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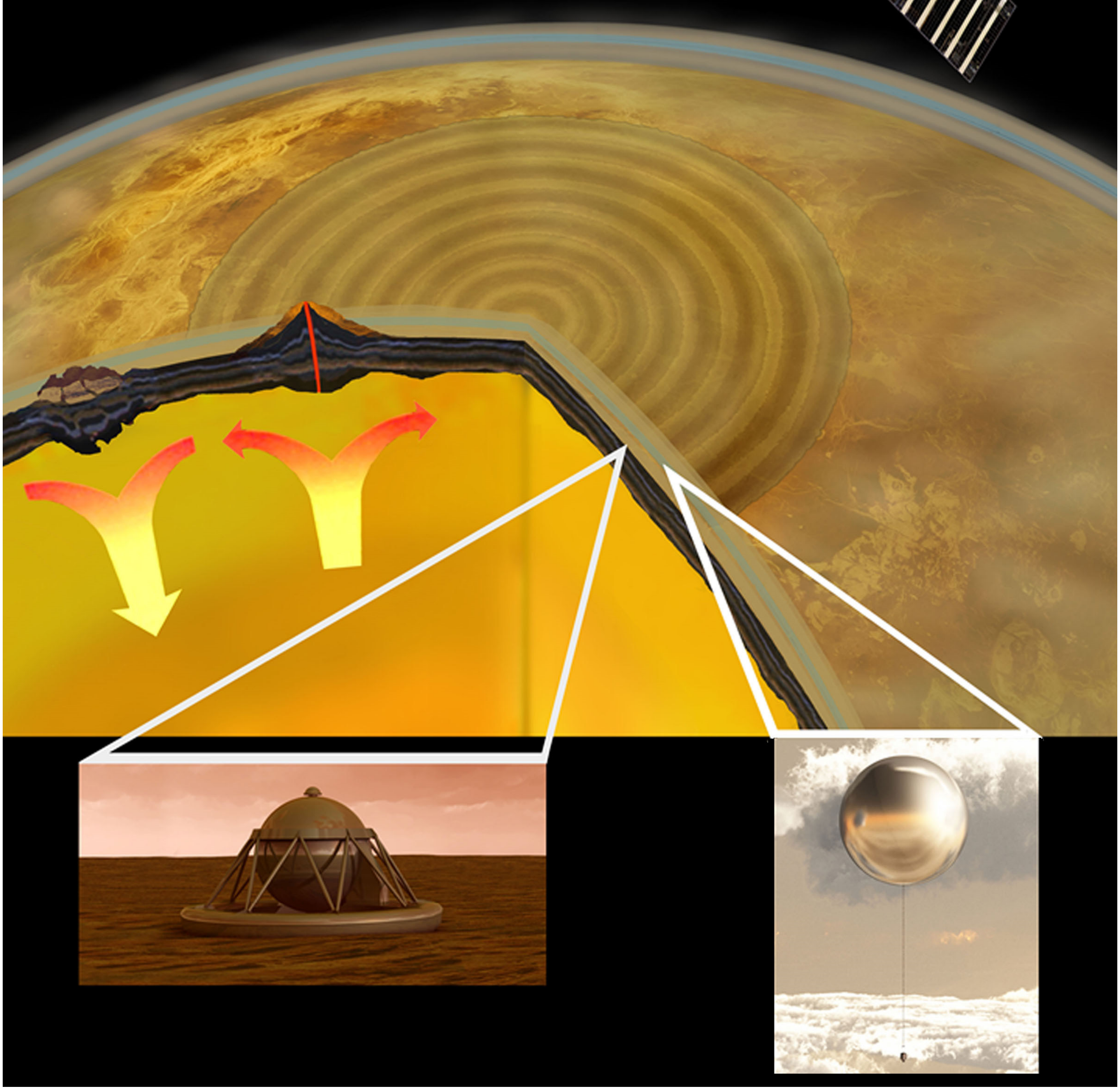
Probing the Interior Structure of Venus



Probing the Interior Structure of Venus

Report by:
Keck Institute for Space Studies (KISS)
Venus Seismology Study Team

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Executive Summary

The formation, evolution, and structure of Venus remain a mystery more than 50 years after the first visit by a robotic spacecraft. Radar images have revealed a surface that is much younger than those of the Moon, Mercury, and Mars as well as a variety of enigmatic volcanic and tectonic features quite unlike those we are familiar with on Earth. What are the dynamic processes that shape these features, in the absence of any plate tectonics? What is their relationship with the dense Venus atmosphere, which envelops Venus like an ocean? To understand how Venus works as a planet, we now need to probe its interior.

Conventional seismology for probing the interior of a planet employs extremely sensitive motion or speed detectors in contact with the planetary surface. For Venus, these sensors must be deployed on the surface and must tolerate the Venus environment (460^{o}C and 90 bars) for up to a year. The dense atmosphere of Venus, which efficiently couples seismic energy into the atmosphere as infrasonic waves, enables two alternatives: detection of these infrasonic waves in the middle atmosphere using a string of two or more microbarometers suspended from a floating platform or detection with an orbiting spacecraft of electromagnetic signatures produced by interactions of infrasonic waves in the Venus upper atmosphere and ionosphere. This report, describing the findings of a workshop, sponsored by the Keck Institute of Space Studies (KISS), concludes that seismic investigations can be successful conducted from all three vantage points—surface, middle atmosphere, and space. Separately or, better still, together, these measurements from these vantage points can be used to transform knowledge of Venus seismicity and the interior structure of Venus.

Under the auspices of KISS, a multidisciplinary study team was formed to explore the feasibility of investigating the interior of the planet with seismological techniques. Most of the team's work was conducted in a five-day workshop held at the KISS facility at the California Institute of Technology (Caltech) campus from June 2–6, 2014. This report contains the key findings of that workshop and recommendations for future work.

Seismicity of Venus: The study team first performed an assessment of the seismicity of Venus and the likelihood that the planet experiences active seismic activity. The morphology of the structural features as well as the youthfulness of the planet surface testifies to the potential for seismic activity. There is plenty of evidence that the crust of Venus has experienced stress since the relief of stress is expressed in a wide range of structural features. However, the contemporary rate of stress release is unknown and it is possible that, as on Earth, much of that stress release is aseismic. Two competing conditions on Venus will influence the likelihood of stress release. On the one hand, the lack of water would result in a larger fraction of seismic energy release; on the other hand, the higher temperatures would limit the magnitude of stress release events. Experimental measurements on candidate Venus crustal and mantle materials may help define which effect is more important.

Other Sources of Seismic Energy: Volcanic events are also a potential source of seismic waves on Venus. Unlike Mars, where volcanic activity appears to have ended, infrared orbital measurements may indicate that some volcanoes on Venus are still active. Disturbances due to large bolides impacting the atmosphere may also be recorded but are unlikely to be useful for probing the planetary interior. More useful than these point sources of energy will be energy injected into the subsurface from the dynamic atmosphere by atmosphere-surface coupling. This distributed source may be useful for probing the subsurface using the methods of ambient noise tomography.

Atmospheric Propagation: Acoustic waves from a seismic event are coupled much more efficiently into the atmosphere than on Earth. The coupling efficiency is intermediate between that for the Earth's atmosphere and the ocean. Signals propagating from directly above the epicenter or from a surface wave propagating out from the quake epicenter both travel up into the atmosphere. Because the atmosphere is primarily carbon dioxide, attenuation is higher than it would be in an atmosphere with non-polar molecules. The attenuation is frequency dependent and only impacts frequencies well above 10 Hz at the altitude of a floating platform (54 km). For observations from a space platform, it may be important at much lower frequencies to 1 mHz.

Detection from a Floating Platform: Infrasonic pressure signals emanating either directly above the epicenter of a seismic event or from the (surface) Rayleigh wave can be picked up by microbarometers deployed from a balloon floating in the favorable environment of the middle atmosphere of Venus atmosphere. Two or more microbarometers deployed on a tether beneath the balloon will be needed to discriminate pressure variations caused by an upwardly propagating surface wave resulting from the effects of altitude changes (updrafts and downdrafts) and changes in buoyancy of the balloon. The platform will circumnavigate Venus every few days enabling a survey of Venus seismicity.

Orbital Detection: Observations from a spacecraft in orbit around Venus enable a broad range of techniques for investigating the perturbations of the neutral atmosphere and ionosphere by seismic waves. Our initial analyses confirm that non-local thermodynamic equilibrium CO_2 emissions on the day side (at 4.3 μm) will present variations induced by adiabatic pressure and density variations and energy deposition created by both acoustic and gravity waves. For detection purposes, the advantage of this emission compared to other ones considered during the study (O_2 night side airglow at 1.27 μm or ultraviolet [UV] day side emission at 220 nm) is a smoothly varying background with solar zenith angle, because of a strong CO_2 absorption at this wavelength below 110 km.

Surface Detection: While important seismic measurements can be made from both balloon altitudes and from orbit, the measurement of all three dimensions of the ground motion can only be made by a sensor on the surface of Venus. However, at present, the technology for seismic experiments on the surface of Venus does not exist. Development of a seismic measurement capability equivalent to the Seismic and Interior Structure (SEIS) for the Mars InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) spacecraft is many years if not decades away. However, useful measurements of the ambient noise on the surface of Venus are feasible with existing technology and would be vital for both the design of a future seismic station with high sensitivity for teleseismic events and a pair or network of stations that could probe the interior using ambient noise tomography.

Synergistic Observations in All Three Modes: The synoptic orbital view for a remote sensing spacecraft in a high orbit would enable not only sensitive detection and localization of Venus quakes with excellent background discrimination but potentially precise measurements of the propagation of the seismic surface wave counterpart in the higher atmosphere. Complementary observations of the same event at the much higher frequencies that are possible from in situ platforms on the surface and in the middle atmosphere would greatly enhance the ability to survey seismicity and probe the Venus interior.

The Path Forward: The first step going forward is to develop the detailed requirements of the proposed payloads and to carry out related technology developments and laboratory or field demonstrations. In undertaking this process, we need to know more about the properties of potential Venus crustal and mantle rocks through laboratory studies and the potential of ambient noise tomography at Venus through analysis. Once this is done, our strategy for investigating the internal structure of Venus is built around programmatic realities—the missions that NASA, European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and the Russian Federal Space Agency (RFSA) are currently flying, are under development, or are being planned. A primary goal should be technology demonstration experiments on Venus missions where seismology is not currently an objective. These include infrasonic background measurements from a Venus balloon and infrared and visible signatures from an orbiter that might be implemented under NASA's Discovery program or as an ESA M-series mission. It would also include seismic background signals and a potential active seismic experiment from a short-duration lander such as NASA's proposed New Frontiers Venus In Situ Explorer (VISE) mission. This would be followed with a much more capable mission equipped to investigate seismicity and interior structure. The orbital and balloon platforms needed for such a mission are also features of the Venus Climate Mission (VCM), a Flagship mission endorsed by the Planetary Science Decadal Survey in 2011. The study team recommends study of a Venus Climate and Interior Mission (VCIM), which could benefit from commonalities in spacecraft systems, and secure the support of the broad planetary science community for its Flagship mission for the next decade.

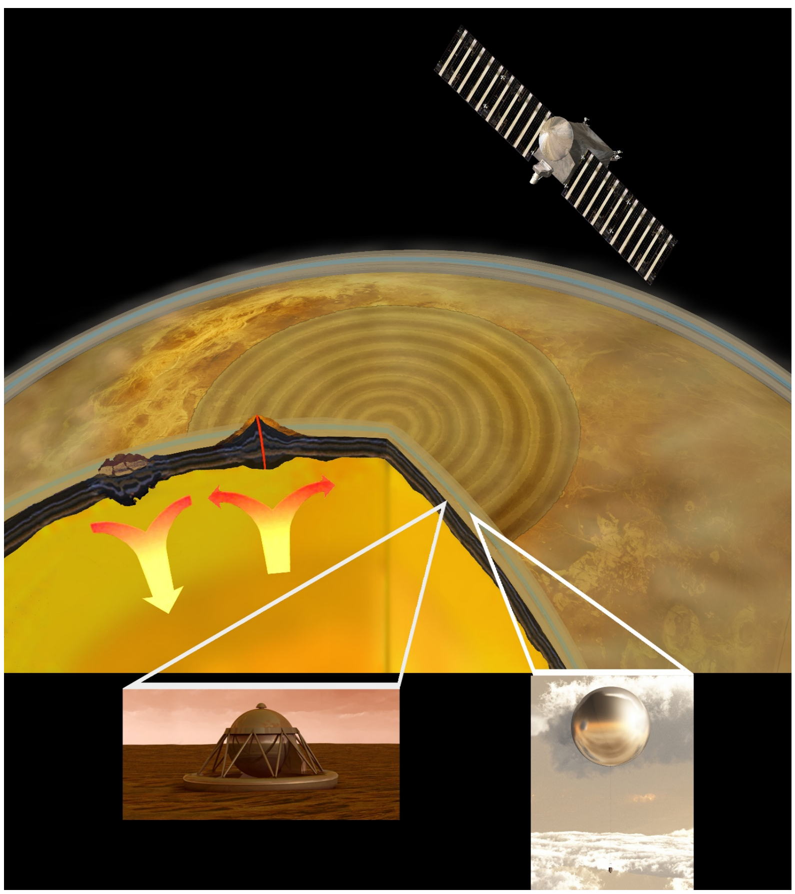

Figure ES-1. Venus does not exhibit plate tectonics but tectonic and volcanic features must reflect the structure and dynamics of the planet's interior. Seismic events can be used to probe the structure and on Venus can be observed from three vantage points. The surface platform (left) detects seismic wave in the conventional way but requires sensors and systems that operate at high temperatures for extended periods of time. The balloon platform, operating at altitude of 53–55 km at Earth-like temperatures detects infrasonic waves from Venus quakes. The orbital platform (upper right) acquires a synoptic view of the planet and detects optical and infrared signatures of seismic events.

1 Introduction

The formation, evolution, and structure of Venus remain a mystery more than 50 years after the first visit by a robotic spacecraft. Radar images have revealed a surface that is much younger than those of the Moon, Mercury, and Mars, as well as a variety of enigmatic volcanic and tectonic features quite unlike those generated by plate tectonics on Earth. To understand how Venus works as a planet, we now need to probe its interior. The growing interest in the exploration of our planetary twin, not only to understand Earth's place in the solar system but the place of Earth-like planets in the cosmos, motivates a concerted effort to determine how seismology could be implemented on Venus.

Conventional seismology for probing the interior of a planet employs sensors in contact with the planetary surface but for Venus these sensors must tolerate the Venus environment (460°C and 90 bars). With current technology, surface missions can only survive for a few hours, which is totally inadequate for passive seismic experiments. The dense atmosphere of Venus, which efficiently couples seismic energy into the atmosphere as infrasonic waves, enables two alternatives: 1) detection of infrasonic waves in the upper atmosphere using high-altitude balloons flying in a region of the Venus atmosphere where temperatures are compatible with conventional electronics, or 2) detection of the perturbation in either the atmosphere or ionosphere from an orbiting spacecraft. In the case of seismology, it appears that the dense and hot atmosphere of Venus, which generally presents an impediment to investigation of its surface and interior, may create new investigative possibilities.

Under the auspices of the Keck Institute for Space Studies (KISS), a study team was formed composed of 31 experts in all of the relevant disciplines drawn from the California Institute of Technology (Caltech), Jet Propulsion Laboratory (JPL), and eight other institutions in the United States and France. The study team includes experts in the surface, interior, and atmosphere of Venus; terrestrial infrasonics and hydrophonics; high-temperature electronics and sensing; development of seismometers for the InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission to Mars; atmospheric airglow; infrared remote sensing from space; ionospheric propagation; and space mission architecture and design.

Members of the KISS study team conducted a series of three teleconferences in May 2014 and then assembled at the KISS facility at the Caltech campus for a one-week workshop from June 2–6, 2014. The first day of the workshop featured a short course designed to bring team members up to common terms of reference with respect to the most important scientific questions about Venus, the missions and technologies that had been used in prior attempts to explore the planet, and our current state of knowledge of the three approaches to seismological investigation that we planned to explore. In the remainder of that week, the feasibility of these techniques was explored through both plenary and splinter sessions. Following the workshop, the study co-leads took the responsibility of putting together this report describing the conclusions of the study. Several independent researchers who were not involved in the original study have reviewed this report.

The results of this effort have been extremely encouraging. Based on the work performed to date, we have been able to establish basic feasibility of all three techniques. This report lays out the motivations for conducting seismology at Venus and presents an analysis of the feasibility of these techniques, as well as the major areas of uncertainty. It also defines a clear path forward beginning with low-cost precursor missions that would lay the foundation for a comprehensive investigation of the Venus interior.

2 Science

This section reviews three study objectives: 1) the nature of the Venus atmosphere, surface, and interior, as we understand it today; 2) the importance of Venus in a planetological sense and how critical it is to understanding the Earth; and 3) the vital role that seismology can play in the future exploration of Venus.

