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 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.

The VILM 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 presentation and discussion 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 discussion with the full group, paying particular attention to technologies and measurements that address cross-disciplinary science questions.
An important goal 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 workshop by recording notes of break-out session discussions and presenting 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 and in the same location. 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.

Enabling Technology

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.

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 Venustian 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 N₂ and CO) in the Venus atmosphere remains relatively unconstrained. At Venus surface pressures, the chemistry of supercritical CO₂-N₂ 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 H₂O-SO₂ 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, CO2 and SO2.

**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 about the planet, future missions need to procure highly spatially and temporally resolved data. In the atmospheric regime, this means instruments 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.

**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 environment (specifically, atmospheric and surface) 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) provide 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 insight into the composition, dynamics, and history of the planet. Yet the harsh environment of its atmosphere and surface continue to preclude the long-duration observations that are needed in order to develop a comprehensive picture of a terrestrial body that displays a complex interaction between geological processes, surface topography and materials, atmospheric weather and chemistry, space 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.

In order 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 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 capable of withstanding the harsh operating environment for extended durations.

This report is organized by logical operating regimes of actual or potential missions to Venus, classified as either “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 the Earth-based laboratory measurements necessary to support these investigations, often have very different requirements. The last section of this report will provide a highlight of significant overlap between these mission regimes and illustrate 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 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.

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 near 1 um 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 may relate to topographic features, detecting time-varying thermal emissions due to surface processes, and obtain compositional information about surface mineralogy. Furthermore there is intense interest in the possibility of active volcanism with transient thermal emissions that have been attributed to such activity.

Status: Although thermal cameras have a strong flight heritage, the interpretation of emission sources is complicated by the assumption that emissions detected near 1 um originate at the surface rather than 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.

Needs: The spectral character of minerals is modified by the high temperature of the Venus surface environment. Laboratory investigations under high temperature continue to constrain the IR spectra of common surface materials. 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 CO₂ that is 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 has 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. Cloud motion can also be used to provide information about 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 small-package optics to do long-duration high altitude balloon observations from Earth.

Since 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 ratio of SO and SO$_2$ increases 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, CO₂, and SO₂ in Venus’ atmosphere can vary measurably even on time scales as short as a few hours. The source of these variations and their relationship to weather patterns is 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.

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 CO₂ and H₂O 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. No new technology development is required to mature these instruments.

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 um that may be detectable from an orbital platform. Other potential emissions around 4.72 um (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.

2.6 Topography

The 5 km²/pixel resolution of topographic models derived from Magellan SAR have 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.

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 is an important way of probing the interior composition, but the atmosphere of Venus precludes a dual-spacecraft (i.e. GRAIL) type of mission. 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 the only source of gravity data. 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 spherical harmonic models of degree and order ~110.

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.

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 is the 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.

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 observation. In some cases, these observations must be made from orbit in order 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 which 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, or balloon.

3.1 N₂ content

Although nitrogen is the second most abundant component of the Venus atmosphere, the concentration relative to CO₂ 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 CO₂ mixture is not well understood.

Status: Current equipment is capable of measuring N₂, with some practical limitations. The molar mass of N₂ 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 N₂ and the ratio of N₂/CO₂.

3.2 Near-surface CO₂

At mid and high altitudes, the chemical behavior of CO₂ can be modeled in a straightforward approach. However, under the high pressure and temperature of the near-surface environment, CO₂ 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 CO₂ 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.

3.3 Aerosols/Clouds

Radiative transfer models of Venus’ atmospheric thermodynamics is 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, ideal for measuring the characteristics of suspended particles, has been delayed. Raman spectrometers are flight ready and would likely be capable of determining aerosol composition.

3.4 Upper atmosphere SO₂ chemistry

Above the cloud layer, the photochemistry of SO₂ 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 SO₂ chemistry has been completed. Further laboratory studies, especially those that include the effects of gas-aerosol interactions are needed to supplement these models. These experiments may also provide a path for understanding the nature of the UV-absorbing material.

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.

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. It is not known if environmental hardening of these platforms, as would be required for functioning in the middle and lower atmosphere, would significantly delay development.

3.7 Summary

Of all potential instruments, a Raman spectrometer likely offers the most opportunity for needed observations. It is flight-tested, particularly well suited for measurements of the Venus atmosphere, and capable of distinguishing between major chemical species (i.e. N₂ and CO). Earth-based laboratories are capable of generating reference spectra and investigating the effects of high pressure and temperature upon those spectra.

Further studies are needed to address the long-standing question of UV interactions with upper atmosphere aerosols, particularly SO₂. 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, instruments at the surface can provide a level of detail that cannot be surpassed by orbital or atmospheric instrumentation. 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 heat tolerant flux sensors and resistant insulation. Gamma ray spectrometers must have higher precision than those aboard the Venera landers.

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
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 that with a tectonic origin, require 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.

4.3 Deep crust structure

While seismology is the definitive investigation for determination of deep interior structure, electromagnetic sounding can provide insight 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.

4.4 Shallow surface structure

This 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 widely used on Earth, especially in arid environments. However, the relatively large power requirement and low depth of penetration have resulted in it not being included as a payload instrument.

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.

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 during 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 Venus and Mars. 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.

4.5.2 Gamma ray and neutron spectrometers have the ability to rapidly acquire elemental spectra (especially with regard to radioactive elements) and 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 acquisition 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 sieved by robotic arm.

Needs: This instrument would require significant adaptation to operate on the Venus surface. At the 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
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. 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.

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.

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 wind velocity, pressure, air and ground temperatures, H and S 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.

**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 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 observation 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 would 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 missions to terrestrial bodies. 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 SO₂ 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.