Alpha Particle spectrometer	Atomic species identification		Shielded environment, High P-T operations						
Gamma Ray / Neutron spectrometer	Atomic species identification		High P-T operations				Atomic species identification		N/A
Mass spectrometer	Chemical species identification		Operation with high P-T source	Chemical species identification		N/A			
Radar/SAR							Topography		N/A
Radio science	Geodesy		High P-T operations	Weather, Atmospheric circulation		Long-duration mobile platform	Gravity		DSN upgrade to Ka-band
Heat sensors	Temperature, Heat flow, Thermal gradient		High P-T electronics						
X-ray diffraction	Mineral identification		Shielded environment, sample delivery						
EM sounding / Ground penetrating radar	Crustal structure		High P-T operations						
Imager / Microimager	Multiscale environment characterization		High P-T operations, sample retrieval, remote boom						
Seismometer	Crustal structure		Mechanical or MEMS system						
Penetrometer	Surface structure		N/A						
Pressure sensor	Weather		High P-T electronics	Weather, Infrasonics		N/A			

Status key:

	Mature and flight ready			In development
	Mature but requires modification for Venus			Conceptual

Table 2. Applications of Earth-based Laboratories and Observations

Laboratory / Observation	Surface			Atmospheric		
	Use	Status	Needs	Use	Status	Needs
Telescopic (Radar, UV, NIR)	Topography, Thermal emissions		More targeted observations	Cloud structure, Atmospheric chemistry	Mature	More targeted observations
Venus environment simulant	Mineral stability/dynamics, Instrument performance testing		Chemical equilibrium modeling	Chemistry analysis, Instrument performance testing, Aerosol formation		Altitude chemistry profiling experiments, Chemical analysis of complex gas mix
Mineral/chemical spectroscopy	High T (or P-T) reference spectra		Larger suite of reference data, High pressure also needed?	Chemical species identification		Integration with Venus environment experiments

Table 3. Platforms and Infrastructure

Infrastructure Technology	Surface Operation			Atmospheric Operations			Orbital Operations		
	Use	Status	Needs	Use	Status	Needs	Use	Status	Needs
Fixed wing aircraft (powered or unpowered)	N/A			Mid and upper atmosphere mobility		Prototype	N/A		
Balloon	"hopper" mobility, multiple-module deployment		Upscaling, environmental testing						
SMA linear actuators	Robotic armature, mobility, sample retrieval, boom instrumentation			Gimbals, mobility			Gimbals		
Rotational motors	Robotic armature, mobility, sample retrieval, boom instrumentation			Gimbals, mobility			Gimbals		

Hinge and ball joints	Robotic armature, mobility, sample retrieval, boom instrumentation			Gimbals, mobility			Gimbals		
Communications	Telemetry, data collection								
Electronics	Sensors, control, communications								
Wheels and chassis	Mobility			N/A			N/A		
Power generation			eMMRTG, ASRG						
Cooling									