2.1 Venus—its Atmosphere, Surface, and Interior

Often known as Earth's sister planet or even Earth's twin, Venus bears a strong resemblance in some of its vital statistics (**Figure 2-1**). The planet's diameter (12,104 km) is only 6% less than that of Earth. Its mass (4.86×10^{24} kg) is 25% less than that of Earth and its escape velocity, important to space exploration and ultimately sample return, is 10.4 km/sec or 8% less than that of Earth's 11.2 km/sec. There are some profound differences between the two planets, however, including Venus' slow retrograde rotation, the vast dense ocean-like atmosphere that enshrouds it, and the lack of water. Current best estimates[1] indicate that Earth has 100,000 times as much water as Venus, which may have played a critical role in failing to develop plate tectonics and possibly determining the rate of seismic as opposed to aseismic fault motion.

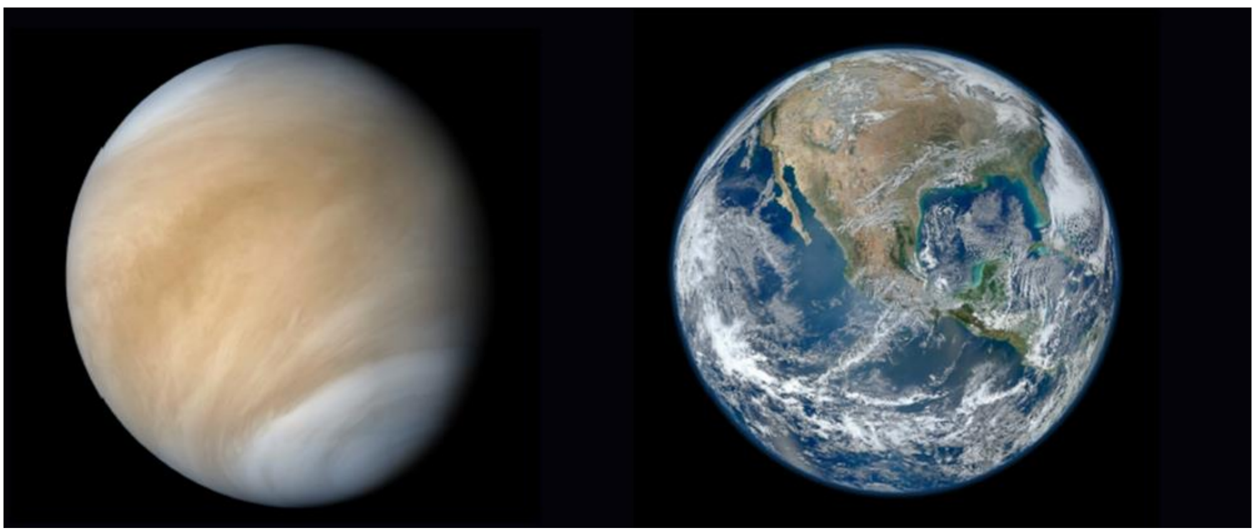

Figure 2-1. Venus is almost as large as Earth with similar mass and escape velocity. There is one big difference—Earth has 100,000 times as much water as its planetary sibling.

Because of the dense atmosphere and cloud cover, the use of visible and infrared imaging is severely constrained for observing the surface of Venus. However, radar signals do penetrate the atmosphere and a series of missions with imaging radar sensors have provided a remarkable global view of Venus including an extensive rift system. Faults and other structural features can be seen in much of the Venus radar imagery (**Figure 2-2**). Whether any of these are still active is the subject of debate. There appear to have been several episodes of structural activity. Volcanic structures are also numerous (see examples in **Figure 2-3**) and there is evidence that some of them may still be active.[2] Panoramic images of the surface of Venus obtained from the short-duration Soviet Venera landed missions in the 1970s and 1980s have added little definitive to the understanding of the surface geology. However, the KISS study team did learn that the Venera 13 and 14 missions not only obtained the first color images of the surface of Venus in 1982 (**Figure 2-4**) but also made the first attempt to detect seismic signals—a little known accomplishment, which is discussed later in this report.

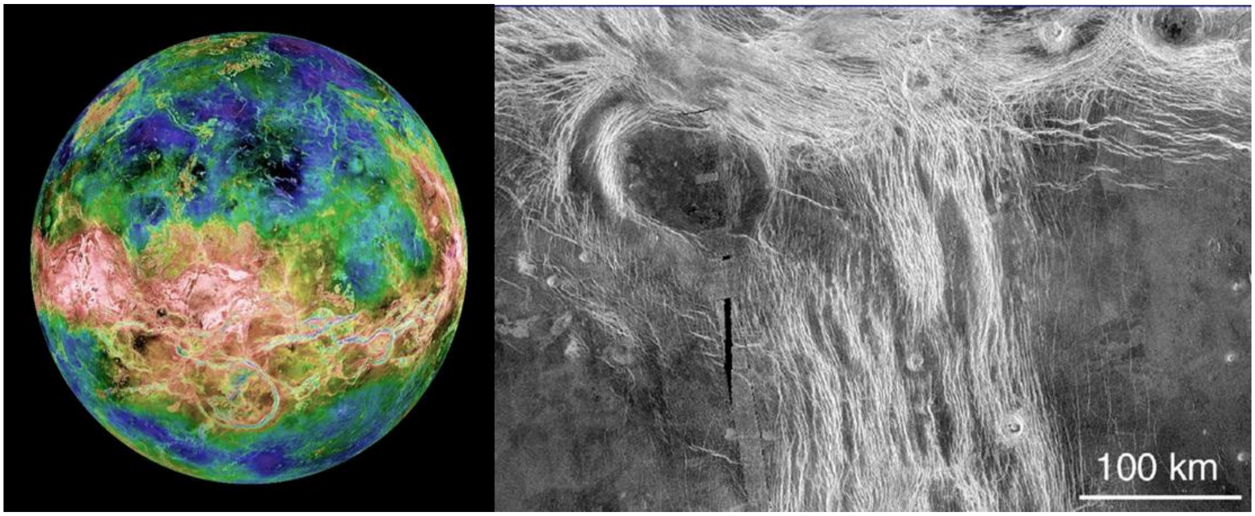

Figure 2-2. *Left:* Global radar view of Venus indicates terrain diversity and elements of the 40,000-km-long Venusian rift system. *Right:* A younger east-west rift system is seen cutting an older north-south one. (NASA Magellan imagery).

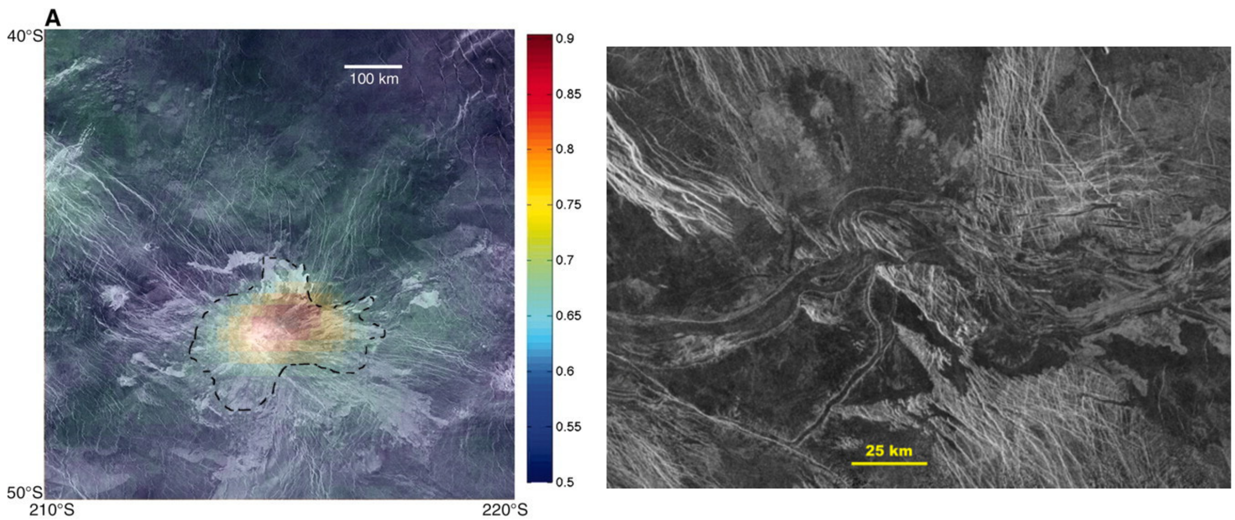

Figure 2-3. Radar views of volcanic features on Venus. *Left:* Idunn Mons (46.0°S, 214.5°E) is a candidate for an active volcano. *Right:* Kallistus Fluctus (51.1°S, 21.5°E) an area of erosive lava emplacement.

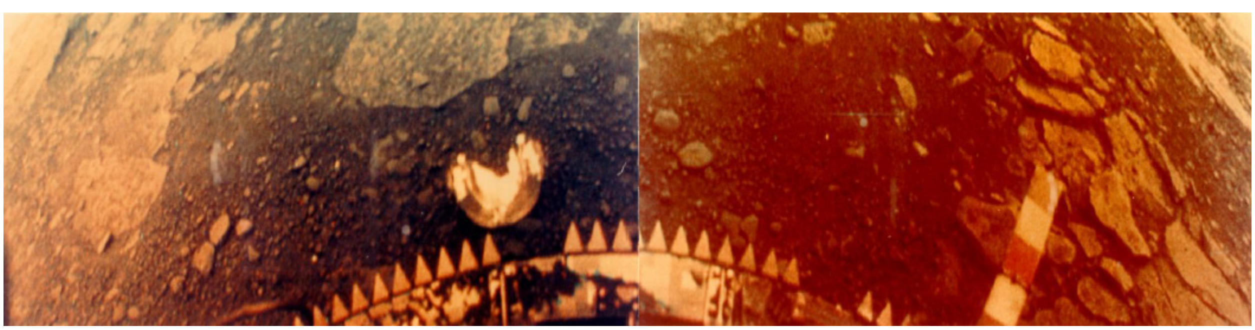

Figure 2-4. The surface of Venus from Venera 13. This mission and the companion spacecraft Venera 14 not only acquired the first color images of the Venus surface but also made the first attempts to detect seismic signals on Venus.

2.2 The Importance of Venus

We want to understand the formation, evolution, and structure of Venus as part of building an understanding of the nature of terrestrial planets and planetary systems. In particular, we want to understand the similarities and differences between Earth and Venus, both present day and through geologic time. Our understanding of how planets form and evolve and whether they do or do not lead to habitable environments is greatly enhanced if we can understand our nearest planetary neighbor. Venus has a similar size, mass, and thus mean density to Earth but is strikingly different in its atmosphere, tectonic and volcanic state, rotation, magnetic field, and lack of a moon and of a habitable environment.

Many, perhaps all, of these differences involve the nature of the interiors of these bodies and not just the atmosphere or external temperature (distance from the Sun). Moreover, the nature of the atmosphere depends on how the planet is assembled and evolved, aspects that are intimately connected to internal structure. No exploration strategy that attempts to understand the nature and evolution of Venus and of planets in general can be complete or even substantial without approaches that seek to understand the interior.

If there is one central question for Venus, it is this: *Why is Venus so different from Earth?* This question has many aspects but they all have a likely connection to understanding the interior:

1. *What determines the different atmosphere for Venus?* The standard answer for this is the runaway greenhouse effect, with Earth sequestering a similar amount of near surface carbon (~100 bars atmosphere equivalent CO_2) as carbonate rocks. But the circumstances that led to this outcome are not well understood, especially the role of water. Distance from the Sun may not be the only factor determining the state of Venus.
2. *Why is Venus (apparently) dry?* The absence of water, at least in the atmosphere and crustal rocks, is attributed to atmospheric escape, but again the history of this is unknown. Venus should have received a similar amount of water as Earth in the accretion process; we do not know whether the interior is dry. This is very important for understanding the next question.
3. *Why does Earth have plate tectonics while Venus does not (at least at present)?* The absence of internal water may have played a role but perhaps the surface temperature also plays a role by allowing annealing of the lithosphere, as recently suggested by Bercovici and Ricard.[3]
4. *What determines the volcanic and tectonic evolution of Venus. Is it currently active?* We have abundant evidence of past activity and hints or controversial indicators of current or recent activity. If Venus has transitioned from a previously more mobile lithosphere to a stagnant lid regime (as suggested by the mean age of the surface being less than a billion years), then this might be accompanied by relatively less activity and lower heat flow. The nature of the plume volcanism is not well understood; why would a planet with no magnetic field have the ability to provide the heat at great depth needed for plumes?
5. *Why does Venus have no magnetic field?* Venus is expected to have a core that is at least partly liquid, but this needs to be confirmed by geodetic or seismic observations. Our current understanding of dynamo theory suggests that slow rotation is not an explanation; indeed, it could even be an advantage. The explanation likely lies in the absence of core convection. The absence of an inner core is one possibility. Since the mantle determines the cooling of the core, absence of core convection could be related to the way the mantle is convecting, suggesting an intimate connection between the state of the core and the

nature of mantle dynamics. The state of the core might even be related to how the planet accreted, which is in turn related to its rotation state and absence of a moon.

6. *Why is Venus a slow rotator?* The standard explanation for Venus rotation appeals to the despinning due to gravitational tide from the Sun, eventually to be balanced by the thermal tide (the action of Sun's gravity on the thermal bulge raised in the atmosphere by the differential heating of the Sun). This leaves unanswered the puzzle of how Venus came to have a sufficiently low spin (of either sign) so that the solar tide could lower the spin rate down to the very low observed value. Even if the explanation by Correira and Laskar 2012[4] provides additional details on the coupling of the dynamics state of the planet with its atmosphere, we still do not know if Venus rotation is exactly constant (this is unlikely) and the length of day variations can help us understand the state of the core.
7. *Why does Venus have no Moon?* The large moon of Earth is attributed to a giant impact late in the accretion of the planet. But giant impacts are thought typical of planet formation so Venus should have had one or more similar impacts, possibly earlier in its accretion. Perhaps Venus once had a moon but lost it through ejection by a passing planetary embryo. This may also be related to the slow rotation since tidal evolution can despin Venus before the moon is lost.

The common feature of all these questions is that part and in some cases all of the answer lies in an explanation that requires us to understand the interior, a crucial part of which is seismology.

2.3 The Scientific Case for Venus Seismology

Seismology has two aspects: it is a tool to study internal structure and a means of assessing internal dynamics (sudden movements on faults). Terrestrial geophysics has taught us that seismology is an approach that is uniquely powerful in its ability to characterize internal structure. It also presents particularly severe challenges when we seek to do it for another planet and as a consequence most planetary exploration so far has not met the challenge of seismological investigation. The Apollo missions allowed for limited seismology of the Moon, and InSight is expected to do a pioneering investigation of Mars structure with a single surface station. **No combination of other geophysical measurements such as gravity, topography, heat flow, and geodesy can completely supplant the value of seismology as a tool of exploration.** There may be other methods of assessing the dynamic behavior of a planet, such as detecting surface deformations and volcanic activity but seismology offers the additional prospect of determining the thickness of the crust, presence of boundaries (phase transitions or compositional interfaces), and nature of the core. The power of seismology is further enhanced immensely when it is combined with other measurements and no geophysically oriented exploration would rely on seismology alone, but it is so powerful that one would wish to take advantage of it if possible. A key question to be examined in the next section is sources of seismic energy on Venus.

3 Seismic Sources on Venus

An essential prerequisite for conducting a seismic investigation on Venus is to determine a preliminary estimate of the seismic activity. As a matter of fact, seismic events, even though the proof of their very existence would constitute by itself a great scientific achievement, are also the source of seismic energy for generating elastic waves in the solid body of the planet. In return, the properties of those waves along their propagation path are used to determine the interior structure of the planet, as described in Section 4.

In addition, many other potential seismic sources can be expected on Venus: volcanic eruptions, impacting bolides, and atmospheric disturbances. In this section, we evaluate each of these sources in terms of its relevance to investigating the interior of Venus.

3.1 Venus Quakes

Although Venus might seem very similar to Earth (this is a close neighbor of about the same size), and, being at 0.7 AU from the Sun, was probably formed from the same sort of materials, estimating the seismic activity on Venus is a difficult exercise. On Mars, the level of seismic activity can be derived from the analysis of the fault network properties (e.g., Golombek et al.[5]): from the length of the fault and their ages, an estimate of quakes seismic moment, as a function of time, is derived. Therefore a rate of seismic moment per year can be inferred, assuming that the crust materials behave similarly on Mars and on Earth (which appears to be logical).

On Venus, such assumptions are even more hypothetical: the Magellan spacecraft has not detected morphological features such as mid-ocean rifts or clear subduction zones. Features that could be compared to continents are rare (see **Figures 2-1** and **2-2**) and the observational data do not provide sufficient evidence to support or refute plate tectonics. In addition, the high temperature of the surface and the low water content may significantly change the behavior of the crust, making it more brittle than on Earth.[6] On the other hand, the Venus surface is mainly composed of basalt, looks young, presents fault lines in several places (see **Figures 2-1** and **2-2**), and there is a high probability that volcanoes might be active.

Therefore, the consensus during the workshop was that there is a reasonable chance that significant tectonic activity still takes place; on the other hand, the unknown mechanical properties of the crust may limit the magnitude of the quakes to ~6.5.[7]

3.1.1 Active Faulting

Radar images of Venus show abundant evidence of faulting. However, evidence for current motion of these features is lacking. According to some researchers, the surface of Venus was subject to a catastrophic resurfacing about one billion years ago since this is the age recorded by the present impact crater distribution. However, because of the dense atmosphere and resurfacing by lava flows, impact craters are few and these results do not definitively prove that there has been no activity locally and in regional areas since then. The best argument for current activity is the case for recent resurfacing in the vicinity of volcanoes (see Section 3.2).

The absence of current plate tectonics and subduction zones removes a source of seismic activity from consideration that is extremely important on Earth. However, on Earth there are significant intraplate quake sources linked to lithosphere cooling; this is also one of the major source of shallow quakes on the Moon. Features such as Venus coronae could be examples of potential intraplate sources on Venus, even if nothing in the radar data demonstrates that these features are still active or not.

3.1.2 Seismic or Aseismic Strain Relief

On Earth, most faults dissipate their strain aseismically, i.e., by the process known as creep. The causes of fault creep have been the subject of much study, but are most commonly attributed to factors such as low frictional strength on the fault, the low values of normal stress acting on the fault in the shallow crust, and elevated pore-fluid pressures, which act to decrease the effective normal stress on a fault. The creep rate expressed at the Earth's surface depends on the rate of elastic strain in the lower crust, the fault's ability (or lack thereof) to resist against the building shear stress. For deep earthquakes, higher temperatures play a role in promoting creep.

On Venus, temperatures at the surface are much higher than on the Earth but the planetary surface is dry and the interior is believed to be dry although this is not conclusively known. Accordingly, there are two competing effects. The higher temperatures would appear to promote aseismic strain relief and the extreme aridity would enhance seismic activity. It is not known which effect dominates.

3.1.3 Estimates of Seismic Activity

Diverse views on the seismicity of Venus were presented at the workshop. One view was that the Venus seismicity is essentially comparable to that of the Earth, although, because of the lack of plate tectonics, it is more uniformly distributed across the planet. At the other extreme, was the view that most stress relief is aseismic, meaning there would be little if any seismic activity. The consensus view that we arrived at for planning and design purposes is that the activity is between these limits and significantly above Mars, which is both smaller in size and where tectonic and volcanic activity appears to have ceased much earlier.

In **Figure 3-1**, we compare our estimates for Venus with data on the seismic activity of the Earth and estimates for seismic activity at Mars. The Mars estimates were bases on fault counting. Also included here is an estimate made by the team developing the Venus Interior Structure Mission (VISM) in 1994, which was a concept for a radioisotope-powered and -cooled seismic experiment that would have operated for up to a year on the surface of Venus. Future laboratory work on candidate Venus rock materials at very low water contents and elevated temperatures could help clarify the degree to which aseismic deformation is present on Venus.

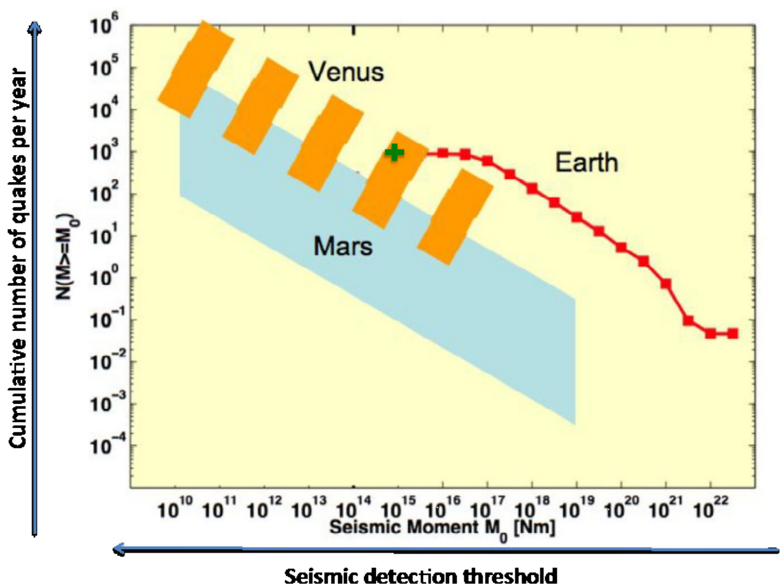

Figure 3-1. Estimate of Venus seismic activity.[7] Included on this chart are data on seismic activity on Earth, the projections for Mars that were used for the InSight mission. The VISM (green cross) was made in 1994 but since that time little new data has been collected that would change the earlier results.

3.2 Volcanic Activity

The history of Venus volcanism has profound connections with the geophysical history of Venus. With a size similar to Earth, and therefore a similar heat production, the mechanism for releasing this heat is different: plate tectonics on Earth, and a stagnant lid mechanism for Venus. There is also some degree of controversy in the possible sequence of events: ranging from a catastrophic resurfacing event such as mantle overturn or global melting, to more gradual, Earth-like processes. This volcanic history is extensively discussed in Ivanov et al. 2013.[8] But from the Magellan topographic data, it has been difficult to infer the present rate of resurfacing, and therefore, the present level of volcanic activity. However, recently, the Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on the ESA Venus Express spacecraft has provided a map of thermal emissivity Venus at 1.02 μm.[2] This map has revealed 'anomalous' thermal emissions in the vicinity of volcanic structures and Coronae (Coronae are circular volcano-tectonic features average diameter of about ~250 km, often associated with lava flows). The consensus during the workshop was that this result was significant enough to guarantee some level of tectonic activity in these regions.

3.3 Impacting Bolides

The impacts of cometary and asteroidal objects with the planetary surface played an important role in the investigation of the lunar interior with the Apollo seismic network (see Section 5) and will also play an important role in investigating the interior of Mars with the InSight mission. Unlike Mars, with its thin atmosphere, on Venus all but the very largest bolides will disintegrate in the atmosphere. The question addressed here is whether these impacts can be used as seismic sources for probing the interior.

Relevant information comes from the Chelyabinsk meteor, which struck southern Russia on February 15, 2013. The impact generated an infrasonic disturbance, which coupled into the surface and generated a seismic disturbance equivalent to a 2.7 magnitude earthquake. Seismic signatures from the quake were observed 2,000 km away. The infrasonic signals from this event were observed as far away as Antarctica.

In assessing whether bolides exploding in the upper atmosphere would be a useful source at Venus, we need to consider several factors:

1. Seismic energy from a bolide at Venus will couple more efficiently into seismic waves than at Earth because of the smaller density contrast between the atmosphere and solid surface.
2. The Chelyabinsk meteor was an extremely rare event. It is estimated to have been about 18 m in diameter, with a mass of 12,000 tons, traveling at a velocity of 19 km/sec and releasing an explosive energy of 500 kilotons of TNT.
3. Meteor impacts with the frequency relevant to a seismic experiment (1 or 2 per month) would be typically 1 m in size at Earth with an explosive energy a small fraction of a kiloton.
4. Although the flux of asteroidal objects at Venus is not known with any precision, if the frequency and energies are similar to the Earth, it is questionable that there would be sufficient energy for probing the interior of the planet.

3.4 Atmospheric Sources

Various possible sources of infrasonic energy can be imagined on Venus but it seems unlikely that enough energy can be concentrated in a single event to be a useful source. On Earth, a typical thunderstorm might involve 5×10^8 kg of water vapor, which, when condensed, would yield 10^{15} Joules equivalent to about 10 kilotons of TNT. While there is some evidence of lightning on Venus, the results are not yet definitive. However, the dense atmosphere of Venus causes strong coupling between the atmosphere and the solid Venus at long periods (see Section 4.2.2).

Given that impacting bolides are not likely to be useful for probing the interior of Venus, attention should be given to the possibility of using atmosphere surface coupling as an ambient noise source for probing the planetary interior. Claierbout[9] conjectured in 1968 that it was possible to create synthetic seismograms between any two points on or inside the Earth by cross correlating seismic wave fields measured at those two points. However, the first practical demonstration of the techniques was in helioseismology.[10]

Following further theoretical analyses (e.g., Wapenaar[11]) and laboratory experiments (e.g., Wobkis and Weaver[12]), the technique soon emerged as a common practice in seismology and has been invaluable in probing the Earth's subsurface in seismically quiescent areas. Most of these techniques have relied on surface waves excited directly at the surface but body wave synthetic seismograms have also been generated that have enabled the retrieval of Moho-reflected shear wave arrivals in seismically quiescent regions.[13] Pairs of stations are used for most of these analyses but some recent work has included analyses of what can be accomplished with single stations that will be relevant to future planetary missions.[14]

Atmospheric-surface coupling on Venus is going to create both a challenge and an opportunity for seismology at Venus. As with terrestrial seismology, it will present both a source of noise for conventional investigations using point sources and a source of signal for ambient noise-based retrievals.

3.5 Artificial Sources

Given the short life duration of some of the platforms that were considered in the workshop, it was necessary to consider active seismic experiments.[15] Some of the trades considered were an airburst vs. a ground source and the use of chemical explosion vs. a physical explosion (based on a phase change in an inert material, e.g., water). Artificial sources, however they are implemented, are typically useful for local sounding only. The bottom line issue, then, is whether any kind of active source is compatible with the highest priority science for a mission focused on interior structure.

3.5.1 Airburst vs. Ground Source

Detonating the source in the atmosphere is much simpler from a system point of view. However, there is a question about how efficiently energy would be coupled into elastic waves in the interior of the planet.

The initial shockwave is transformed into an acoustic wave depending on altitude. The distance at which this occurs will depend on the size of the event. Using the impedance relation $Z = v*\rho$, where v is seismic velocity and ρ is density, and the equation for the reflection coefficient for R, we estimate R to be 0.99. The assumptions are that $V_{atmos} = 412$ m/s, $v_{basalt} = 6000$ m/s (p waves), $\rho_{atmos} = 67$ kg/m^3, and $\rho_{basalt} = 3000$ kg/m^3.

We did not analyze the case where the shockwaves are closer to the surface and the transformation to acoustic wave has not occurred. However, the tentative conclusion is that an airburst is unlikely to be a good solution since so much of the energy is dissipated in the atmosphere. Ground coupling is critical and, if feasible, the active source should be buried.

3.5.2 Chemical vs. Phase Change Explosive Sources

Although explosive sources have been used in other missions (including manned missions to the Moon, Apollo 14, 16, and 17) and will be part of the JAXA Hayabusa 2 mission to be launched in December 2014 to investigate an asteroid, concerns were raised about the stability and risk of chemical explosives. These concerns are exacerbated at Venus where the explosion takes place on the surface and there may be mechanical shock involved in burying the source to achieve good ground contact. Accordingly, we examined exploiting the high temperature of the Venus atmosphere to induce a purely physical explosion resulting from the heating of a volatile fluid in the Venus environment.

In energy density terms, chemical explosions are the most efficient source of explosive energy. For example, TNT has an energy density of ~4×10^6 J/kg. However, for a Venus mission to a unique high-temperature, high-pressure environment, there is an interesting alternative that may have practical advantages. The concept here is to exploit a phase change involving a substance that is liquid or solid on Earth and during descent to the surface of Venus, but becomes a gas at Venus surface temperatures and pressures. The logical choice is water. A tank would be filled with water on Earth and passive heating on Venus surface would cause phase transition and massive over-pressurization.

The tank would be designed to fail at an overpressure of approximately 1,000 bars and, optimally, would be half filled with water. Under this circumstance, the temperature of the water rises as it heats up and become supercritical at about 35^{o}C and 17 MPa. It reaches the burst pressure of 100 MPa when the temperature of the supercritical fluid has reached 470^{o}C and the water has gained the maximum amount of heat energy from the environment. The total energy released is 19 GJ/m^3 or 0.5 ton TNT.

3.5.3 Discussion

The analysis above did not consider all possible sources. However, in all possible applications considered, the level of energy released remains relatively small, only permitting shallow subsurface sounding. Given the complexity and the risk to the mission involved in using chemical sources, a consensus was reached that that approach is not a priority at this stage of exploring Venus. Artificial sources in no way represent an alternative to some of the challenges involved in using natural sources of seismic energy on Venus. However, because of the simplicity of phase change sources, they may play a role in a seismic experiment from a short-duration landed mission. A small phase change device would be deployed during the final stages of descent so that it would come to rest within a few hundred meters of the lander and detonate approximately an hour after landing.

4 Seismology Techniques

4.1 Historical Perspective

If the first written accounts of earthquake recording date back to old China, the first recording of a distant earthquake (and identified as such) was made in 1889. Not long after this first detection of a teleseismic event, the study of earthquakes, which had been an observational science for centuries, shifted to quantitative physics, when, in 1906, Mohorovičić described how the difference in seismic wave propagation inside Earth could help in understanding the Earth's internal structure (**Figure 4-1**).

Today, more than 20,000 long period stations have help us achieve the current view of the internal structure of Earth, the inversion of the seismic wave velocity data giving us an unprecedented level of detail on the 3D structure of the solid Earth (**Figure 4-2**).

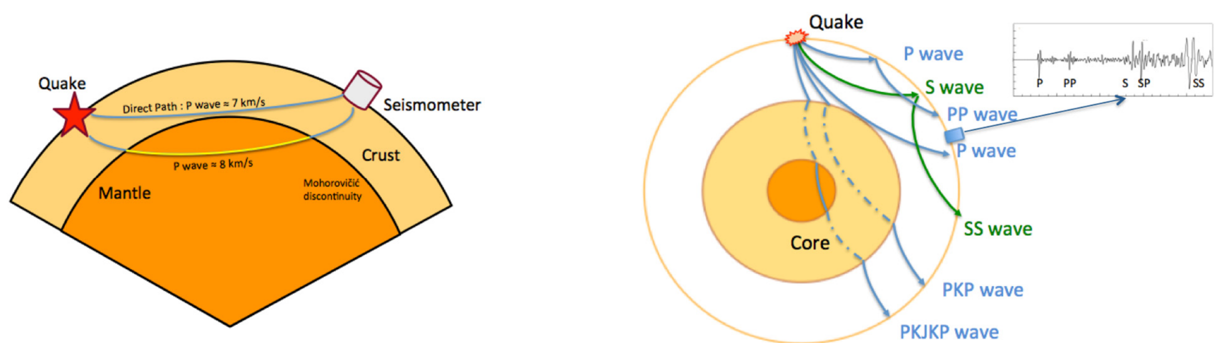

Figure 4-1. *Left:* Mohorovičić discontinuity discovery: the seismic P-wave propagates through the various layers of Earth, leading to several wave arrivals after propagation and refraction at interface boundaries. *Right:* The various waves are recorded sequentially enabling determination of the planet's structure.

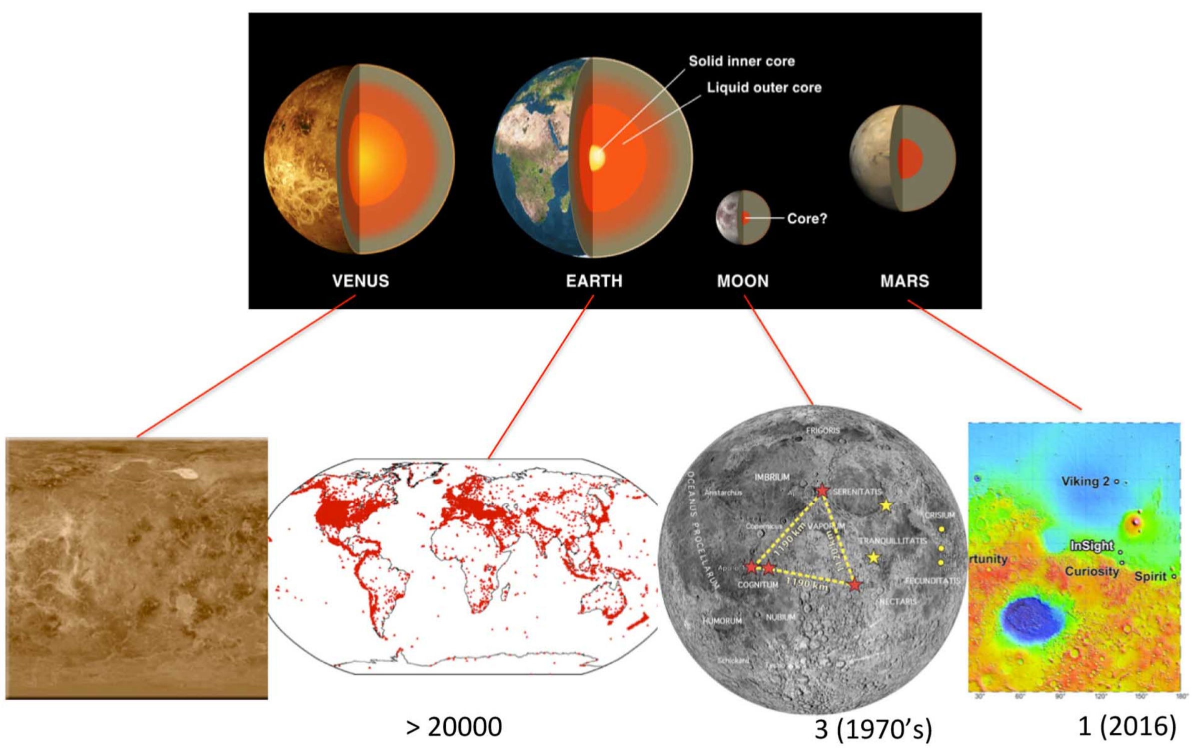

Figure 4-2. Current state of planetary seismometer networks.

By comparison, planetary seismology is in its infancy. The major success was the seismic network established on the moon by astronauts during the Apollo program. Seismometers were established as part of the Apollo Lunar Surface Experiments Packages (ALSEP) deployed at five sites (Apollo 12, 14, 15, 16, and 17) and operated from the time of deployment until 1977. Active seismic measurements were included on the later missions. The Apollo network has contributed profoundly to our current understanding of the Moon structure, and providing decisive insight leading to our current knowledge of the origin of the Moon. Although seismic sensors have been deployed on past missions to Mars and Venus, only very limited data has been returned. The next significant step is expected to be the Mars InSight mission, planned for launch in 2016.

4.2 Seismology Basics

4.2.1 Classical Seismology

Quantitative seismology uses the theory of elastic waves propagation to derive the structure of the propagation medium seen along the path. These elastic waves include compressional and shear waves that propagate into the solid part of the planet, and surface waves (Rayleigh and Love), which propagate along free surfaces. As the propagation speed of compressional waves is greater than that of shear waves, they are referred to as ‘P’ or ‘primary’, whereas shear waves are named ‘S’ or ‘secondary’ waves.

Propagation speeds also depend on the physical properties of the transmission media (density, Young modulus). In classical seismology (see **Figure 4-3**), the arrival times of the various wave paths are measured and provide constraints on the planet layering (they reflect the propagation speeds along the various layers, and the reflection/dispersion that happened at the interfaces). These data can be inverted to determine seismic wave velocity profiles as a function of depth. These seismic velocity profiles, in turn, provide constraints on material composition, based on laboratory measurements of seismic wave velocities in various materials. Of course, the parameters are also modified by pressure, porosity, lithification, and fluid saturation.

This ‘classical’ seismic ray inversion requires several stations to record wave arrivals at the same time, but they do not require a priori information on the planet internal structure. Recent

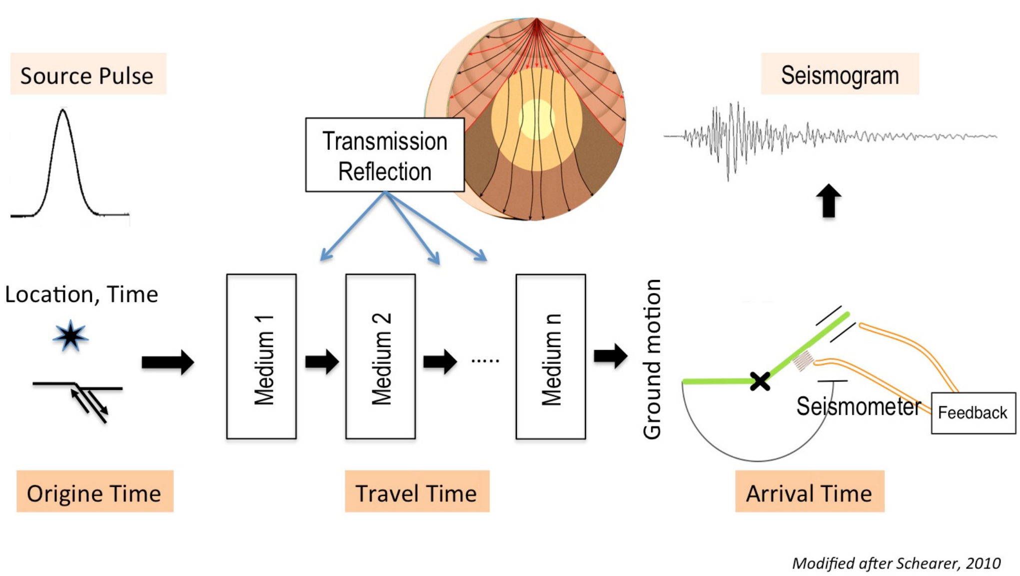

Figure 4-3. Summary of classical seismology approach.

approaches, such as the one planned for the InSight mission to Mars (see e.g., Panning et al.[16]) make use of the data of a single seismic station and of the surface wave properties to provide constraints on the internal structure. In addition, when generated by a powerful event, Rayleigh (surface) waves tend to make several turns around the Earth and develop into stationary waves that can be interpreted as resonance modes of the planet: these normal modes resulting from 'big' seismic events make the planet 'ring' for several days and provide constraints on the deep interior structure of the planet (see Gudkova et al.[17]).

4.2.2 Propagation of the Seismic Waves in the Atmosphere

For many decades (e.g., Wolcott et al.[18]), it has been recognized that Earth's atmosphere dynamics are affected by interactions with solid Earth. Volcanic eruptions are the most obvious example injecting clouds of ash into the stratosphere with climate-modifying effects. Earthquakes also produce atmospheric disturbances. Ground motion near the epicenter of an earthquake produces a broad spectral range of infrasonic waves propagating upward. Far from the epicenter, long-period Rayleigh surface waves couple at the surface to create atmospheric gravito-acoustic waves propagating upward in the atmosphere.[19,20,21]

As they propagate upward, the amplitude of these waves increases as a result of kinetic energy conservation together with the exponential decrease in the atmosphere density. For near vertical propagation, since ρv^2 is constant along the ray, the amplitude of velocity (v) increases inversely as the square root of the density (ρ). Significant perturbations in the thermosphere/ionosphere system result and, for the Earth, have been observed with a variety of ground-based and space-based techniques (see e.g., Wolcott et al.[18], Lognonné et al.[19], Occhipinti et al.[20]).

The coupling between the Venus interior and its atmosphere has been already identified as a source for normal modes excitation or a window for seismic detection by a few pioneering papers. In a comparative way between Earth, Mars, and Venus, Kobayashi and Nishida[22] estimated the amplitude of the continuous excitation of Venus normal modes while Lognonné and Johnson,[7] compared the strength of the atmospheric coupling of Rayleigh waves (see **Figure 4-4**). The detection of waves from orbital measurements was proposed by Lognonné et al. 2003[23] and Artru and Lognonné 2005,[24] and estimation of the amplitude of seismic waves has been provided by Garcia et al.[25] and Lognonné and Johnson[7] either above the epicenter or at teleseismic distances and for body waves and surface waves, respectively.

For body waves and short period surface waves and more generally for periods smaller than 10 sec, the increase in wave front velocity with altitude is moderated by competition with atmospheric attenuation. Frequency dependence of the attenuation coefficient on four planets is shown in **Figure 4-5**. Acoustic wave amplification as a function of altitude on Venus is shown in **Figure 4-6**. The attenuation of acoustic waves is a complex process (see e.g., Williams[26]); a mix of several physical processes including viscosity, heat conduction, diffusion

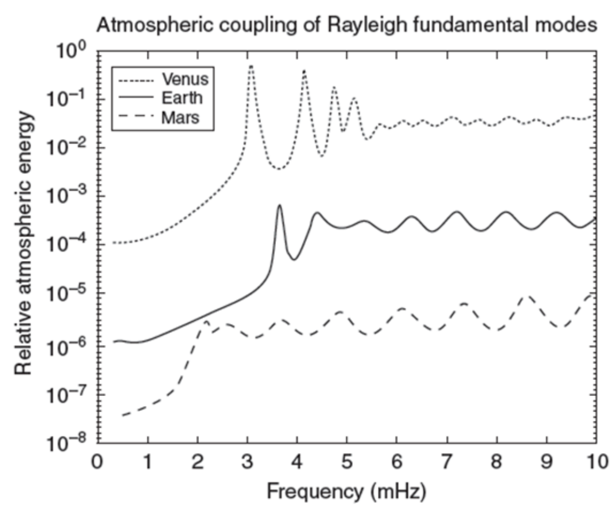

Figure 4-4. Fraction of the energy of surface waves in the Venus, Earth, and Mars atmospheres. (Reprinted from Lognonné and Johnson.[7])

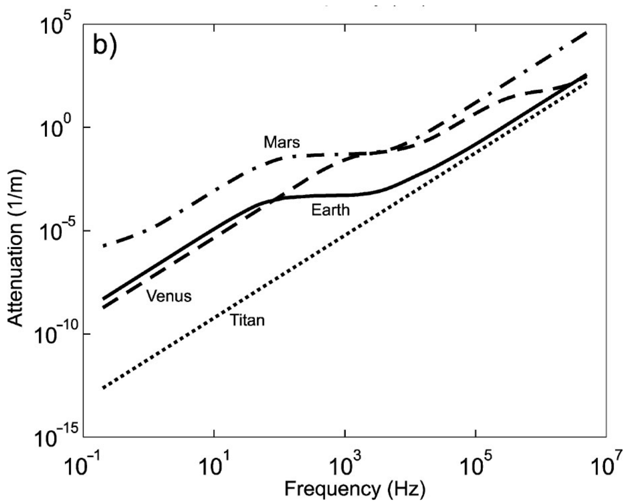

Figure 4-5. Frequency dependence of the attenuation coefficient on four planets. (Reprinted from Petculescu et al.[27])

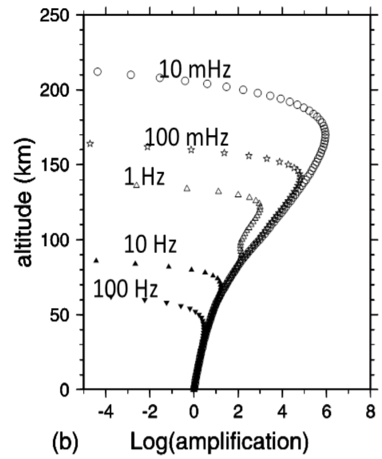

Figure 4-6. Acoustic wave amplification as a function of altitude on Venus. (Reprinted from Garcia et al.[25])

plus molecular relaxation-related absorption. Depending on the actual pressure and temperature of the considered atmosphere, large corrections with respect to ideal gas approximation have to be taken into account in 'dense atmosphere' cases (Venus and Titan).

The effects of the increasing amplification with height and the frequency dependent attenuation have been computed by Garcia et al.[25] and are shown in **Figure 4-6**. The amplification is very important, with an amplification value of ~10^6 computed for an altitude of 170 km.

One can also note that at very low frequencies (less than 10 mHz) the effects of attenuation are only experienced at altitudes above 150 km, and surface waves are therefore expected with large amplitudes at altitudes of 120–150 km and above (see **Figure 4-7**). Due to the difference in the acoustic coupling at the ground, ionospheric signals at 150 km altitude are about 100 times stronger on Venus for the same magnitude. At 20s, they would be about one order of magnitude larger. In the upper atmosphere, the motion of the atmosphere induced by the upward wave

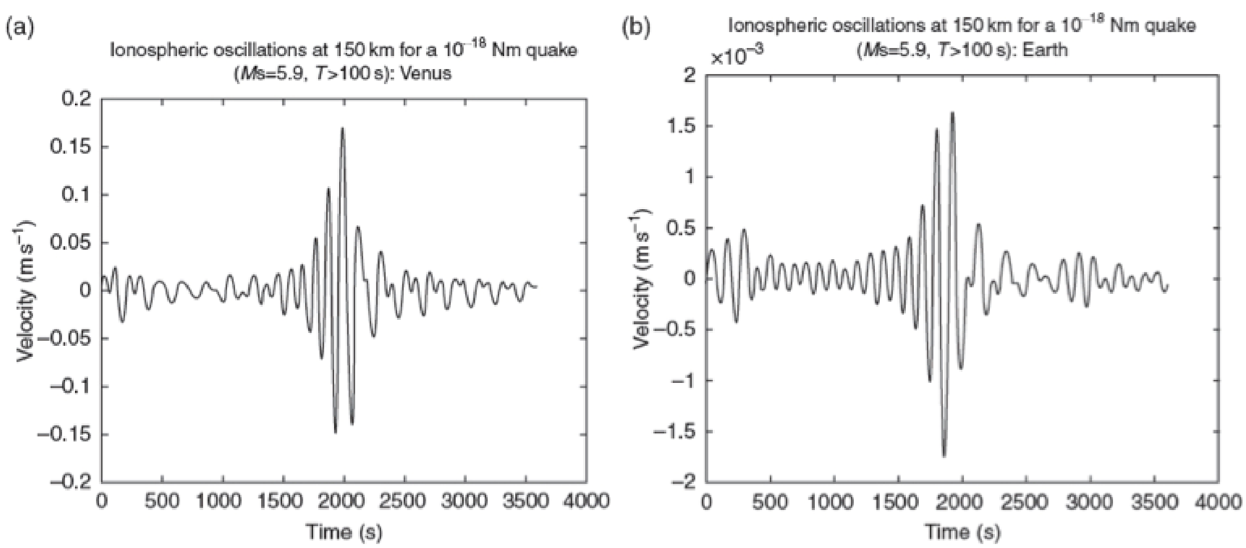

Figure 4-7. Long period vertical atmospheric oscillations, for a 10^{18} N m quake (Mw=5.9) and for period larger than 100s on Venus (a) and on Earth (b). (Reprinted from Lognonné and Johnson.[7])

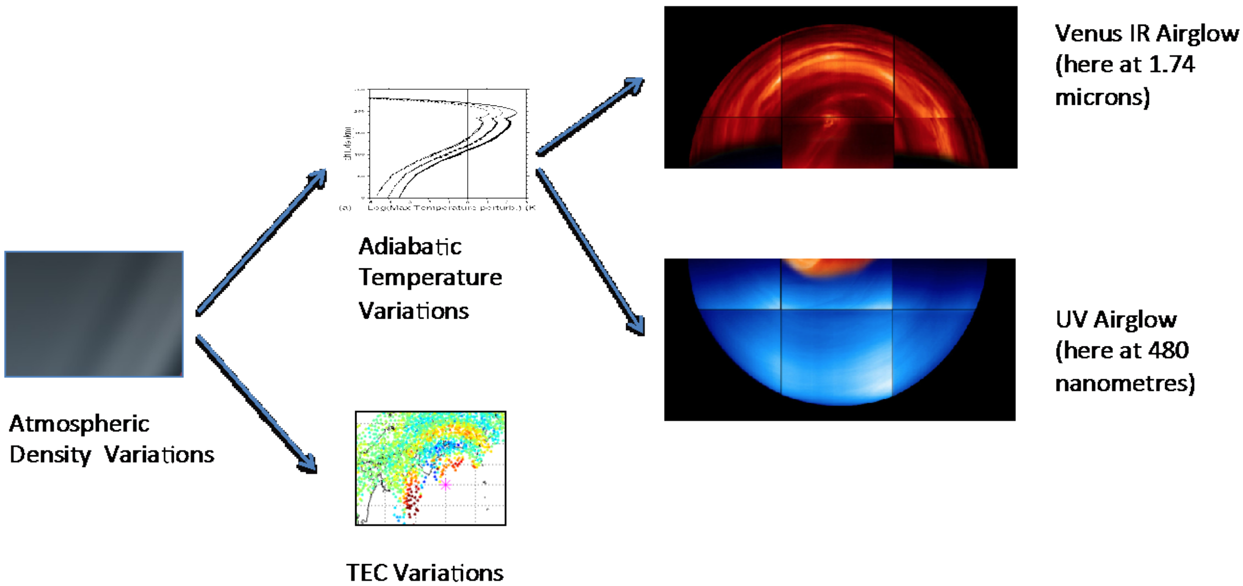

Figure 4-8. Simplified 'cascade' of physical events in the upper atmosphere.

travelling first has an impact on the neutral atmosphere but then induces changes in the local temperature and species ionic equilibrium. A cascade of physical events arises (see **Figure 4-8**) and the resulting changes in the physical parameters of the upper atmosphere such as pressure, total electron content (TEC), or even the modulation of airglow emission, can be used as a tracer of the seismic wave.

If the atmospheric density variation, such as the one on Earth with the GOCE (Gravity field and steady-state Ocean Circulation Explorer) or GRACE (Gravity Recovery and Climate Experiment) satellites, (see Garcia et al.,[28] Yang et al.[29]) remains small and is not detectable without great attention, the state of the ionosphere equilibrium can be monitored through the changes in the TEC variations (Rishbeth and Garriott[30]).

The local temperature increase also excites the airglow emission of local chemical species, such as O_2 (infrared [IR] Airglow) and CO, CO_2 (UV Airglow). Airglow is an electromagnetic radiation located in the UV, visible, and infrared spectrum. It is generated by the de-excitation of atoms and molecules spread over certain layers in the atmosphere (see Garcia et al.[28]). Airglow emission testifies for the evidence of the relaxation of ionic species (O_2, CO, CO_2) subsequent to local temperature variations.

4.2.3 A 'Generalized' Seismology Approach

Since coupling of seismic energy into the atmosphere is very efficient on Venus and since the amplification of the signal amplitudes with height in the atmosphere is also very important due to the sharp decrease of the pressure as a function of the altitude, we are not limited to measuring seismic signatures in the high-temperature surface environment.

Balloon platforms in the middle atmosphere in the 55–70 km altitude region, where the atmospheric pressure and temperature are near Earth ambient, could measure the infrasonic disturbance directly as pressure fluctuations. Spacecraft orbiting Venus could measure other signatures resulting from the disturbances higher in the thermosphere and ionosphere (see **Figure 4-9**).

We can therefore envision 'flying' seismometers attached to balloons in the Venus atmosphere, or orbiting seismometers around Venus.

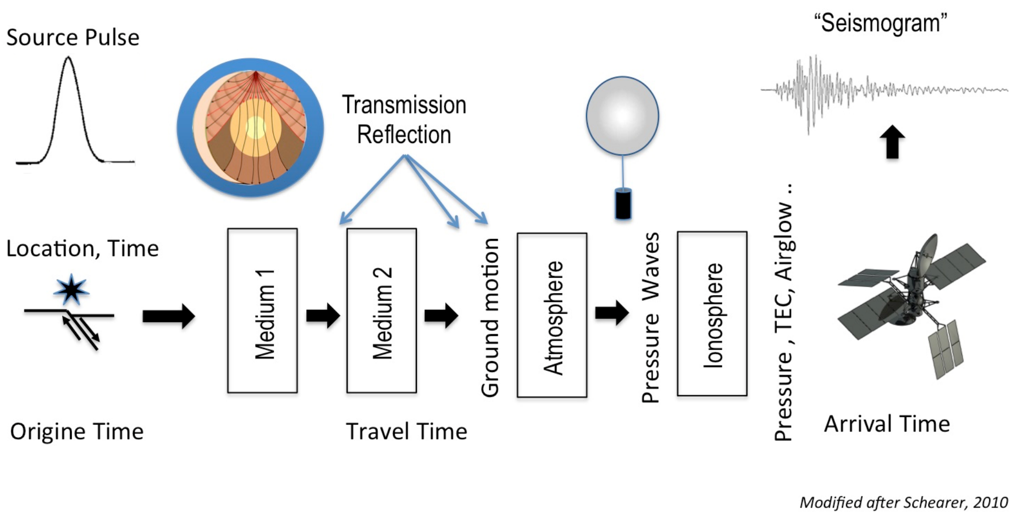

Figure 4-9. Transmission of the signal from a seismic event to a point of observation on the surface, in the atmosphere (balloon) or in space (orbital spacecraft).

4.3 Surface, Middle Atmosphere, and Space Vantage Points

In the next three chapters, we perform an assessment of the feasibility of investigating the interior of Venus using seismology techniques implemented with landers on the surface, with balloons in the middle atmosphere and with an orbital spacecraft. The focus is on understanding the ability to detect signals and to separate them from background noise. This provides the framework for formulating actual spacecraft missions to make the needed measurements.

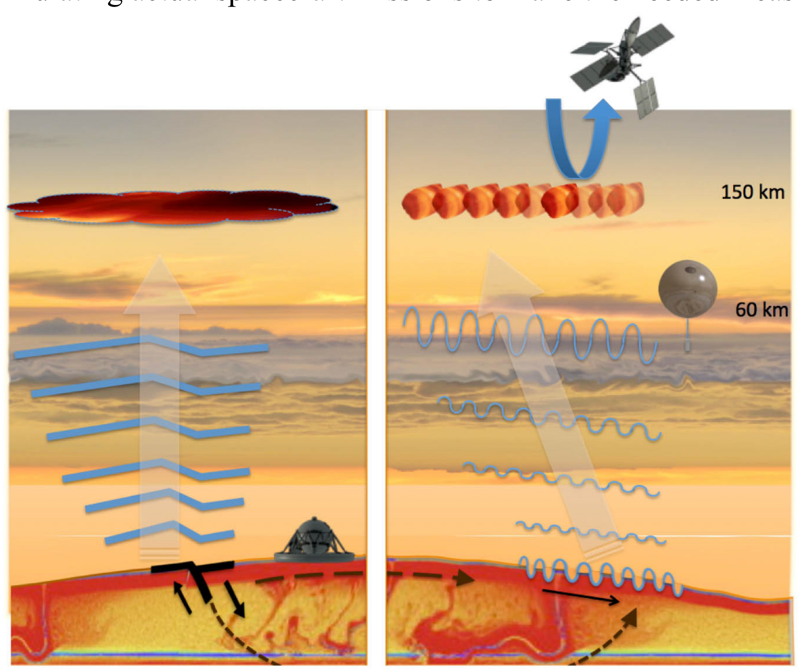

Figure 4-10. Propagation of seismic waves from source to point of observation. Waves propagate directly upward above the epicenter and also propagate as Rayleigh waves, which couple into infrasonic waves with increase in amplitude as they travel upwards in the atmosphere.

5 Seismology on the Venus Surface

This section examines the feasibility of performing scientifically productive seismic investigations on the surface of Venus. It begins with a review of the relevant experience from seismic experiments on the Moon, Mars, and Venus, continues by defining performance requirements for Venus seismology, identifies the status of the needed technologies, and concludes with a roadmap for surface seismology at Venus.

5.1 Prior Planetary Surface Seismic Experiments

While investigating another planet's internal structure dates back to the Ranger missions, clearly the most ambitious experiments with surface seismometers were conducted on the Moon during the Apollo era. The attempts so far on Mars and Venus have neither been as ambitious or successful although the InSight mission, which is dedicated to the investigation of the interior structure of Mars, is planned for launch in 2016, with a payload unambiguously focused on seismic measurements.

5.1.1 Lunar—Apollo Lunar Seismic Experiments

Although the first Apollo Passive Seismic Experiment package deployed on the Moon did not survive the lunar night, the next packages deployed by the Apollo astronauts were highly successful; the Apollo seismic network, which was composed of four stations (at the sites of Apollo 12, 14, 15, and 16) remained operational for more than five years until September 1977. Although not primarily focused on geophysics, the Apollo missions were conceived with specific constraints in mind, and the ALSEP packages were positioned well away from the lunar descent modules and nuclear power sources in order to avoid any source of disturbance, such as the radiated heat or the leak of the remaining propellant. Active seismic experiments were also conducted from Apollo but are not discussed further in this report.

The Apollo seismic network recorded 28 powerful shallow moonquakes between 1972 and 1977—some of them registering up to 5.5 on the Richter scale. The analysis of these impacts gave unprecedented insight into the internal structure of the Moon. It also recorded about 300 meteorite impacts/year as well as the signatures of the impacts from spent Saturn IVB and lunar module ascent stages. In addition, the network detected astronaut operations on the Moon, including motion of lunar rovers as far away as 5 km from the sensors. On the Moon, there are no wind disturbances, but background signals ('thermal cracks') attributable to diurnal thermal expansion of the surface and near surface layers were observed. The seismometer also detected the release of residual propellant on the lunar module.

5.1.2 Mars—Viking 1 and 2

Both the Viking 1 and 2 spacecraft, which landed successfully on Mars in 1976, carried seismometers. Unlike the seismometers of the Apollo network, they were not deployed to the surface but were mounted on top of the lander platform where they were more susceptible to wind and lander vibration. The seismometers were three-axis instruments with an instrumental sensitivity of 10^{-6} m/s^2/√Hz at 1 Hz and 10^{-5} m/s^2/√Hz at 0.1 Hz. The Viking 1 seismometer was not released from its caging mechanism on landing and so only the Viking 2 instrument collected data.

Based on the instrument sensitivity and the results of ground tests it was estimated that the Viking seismometer would be able to detect events with m_b=5 at 900 km and m_b=6 at 5,300 km

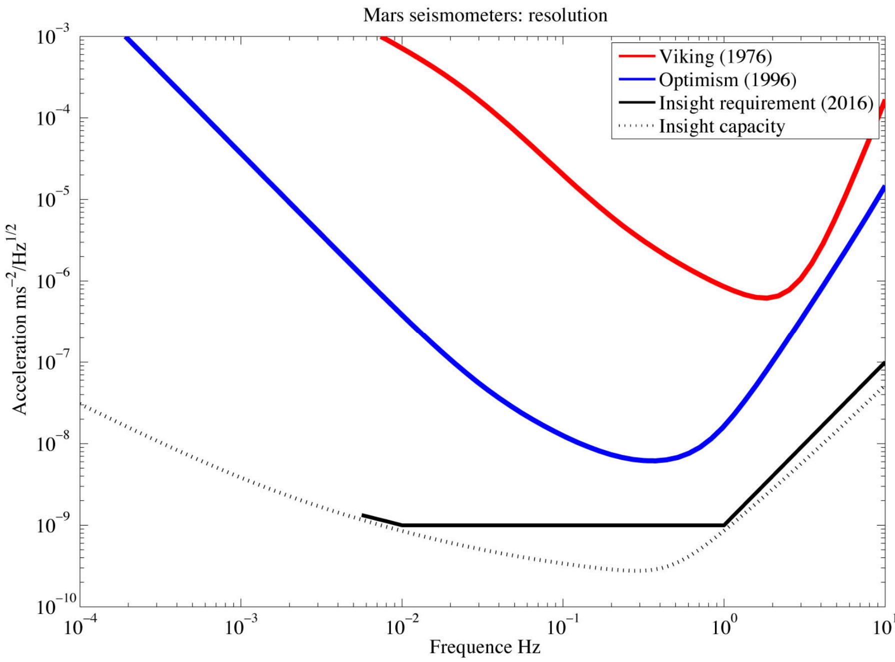

Figure 5-1. Compared sensitivities of Viking seismometer (1976); Optimism, onboard unsuccessful (1996); and InSight (2016).

distances (**Figure 5-1**). The mission had the capability to detect approximately three events a month if Mars had an Earth-like level of seismicity.[31,32]

An initial objective was to determine the level and nature of the background noise. Although under calm conditions, the background noise was close to the instrument limits, the instruments routinely detected wind gusts. Operation of the lander tape recorder and surface sampler also resulted in signals as well as impulsive events that varied diurnally with the thermal cycle. Given the unknown nature of the Mars quakes and the difficulty of discriminating between a Mars quake and atmospheric signals, no unequivocal Mars quake event was observed over the duration of the mission.

5.1.3 Venus—Venera 13 and 14

The Soviet Union's Venera 13 and 14 carried an experiment called Groza 2 that included both a microphone and a seismometer. While the results from the microphone experiment have been well known in the West for many years, the seismometer results were not known to U.S. scientists until recently[i] and were first widely discussed at this workshop. The instrument was a single-axis seismometer with a vertical sensitivity better than 1 µm (as described in Ksanfomaliti[33]). The seismic sensor was not coupled directly to the surface but was located on the landing ring, which sat directly on the surface. The goal of the very short lifetime missions (~2 hours) was to determine the level and nature of background noise or microseismic activity on Venus.

[i] Ralph Lorenz made the workshop participants aware of these measurements and distributed copies of an English translation of the original paper. He was made aware of it by Colin Wilson of the University of Oxford. Lorenz met with Leonid Ksanfomaliti in Moscow in August 2014 to discuss the instrument. Unfortunately, the original data could not be located. It is possible that an example of the instrument can be inspected in the Museum at IKI, but a visit could not be arranged at short notice. Dr. Ksanfomaliti speculates that the signals recorded could have been the ground settling after the heavy landing. He also recalled that when the instrument was tested at IKI, it was found to be sensitive to anthropogenic noise, notably the public transport outside IKI, and proper sensitivity testing had to be conducted in a remote, quieter location.

Some signals were recorded during the short lifetimes of both the Venera 13 and 14 experiment (2 hours) (**Figure 5-2**), but due to the strong thermal variations of the probe during the period of recording equilibration with its environment, it is not clear whether the recorded signals were linked to the thermoelastic relaxation of the structure of the probe, the impact of small pebbles (wind was particularly high at that time), or due to real seismic activity. As in the Viking case, perturbations possibly coming from the lander and or the wind have cast doubt on the validity of measurement, particularly as the microphone has recorded no correlated sound. Wind speeds of between 0.3 and 1.0 m/sec have been inferred using the microphone on the Groza 2 experiment.

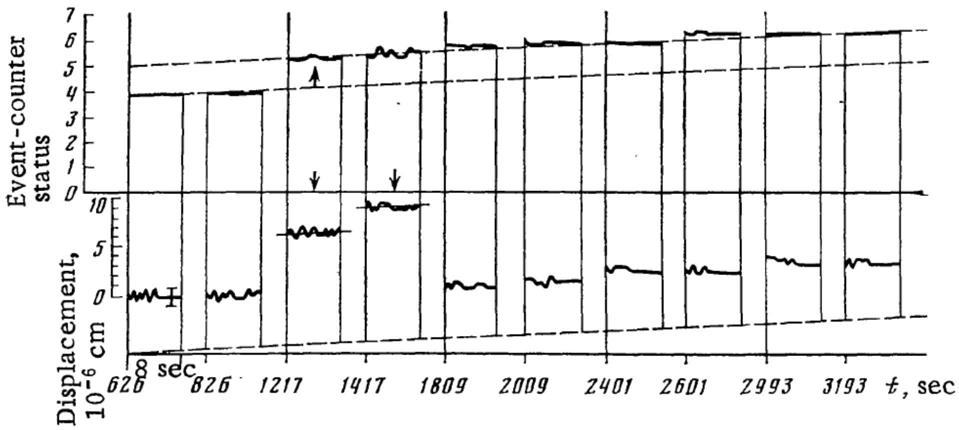

Figure 5-2. Signals recorded on Venera 14—vertical displacements (events) that occurred after landing are indicated by the arrows.

5.1.4 Mars—InSight Seismic Interior Structure Experiment

Drawing on the Viking experience and a multidecade development program including an instrument flown on the Mars 1996 (Optimism) mission, which failed shortly after launch, the SEIS experiment on the InSight mission has been developed as a single station experiment with a sensitivity of more than three orders of magnitude better than the Viking experiment. Based on conservative assumptions on Mars seismicity, SEIS will have the capability of detecting more than 13 Mars quakes globally during its lifetime, and also of detecting meteorite impacts. The SEIS sensor assembly is actually a hybrid instrument, which encloses two sets of seismic sensors: three very broad band (VBB) sensors in an evacuated sphere, and three short period (SP) sensors; both sensor sets are located on a precision leveling structure

In order to optimize the sensor detection capabilities, the SEIS sensor head will deploy to the surface of Mars and connect to its electronics located in the lander with a tether, while being covered by the wind and thermal shield (WTS). The WTS will mitigate the effects of temperature variations and wind on the instrument. Even so, careful monitoring of these parameters is needed in addition to monitoring of the magnetic field and atmospheric pressure, so that seismic events can be discriminated or decorrelated from the effects of other environmental disturbances. These design features are intended to support a system sensitivity requirement of 10^{-9} $ms^{-2}/\sqrt{Hz}$ in the frequency range from 1 to 10^{-2} Hz for the vertical acceleration signals, and from 1 to 10^{-1} Hz for the horizontal acceleration signals.

Although the single station system used at Mars can only detect the approximate location of Mars quakes, it is expected that the location of seismic events produced by meteorite impacts can be estimated more precisely, by locating the craters with orbital imaging from the Mars Reconnaissance Orbiter (MRO) spacecraft.

5.2 Key Constraints for a Seismic Experiment on the Surface of Venus

Two main constraints have to be considered in order to implement a successful seismic experiment at the surface of Venus: the instrument has to reach a signal-to-noise (S/N) ratio sufficient for detection of Venus quakes and the experiment must operate long enough for a sufficient number of events to be observed.

The signal-to-noise ratio includes not only the intrinsic sensitivity of the seismometer but also the contributions of the environment, including both 'natural' noise sources (such as pressure-related tilt, temperature variations, or wind) and 'anthropogenic' sources coming from the lander. In an environment, such as Venus, wind disturbances or any noise coming from the lander (such as mechanical power source vibrations) could be significant.

The second important constraint is the operational life on Venus. The inversion of tele-seismic measurements requires the recording of a sufficient number of quakes (with an appropriate signal-to-noise ratio). Given the probabilistic nature of the occurrence of quakes, and the expected seismicity on Venus (**Figure 3-1**), about one year of data acquisition is needed.

Spacecraft lifetime is a very significant constraint on the Venus surface. Past Venus probes have lasted only a few hours, and using passive techniques, it is not possible to increase surface lifetime by more than a factor of 10. As described in Section 5.5, active cooling, which offers the prospect of months or years of operations is a very distant prospect. The development of instrument and spacecraft systems that can operate at Venus ambient is also a formidable challenge.

5.3 Performance Requirements

As described in the Section 1, the size of quakes recorded will determine how deeply the internal structure can be probed. Fundamentally, bigger quakes will propagate farther and the different arrival times allow recovery of 'deeper' information than small quakes, which provide shallower, more regional information. In order to detect distant quakes, the seismometer needs to have a higher sensitivity. The sensitivity required for local/regional structure investigation is indicated in **Figure 5-3**. It is about an order of magnitude less sensitive than the InSight SEIS experiment.

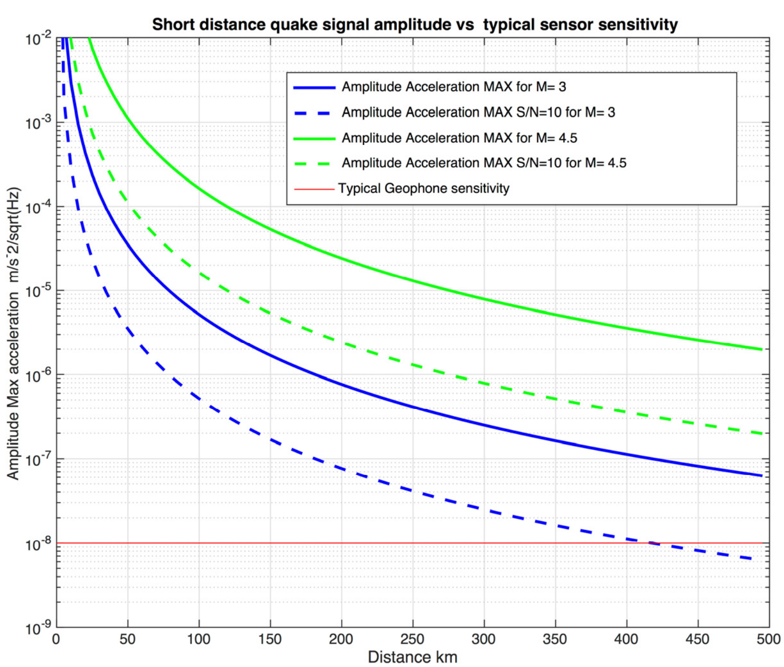

Figure 5-3. Signal amplitude for a typical M=3 (Left) and M=4.5 (Right) quake as a function of the distance to the epicenter. Blue and green represent the maximum signal amplitude for an S/N=1 and S/N=10. The red line represents a typical seismometer sensitivity (10^{-8} m/s^{-2}/√Hz).

Figure 5-3 shows the signal to noise for detection of magnitude 3 and 4.5 quakes as a function of distance. The graphic indicates that the magnitude 3 quake can be detected out to a distance of 400 km, where the blue dashed curve crosses the red dotted line, from the source with a S/N=10. For magnitude 4.5 quakes, which are expected to be much less numerous, the events can be detected out to a distance of 600 km.

As a reference, with lower seismicity assumptions (see Mars activity on **Figure 3-1**), the InSight mission expects to measure about 35 quakes (including both 40 P and S waves) during a terrestrial year. Of course, this estimate depends on the S/N ratio. With similar seismicity properties (which is *very* conservative) and a *very* conservative estimate of the environment noise (5.10^{-8} $m/s^{-2}/\sqrt{Hz}$), this leads to about 10 quakes detections per year. These numbers will need to be refined but are definitely no showstoppers, even with pessimistic assumptions.

Achieving these objectives on Venus would require first reducing the background effects significantly below what was achieved on the Venera 13 and 14 mission (if we assume these data to be correct) and then developing an approach for extended life on the surface.

5.4 Seismic Backgrounds on the Venus Surface

The seismic signal has to be detected not only over the self-noise of the instrument, but also over noise from the surrounding environment. This can have a significant, if not primary, impact on the detection capabilities of the system. A preliminary list of environmental noise contributions for a Venus ground seismometer experiment are illustrated in **Figure 5-4**. A methodology for characterizing and mitigating these effects on Mars was a vital part of the design of the InSight SEIS experiment.[34] Lorenz[35] has also discussed the wind and spacecraft backgrounds that would be important on Venus. The use of power generators and cooling systems with mechanical components particularly reciprocating engines such as that adopted for the Advanced Stirling Radioisotope Generator (ASRG) would be an important contributor to the noise if located close to the sensor.

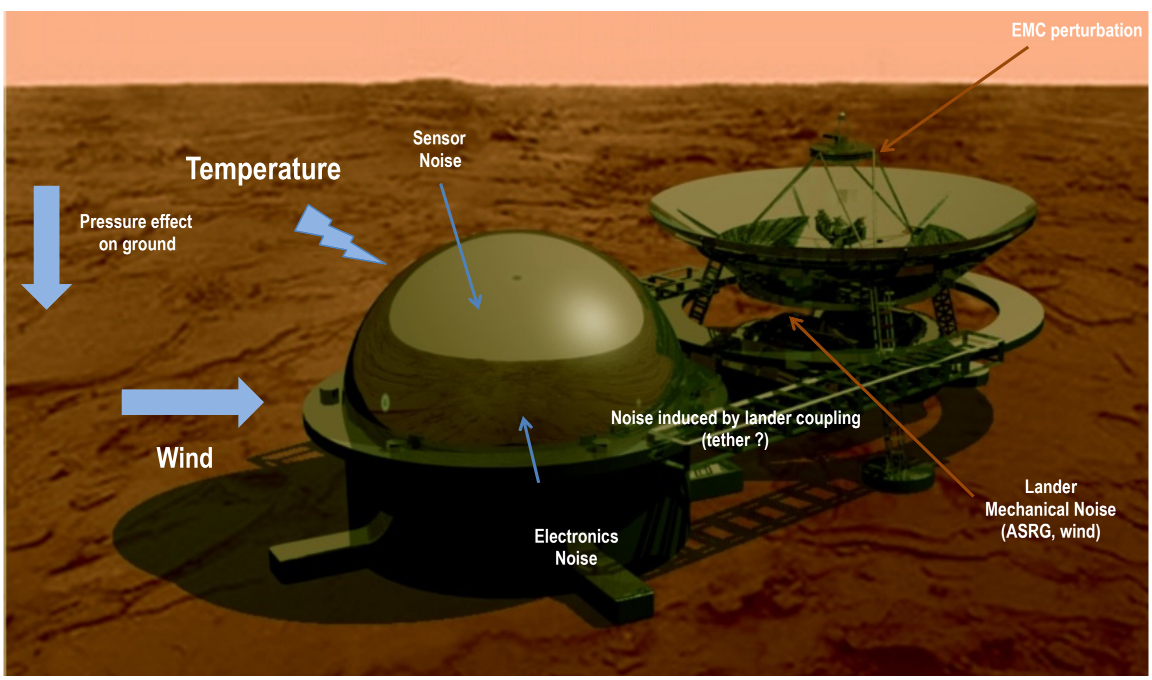

Figure 5-4. Environmental effects contributing to background signals for a Venus surface seismology experiment. (Artwork credit: Tibor Balint.)

5.4.1 Natural Environment

A number of phenomena in the natural environment may contribute to the seismic background, including wind, pressure variations, temperature variations, and remnant magnetism. The likely importance of these effects and ways of mitigating them are discussed below.

5.4.1.1 Wind

Wind effects were seen on the Viking experiment at Mars and they have been inferred to be present in determining the Venera 13 and 14 background levels.[33] Although the wind velocities at the surface of Venus are well below 1 m/sec, the vastly greater density of the Venus atmosphere means that this can still create a disturbance. Moreover, according to Lorenz,[35] this greater density can also translate the impact of wind noise into the frequency range of primary interest to this experiment (0.01–0.05 to 1 Hz). On Venus (just as on Mars), the use of a wind shield with a similar concept to that used on SEIS will probably be necessary to reduce the wind noise. As for InSight, burial would be preferable but likely impractical.

5.4.1.2 Pressure Variations

Pressure variations can be significant at the surface of Venus. According to Gerry Schubert[36] one of the workshop participants, general circulation models (GCMs) indicate they can be up to 1,000 Pascals over time scales of an Earth day. The pressure variations would act in two ways: through a direct depression of the surface of the planet and through the buoyancy of the instrument shield, both of which would directly affect the vertical motion sensor. The major contributor is the tilt of the ground associated with the pressure wave propagation in the vicinity of the landing site. A precise pressure sensor is a vital part of the experiment and could be used to identify and correct for these effects.

5.4.1.3 Temperature Variations

Temperature variations are a primary contributor to seismometer noise and if large enough can result in thermal expansion noise in both the deployment and installation system. Impact on the surrounding terrain is probably a smaller contributor. On Venus, in contrast to almost all other planetary targets except perhaps Titan, temperature variations are exceedingly small and of long period. The length of the solar day is 116.75 days and only 2.5% of the incident radiation penetrates to the surface so that diurnal variations in temperature are expected to be very small (1^{O}C or less). However, temperature variations would be important in the initial deployment. The temperature fluctuation spectrum would also need to be assessed, and convective heating dissipation from power sources would be a background source that would need to be characterized.

5.4.1.4 Electromagnetic Signatures

On Mars, the remanent magnetism must be accounted for in the experiment design. Neither permanent field nor remnant magnetism have been detected on Venus and, at the high surface temperatures, it is unlikely that remanent magnetism would be preserved.

5.4.2 Spacecraft (Anthropogenic) Effects

There are several potential sources of spacecraft-generated noise, including thermo-elastic effects as the spacecraft heats up to match the environment and any mechanical devices operating in the spacecraft. Attention has also to be paid to the electromagnetic compatibility (EMC) perturbations coming from the lander. Ideally, the seismometer should be deployed as far as possible from the spacecraft to avoid spacecraft-generated noise. This approach proved to be reasonably effective on the later Apollo missions. Lander noise had been particularly strong on the first landed mission (Apollo 11), where the seismometer was deployed close to the lander. However, deployment at more than a few meters away may be impractical for a Venus robotic mission and so these effects need to be understood and mitigated to ensure the desired sensitivity is achieved.

5.4.2.1 Thermo-Elastic Effects

As the spacecraft heats up to match the environment, it will expand producing acoustic signals which will be recorded by the seismometer as transients, inducing a large spectrum perturbation. Eventually, it will equilibrate so these signals should decrease with time.

5.4.2.2 Mechanical Devices

Mechanical heat pumps are the most efficient thermo-mechanical conversion devices for both generating power and providing an environment that is cooled beneath Venus ambient. As Lorenz[35] points out they are also a significant source of background that would need to be mitigated in a Venus surface seismology experiment. This is, in principle, very similar to the noise of the ‘flapping’ solar panels that is expected to be a significant source of perturbation for the InSight mission (fortunately, out of the main bandwidth). Alternatives that do not require mechanical devices would be advantageous.

5.5 Technology Status

Achieving the sensitivity needed for the surface seismological measurements and operating on the surface for an extended period is a major technology challenge. This section presents the state of readiness of the relevant technologies.

5.5.1 Seismometer Sensor

Since it must be coupled to the ground and equilibrate with the environment, the sensing part of the seismometer has to cope with a temperature of the order of 460^{o}C in any plausible design. Two of the workshop participants (Gary Hunter and Walter Kiefer) have been engaged in the design of a first generation instrument (see Hunter et al.[37]). The prototype shown in **Figure 5-5** has been tested for several weeks at Venus surface temperatures establishing the principle that a seismometer can be operated at those temperatures for an extended period. The instrument is a short period instrument. Only limited sensitivity data are available to date in the form of testing of the seismometer at room temperature with unoptimized room temperatures electronics in a basement laboratory. The noise level in these tests was ~5×10^{-7} m/s^2/√Hz.[38]

5.5.2 High Temperature Electronics

The seismometer sensor of **Figure 5-5** includes two key elements of the seismometer: the pendulum and associated position sensor, and an amplifier. These components needs to be complemented by several other elements to build a functional seismometer, including the analog to digital conversion, logic required for the instrument remote operation, power, and telecommunications. Two of the workshop participants, Mohammad Mojarradi and Gary Hunter made assessments of the state of technology.[39]

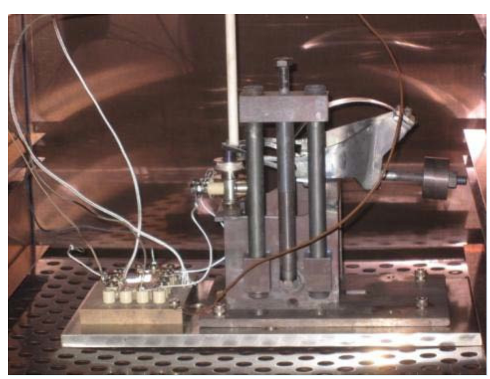

Figure 5-5. A prototype of a high temperature seismometer.

5.5.2.1 High-Temperature Semiconductor Components

Devices operating at high temperatures are needed by the automotive and aerospace industry, for process monitoring, for various energy applications including deep drilling and for military applications. However, few of these applications have current requirements for >450°C (Venus surface temperature) and the list of available components is limited. The status of these technologies is shown in **Figure 5-6** and **Table 5-1**.

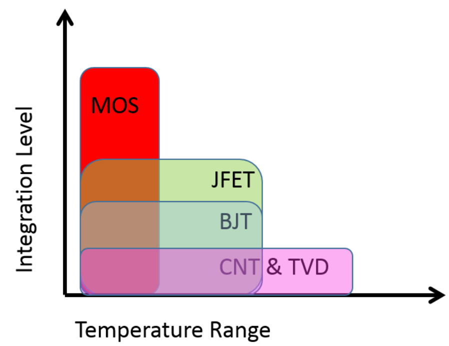

Figure 5-6. Integration for various kinds of active devices. The metal oxide semiconductor (MOS) and junction field effected transistor (JFET) are both silicon devices. The bipolar junction transistor (BJT) can be made with high band gap silicon carbide and the carbon nanotube (CNT) and thermionic Vacuum tube (TVD) are both vacuum electronics devices.

The most commonly used electronic components are based on the semiconductor silicon and are limited to less than 200°C due to problem with leakage and latch up. For functionality to 300°C, these problems may be managed using silicon on insulator (SOI) technology where the silicon devices are isolated from the silicon and each other with a dielectric. But for temperatures above 300°C, alternatives are needed.

The most widely developed semiconductor alternative is silicon carbide (SiC), which has a wider energy band gap than silicon. The design choices available in a small package, capability to directly withstand harsh environments including high pressure/temperature for prolonged time periods, and ability to form more complex circuits, suggest SiC is a viable choice for multiple high-temperature applications. As part of development aimed for aeronautic applications involving high-temperature smart wireless sensor systems for engine systems,[40,41] high-temperature SiC electronic circuits have shown the capability to operate at Venus relevant temperatures for extended periods of time.[42,,44] A range of basic devices were fabricated, such as junction field effect transistors (JFETs), differential amplifiers, inverting amplifiers, and logic gates, and demonstrated with lifetimes from 2,000 hours (~83 days) up to 10,000 hours (~416 days). A short duration, proof-of-concept high-temperature smart sensor system with SiC data processing, wireless communication, and limited power scavenging was demonstrated at 475°C.[45]

Table 5-1. A sampling of specific circuits being fabricated as part on ongoing high-temperature electronics development.

Circuit	Inputs	Outputs	Transistors, I/O Pads	Comments
4-Bit A/D	Analog voltage signal, optional external clock, output type select	4 bit parallel digital latch, pulse width modulated (PWM)	203 JFETs, 23 I/Os	Internal ring- oscillator clock circuit
4×4 Bit Static RAM	Read, write, data lines, address lines	4 bit parallel digital latch	220 JFETs, 30 I/Os	Address decoder, sense amplifiers
Source Separation Sensor Signal Transmitter	Capacitive sensor	Frequency modulated with address code	301 JFETs, 20 I/Os	Each sensor signal is tagged with unique address code
Ring Oscillators	Capacitive sensors	Frequency modulated signals (up to 10 MHz)	10-12 JFETs, 6 I/Os	On-chip large transistors for power amplification
Binary Amplitude Modulation RF Transmitter	Low power binary signal	High-power RF signal to antenna		Could connect with PWM from A/D
Op Amp, 2-Stage	Differential	Voltage gains to 50 w/ on-chip resistors	10 JFETs	For piezoelectric SiC pressure sensors

These circuits are key to the electronics approach used to demonstrate a proof-of-concept seismometer described in Section 5.5. The input signal provided by the seismometer mechanical assembly and position transducer was fed to a SiC-based high temperature ring oscillator. This design approach allowed transmission over a distance of 2 meters of seismometer boom displacement at 475°C for more than 24 days. Increased circuit complexity with extended lifetimes is a major objective of this work. To extend these capabilities, **Table 5-1** shows a sample compilation of circuits presently being fabricated to expand electronic circuit operation at 500°C.[46] The SiC electronics noise floor at high temperature is not believed to be significantly elevated,[47,48] but this needs to be further verified as new, more complex circuits are produced.

5.5.2.2 Vacuum Electronics

An alternative to semiconductors is vacuum electronics. One approach is the thermionic vacuum device (TVD), in which the electron flow is from a heated filament. TVDs have been demonstrated to 1000°C. An alternative is the carbon nanotube device (CND), which does not need to be heated to emit electrons. CNTs have been demonstrated to 700°C. An advantage of both types of devices compared to semiconductors is their low noise at high temperatures. The status of each of these technologies is also described in **Figure 5-6** and **Table 5-2**. The workshop considered an approach using both SiC and vacuum electronics to exploit their respective strengths.

Table 5-2. Electronic active components-technology status.

Material or Device	Theoretical Max (°C)	Noise at Temp	Density	Packaged Durability at Venus Temp
Bulk Silicon	225	High	High	NA
SOI	300	High	High	NA
Silicon Germanium	300	Med-Hi	High	NA
Gallium Arsenide-based	400	Med-Hi	Med-Hi	NA
Galllium Nitride-based	600	Med	Med	Low-Med
Silicon Carbide	600	Med	Med	Med
CNT Vacuum Devices	600	Low	Low	Low
Diamond	700	Med-Hi	Low	Low
Thermionic Vacuum Devices	800	Low	Low	Low

5.5.3 Power and Thermal Control

A power source is needed for operation on the surface of Venus and a thermal control system is highly desirable for maintaining parts of the landed spacecraft at temperatures well below Venus ambient so that more capable electronic systems can be used. Technology options and their maturity were examined in the Technologies for Severe Environments study conducted for NASA in 2007[49] and were updated in the Venus Exploration Analysis Group (VEXAG) Technology Plan published in May 2014.[50]

5.5.3.1 Power Generation

The most practical sustained source of power generation is a radioisotope power system (RPS) that converts the heat from radioisotope thermal sources to electricity. Existing RPS devices, such as the multi-mission radioisotope thermal generator (MMRTG), are designed to operate in deep space or on the surface of Mars, and are not suitable for operation on the surface of Venus. However, thermoelectric materials have been developed that could be used in an RPS that can operate at temperatures in excess of 1,000°C. This would yield adequate efficiencies for operation where the ‘cold end’ of the thermocouple is at Venus surface temperature. A device tailored to this environment would be a major new development. There is significant industry interest in radioisotope power sources capable of operating at elevated temperatures.

Using solar power on the surface of Venus is challenging. According to Crisp[51] only 2.6% of the solar energy entering the top of the atmosphere reaches the surface for a global average of 17 W/m^2. A second difficulty is that converting light to electrical energy at these elevated temperatures is very inefficient although Landis et al. suggest that it is possible.[52] Wind power has more promise but would require complex systems and would also be a source of background noise potentially interfering with seismic detection. A third alternative would be storing energy in a battery that could operate at Venus temperatures. Batteries that release their energy most efficiently at temperatures in excess of 500^{o}C have been developed (see p. 191 of reference[53]) but most batteries developed for this purpose release their energy rapidly in a period of less than one hour. In any case, this is a not a means of power generation only power storage and consequently mission lifetime will be limited.

5.5.3.2 Thermal Control

The 2007 Extreme Environments Report[49] identified an approach to a scalable, efficient, powered refrigeration/cooling system for maintaining temperatures at operational levels for the payload and the subsystems for extended periods of time (as long as months). As presently envisaged, active cooling systems would require a great deal of power and would require large amounts of Plutonium-238 combined with the efficiency of an advanced mechanical converter (using the Stirling cycle) as opposed to a lower efficiency thermoelectric generator. As a result, the state of development of active thermal-control technologies capable of operating in the Venus near-surface environment is very low.

5.6 Surface Seismology Roadmap

As a result of these constraints, and given the likely time to develop the requirement technologies to starting from parts level to a full system operating in Venus conditions, a step-wise approach is proposed.

5.6.1 Pathfinder Experiment

The Pathfinder experiment would determine the seismic background and lay the foundation for the next mission with more ambitious scientific goals. It would most likely be deployed on a host spacecraft with different primary objectives such as NASA’s proposed New Frontiers VISE. Ideally, the spacecraft would also be targeted to a candidate seismically active region.

Conceptually, this experiment would resemble the Groza–2 experiment with sensors deployed in the Venus environment but multiplexing, analog-to-digital conversion, storage and data communications performed in the host spacecraft with a thermally controlled environment (**Figure 5-7**). With only passive thermal control techniques, the experiment would operate at most for a few hours.[ii]

The primary goal of the Pathfinder experiment would be to investigate seismic backgrounds and understand the dependencies on the natural environment (wind and any temperature and pressure variations) and spacecraft backgrounds. If deployed to a seismically active region, local

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[ii] Although the current state of passive thermal technology would limit the mission to 2 to 3 hours, concepts are under development that might increase this by as much as a factor of 10.

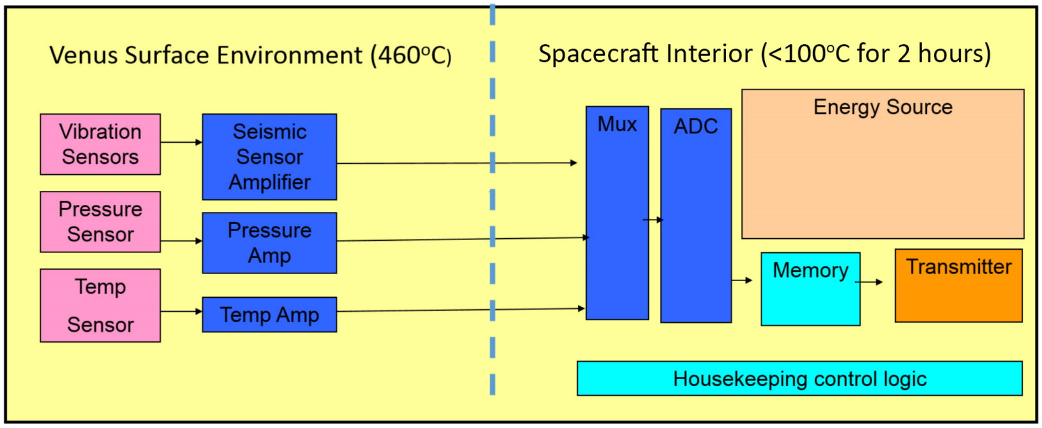


Figure 5-7. Block diagram of the Pathfinder experiment. The sensors and preamplifiers are exposed to the ambient Venus environment and the multiplexing; analog digital conversion and data storage is handled inside the lander.

seismic events might be detected. An active source, deployed before landing, might also be considered.

Locating the pressure sensors outside the lander is preferred but, for reasons of technological maturity, may be unnecessarily restrictive. For the pressure sensor, an alternative would be to conduct the external pressure via a narrow tube into the interior of the vehicle where the sensor is maintained at a more benign temperature. This approach has been used on Pioneer Venus, Galileo, and other missions and has been used in aeronautics applications. There is a time constant consideration but this may not be restrictive. Further analysis is needed; however, high-temperature pressure sensors are gaining maturity and are in the process of commercialization.

Similarly, it is an open trade whether to accommodate the seismometer in the interior of the vehicle accepting a higher noise level as the lander adjusts thermally to its surroundings (see Section 5.4.2.1). Technology progress reported in Section 5.5.1 may lead to the latter solution but the former is achievable today.

5.6.2 Local/Regional Investigation—90 Days

A second-generation experiment would be designed to last for 90 days. It would be targeted to a region where a high level of seismic activity was suspected. It would not depend on the development of active cooling technology. Two approaches have been considered depending on the maturity of high-temperature electronics technology: a digital seismometer with memory and an analog seismometer with orbital data relay. The science goals would be limited to determining seismicity in a local and regional setting.

5.6.2.1 Digital Seismometer with Memory

The digital seismometer option is completely self-contained and relies on no other spacecraft system (**Figure 5-8**). The lifetime target for this mission is 90 days (2,000 hrs). It would transmit for 10 minutes out of every 90 minutes, which would be synchronized with an orbiter. Transmissions would be at either ultra-high frequency (UHF) or L band with a transmit data rate of 16 Kb/sec. The analog-digital converter has auto ranging with 24 bits of resolution. The memory would be designed to accommodate 80 minutes of surface data. Either SiC or CND technologies would be considered for implementing the electronics.

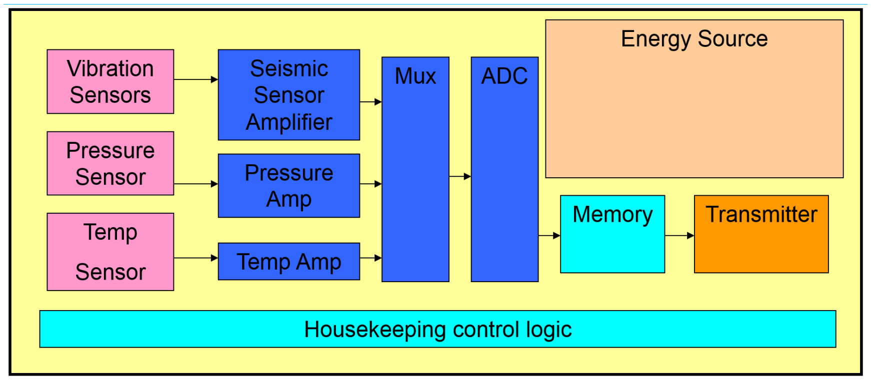


Figure 5-8. Block diagram for a concept of a digital seismometer with memory. All components must operate at Venus-surface ambient.

Electronics Challenges

For the low noise signal chain, a major challenge is operation of circuits at 480°C for prolonged time periods. A hybrid circuit composed of both SiC devices and CNDs could be considered using the strengths of both systems. Development of the high-resolution ADC could also be a hybrid device. For the data recorder and logic, key problems are the physical dimensions of the individual devices at this stage of development and of the power they use. Currently, this is a challenge for both SiC and the CNT technologies. Accordingly, we have also looked at an alternative analog seismometer that avoids the need for digital logic and memory. Communication from the lander to the orbiter is also a challenge to be considered.

5.6.2.2 Analog Seismometer

This concept, shown in **Figure 5-9**, avoids the challenges of developing both an ADC and a digital memory. The sensor must now continuously transmit data and this would require a relay spacecraft in a high-altitude Molniya-class orbiter. It is assumed that the spacecraft could be in view for at least 70% of the time to provide acceptable data recovery. There are still technical challenges with this approach notably the need for a highly linear modulator to ensure data of adequate dynamic range. However, the basic ability to continuously transmit analog data for 24 days over a limited distance in conjunction with a seismometer at 475°C has been demonstrated.

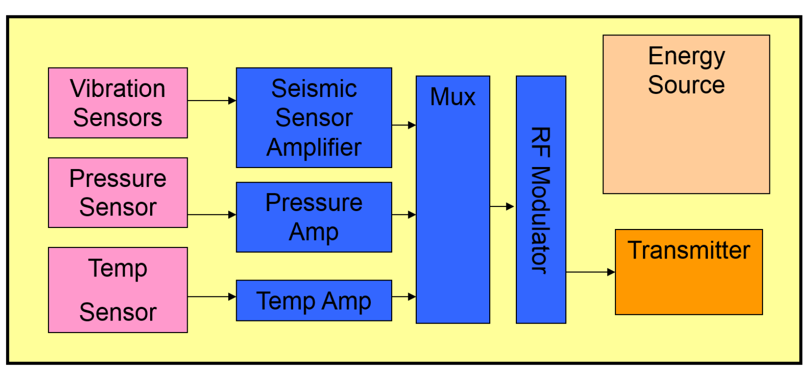


Figure 5-9. Block diagram of a completely analog seismometer for Venus surface operation. This does not require either an analog-to-digital converter or a digital memory, which are both challenging developments for high-temperature electronics technology.

5.6.3 Global Interior Structure Investigation

This third generation mission would be designed to last at least a year. For Venus, the approach to localization of seismic events used on the single station Mars InSight mission is unlikely to be feasible because it depends on surface waves that make more than one complete circuit around the planet. Because Venus is a much bigger planet than Mars, the signal from a quake of a given size is much smaller and attenuation may also be greater. For Venus, this turns out to not be a serious impediment because quakes can be localized with orbital observations (see Section 7.6.3). Multiple surface stations, while not strictly necessary for quake localization, would still be highly desirable for performing ambient noise tomography.

The nominal plan for implementing these stations would be using advanced versions of the Generation 2 digital seismometer with memory. Advances in sensitivity and improved background reduction would be desirable. In the event that thermal control technology progresses much more rapidly than anticipated and high temperature electronics development lags, it is conceivable that an architecture resembling that used in the Pathfinder experiment would be used. For either pathway, the technology challenges are formidable and this multi-station networked mission with InSight-level seismometers may be many years from realization.

5.6.4 Roadmap Summary

Table 5-3 provides a summary of three generations of development of the surface experiment. In Section 9, this data is integrated into an overall Roadmap reflecting the maturity of surface, middle atmosphere, and space techniques.

5.6.5 Other Concepts

The possibility of active experiments to deal with a potential lack of seismic activity was also considered at the workshop. However, practical limitations on the size of the explosive device means that only relatively shallow and local structures could be investigated. The value of acquiring this information should be reassessed.

Table 5-3. Venus ground seismology experiment roadmap.

	Generation 1 Pathfinder Technology Experiment	Generation 2 Local and Regional Seismicity	Generation 3 Global Interior Structure
Main Science Objectives	Seismic background investigation Seismicity in seismically active regions	Local/regional investigation of crustal thickness & structure)	Global investigation of internal structure
Technology	Leaf spring seismometer w/o feedback (geophone or extended geophone)	Pendulum w/ feedback	Very broad band seismometer
Supporting Electronics	Predominately conventional electronics with passive thermal control operating for 2 to 5 hours	Digital or analog seismometer with Si-C or vacuum electronics components at Venus ambient	Digital seismometer with advanced signal processing at Venus ambient
Typical Mission Duration	Several hours	90 days	>1 year
Number of Stations	1	1	1 to 3
Supporting Measurements	Temperature, pressure, wind speed	Temperature, pressure, wind speed	Temperature, pressure, wind speed

6 Seismology in the Middle Atmosphere with Balloons

Among the options for Venus seismology, the most original is the use of balloons to detect infrasonic waves from an earthquake. However, we are not aware of any experiments related to observations from an airborne platform, either on Earth or Venus. This section provides a review of relevant terrestrial and planetary measurements, performance requirements for a Venus experiment, background signals that we will have to be considered, technology developments, and a roadmap for balloon-based seismology.

6.1 Relevant Terrestrial and Planetary Measurements

The mechanism of seismic waves coupling with the atmosphere is explained in Section 4.2.2. On Earth, we know that the pressure correlation with the quake depends strongly on propagation (refraction, wind structure, and for the upper atmosphere, coupling with the magnetic field, etc.). The atmosphere of Venus is much denser than the Earth. In fact, it is close to the geometric mean of the densities of the Earth's atmosphere and the ocean. Accordingly, in considering a Venus experiment that would detect Venus quakes from their pressure waves, there is much to learn from both hydrophonic and infrasonic detection of earthquakes.

6.1.1 Infrasonic Detection of Earthquakes

The monitoring of quakes through infrasonic measurements is routinely done on Earth within the framework of the Comprehensive Test Ban Treaty (CTBT) monitoring program. The CTBT was conceived for monitoring nuclear tests on a global scale, with the help of networks of seismometers and infrasonic pressure) sensors. The infrasonic sensors were designed for detecting the acoustic signatures of atmospheric nuclear tests, but it appears that they are also able to detect the infrasonic/seismic waves from underground tests and earthquakes. **Figure 6-1** is an example of the infrasonic counterpart of a quake (of large amplitude). The two upper diagrams show the ground displacement (nm) and the associated time-frequency analysis, while

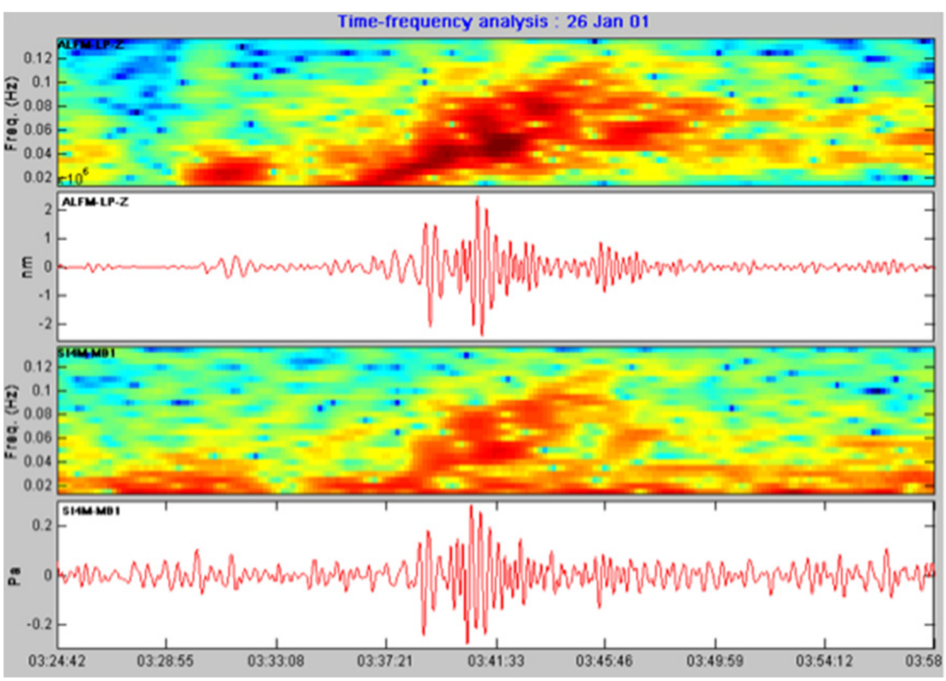


Figure 6-1. India quake, January 26, 2001, Ms=8 (CTBT Station: Javhlant, Mongolia). Top two diagrams: time frequency analysis of ground displacement. Bottom two diagrams: time frequency analysis of pressure measurement. (From Farges et al.[54])

the bottom ones show pressure variations recorded at the same time; the two signals are remarkably similar over a wide frequency range—the infrasonic signal is really a seismic signal.

The rapid growth in the number of Infrasound Monitoring Stations (IMS) over the last decade complemented by expansion of regional networks such as those in Utah, has led to a rapidly expanding knowledge of the acoustic signatures from not only earthquakes[55] but also volcanoes[56] and meteors[57]. In the case of earthquakes, this has recently resulted in more detailed knowledge of the mechanisms by which seismoacoustic waves are generated. Studies of small earthquakes such as the Circleville Utah, magnitude 4.7 event of January 3, 2011, which was observed by all nine stations or the University of Utah's infrasound array,[58] have been particularly useful. Two of the participants in the workshop (Arrowsmith and Blom) have been actively involved.

This trace of a small earthquake (**Figure 6-2**) was detected at all nine stations of the array, which extends across much of the state of Utah. The large signals in the spectral range 1 to 5 Hz bounded by the red lines are 'epicentral sound' signatures that propagate entirely within the atmosphere. The red lines denote group velocities of 0.34 and 0.22 km/sec). These epicentral sound signatures were not seen at the three closest sites because there was no ducting of sound to these locations. The other signatures that are prominent for the closer stations but occur for more distant stations also correspond to ground-air coupled infrasound resulting from Rayleigh waves (see **Figure 4-10**).

These investigations provide great insight on the mechanisms of generating seismic waves for earthquakes of smaller amplitude. Although a much smaller fraction of the seismic energy is coupled into the Earth's atmosphere than would be the case on Venus, it is still sufficient for detection of comparatively small events. Accordingly, the instrumental and analytical framework is in place for applying seismoacoustic techniques on Venus.

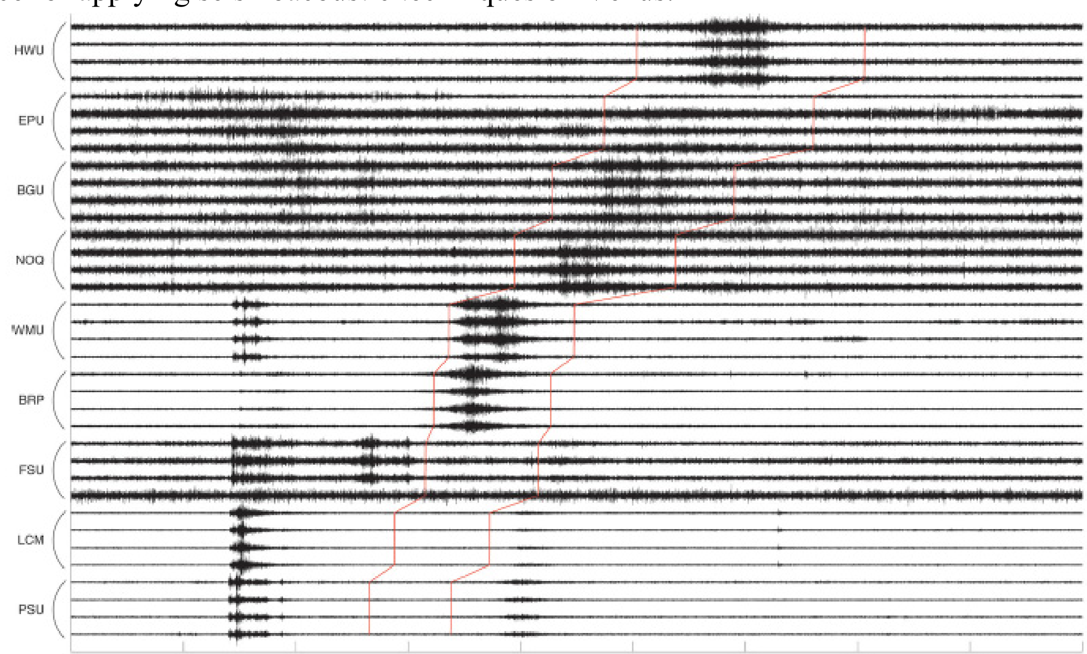


Figure 6-2. Centerville earthquake 2011. Signals from the nine stations in the University of Utah array are shown. This is filtered data in the 1 to 5 Hz passband.

6.1.2 Hydrophonic Detection: the MERMAID Project

Motivated by the desire to extend observations of teleseismic events to major ocean basins, U.S. and French researchers have developed the MERMAID (Mobile Earthquake Recorder in Marine Areas by Independent Divers).[59] Each MERMAID station consists of a hydrophone array deployed beneath the buoyant station (**Figure 6-3**). Earthquakes with magnitude 6 and higher been detected at ranges of 10,000 km. Again the technical and analytical framework is in place for applying this knowledge to detection of seismic activity on Venus.

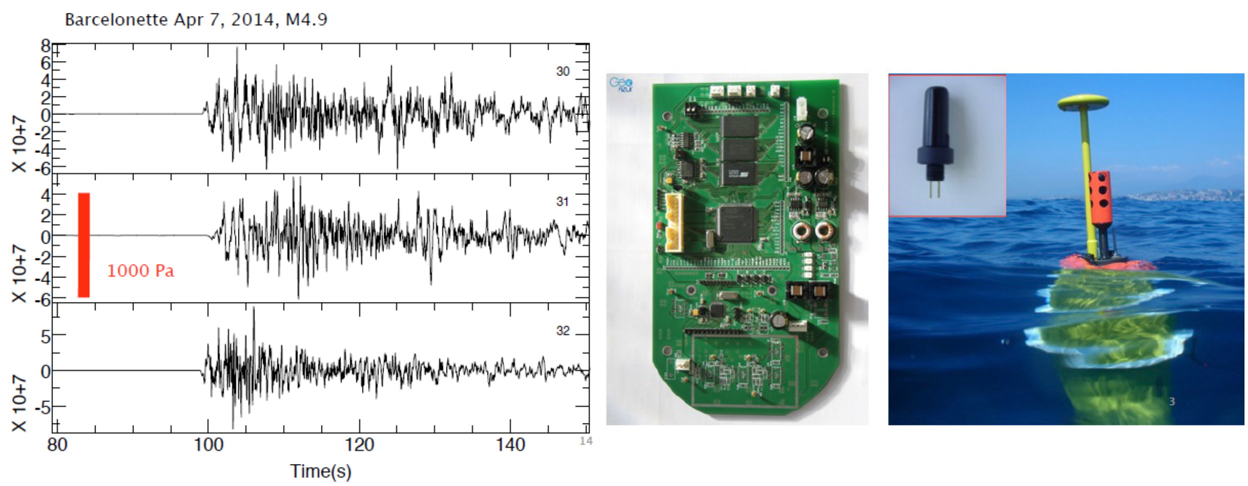


Figure 6-3. *Left:* Recording of an M=4.9 quake at ≈150 km. *Right:* MERMAID buoy data logger and hydrophone.

The installation of a seismometer on Earth's ocean floor, necessary to provide data to advance towards a complete tomography of the interior the Earth,[60,61] has proven to be a costly and challenging task.[62] As a result of this, G. Nolet and his colleagues[59] proposed to use a Lagrangian float coupled with a hydrophone to record the acoustic waves induced in the ocean by the coupling of the P-waves. This strategy has proven to be very efficient and many quakes (both local and teleseismic) were recorded with a very good accuracy. Due to the specificity of the propagation medium (the water column size is small with respect to the length of the seismic wave), only P-wave counterparts have been recorded (and not surface waves counterparts).

They are other striking similarities between the MERMAID concept and a balloon experiment on Venus: the necessity to distinguish between the seismic signal and the background noise and the limited data link, which requires an event detection algorithm. In terrestrial oceans, the MERMAIDs have recorded many signals in the bandwidth of interest: seismic signals of course, but also anthropogenic signals (ships), animals (whales, etc.), or polar ice catastrophic avalanches.

In the MERMAID concept, quakes are recorded at depth, but there is no practical way to return data without returning to the surface and using a satellite relay. Consequently, the buoy has to periodically come back to the surface for this data upload. The frequency of these data transmissions depends on the on-board memory size, and on the efficiency of the detection algorithm. On MERMAID, this algorithm has been tuned on real data, therefore increasing the efficiency of the overall process.

6.1.3 Infrasonic Measurements from a Balloon Platform

Project Mogul (sometimes referred to as Operation Mogul) was a top secret project by the U.S. Army Air Forces involving microphones flown on high-altitude balloons, whose primary purpose was long-distance detection of sound waves generated by Soviet atomic bomb tests. The project was carried out from 1947 until early 1949. The project was moderately successful, but was superseded by a network of seismic detectors and air sampling for fallout, which were cheaper, more reliable, and easier to deploy and operate. In the summer of 1947, a Project Mogul balloon crashed in the desert near Roswell, New Mexico. The subsequent military cover-up of the true nature of the balloon and burgeoning conspiracy theories from UFO enthusiasts led to a celebrated UFO incident.[63]

The balloons developed for Project Mogul were super-pressure or constant volume balloons made from high-strength plastics. In the subsequent 50 years, they have been used to conduct many types of scientific measurement and have achieved operation lifespans of many months and even years. There has been continuing interest in using balloon-borne sensors for studies of meteors and volcanoes; however, we are not aware of an existing active research program.

In 1985, two super-pressure balloons were deployed into the Venus atmosphere and floated for 2 days at an altitude of about 54 km where the atmospheric temperature was near 0^{o}C. Pressure measurements were made but not with the frequency or sensitivity to detect infrasonic waves. The balloons operated for 46 hours, a period determined by the size of the battery pack. Recently, NASA has worked on more advanced balloons, possibly capable of operating for months and carrying payloads of up to 100 kg.

The prospect of developing Venus balloon missions, floating in the middle atmosphere like the Vega balloons, but with durations of a few months, seems considerably closer, in terms of technology maturity, than developing a long-lived probe for the Venus surface. Balloons have already flown to Venus, and despite a sulfuric acid cloud layer, the environment is considerably more welcoming than on the surface.

6.2 Key Constraints for an Infrasonic Seismic Experiment in the Atmosphere of Venus

The same basic constraints for a surface experiment exist for an infrasonic seismic experiment: the sensing instruments have to reach a signal to noise sufficient to detect Venus quakes and discriminate them from non-seismic signals, and the experiments must operate for long enough for a sufficient number of events to be observed.

As with the surface experiment, the signal-to-noise ratio includes not only the intrinsic sensitivity of the seismometer but also the contributions of the environment, including both the natural environment and noises emanating from other payload instruments. In this respect, the floating platform offers some advantages. First, the infrasonic sensors can be deployed to a distance of tens to hundreds of meters from the any noisy mechanisms on the gondola by using a tether deployed beneath the gondola with a winch. This deployment also enables pressure variation due to seismo-infrasonic waves to be distinguished from altitude variations by comparing signals at different locations along the tether.

Second, the platform circles the planet in the prevailing winds—a distinctive advantage of changing the region of measurements, while still being able to record global events. Such a platform would therefore be a major contributor to the global distribution of seismicity mapping.

However, there are also disadvantages to the platform motion. The position of the platform is continually changing in both directions. Motions in the horizontal direction are a contributor to the inlet noise, even though a careful design might mitigate the issue, but vertical motion induces pressure-altitude variations, which are the main signal recorded. Techniques are needed to address this problem.

Lifespan of the platform is the other issue. Even with current technology, it is practical to achieve lifespans that are three orders of magnitude greater than current surface landers. Super-pressure balloons have flown for more than a year on Earth, though a lifespan of several months is more typical ultimately due to limitations from diffusion of the buoyant gas through the envelope. However, since these floating vehicles could operate much deeper in the atmosphere, where the dense atmosphere permits balloons with thicker metallized envelopes, even longer lived platforms might be practical. The atmospheric amplification of the signal will be lower at these altitudes, but there may be a 'sweet spot' for seismic platforms where much longer lifespans can be achieved while still using highly capable electronics.

6.3 Performance Requirements

The ability to survey seismicity using infrasounds that propagate directly upward above the epicenter follows the same approach used for surface seismology. **Figure 6-4** shows the relationship between a motion of 1 mm at ground level and the corresponding pressure signal amplitude as a function of the altitude. This figure will be used to convert the amplitude of the seismic signal at the ground to the pressure wave amplitude at the balloon altitude.

Figure 6-5 shows the signal to noise for detection of magnitude 6 and 7 quakes as a function of distance. The graphic indicates that the M=6 quake can be detected out to a distance of 2200 km where the blue curve crosses the red line, with a signal to noise of 1. For magnitude 7 quakes, which are expected to be much less numerous, these events can be detected out to a distance of 9,000 km (which means globally). As already discussed, and based on **Figure 3-1** seismic activity assumptions, it would be necessary to observe for about 1 year to detect about 10 M=6 events; this is viewed as a minimum for a useful seismic experiment.

In the case of the near field, directly above the epicenter, the amplification is extremely sensitive to local geology and the details of the focal mechanism. However, the geometrical effects amplify the planar wave assumptions made in **Figure 6-5**. Preliminary estimates give a

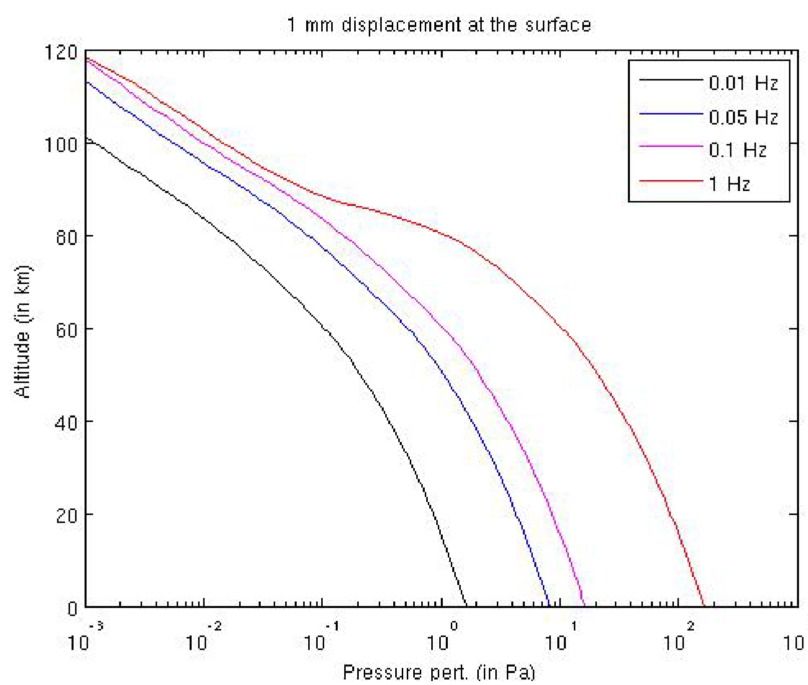


Figure 6-4. Amplification of a 1-mm ground motion as a function of the altitude, for various signal frequencies. This amplification is valid in the case of surface wave (planar wave), and underestimates the amplification near the source.

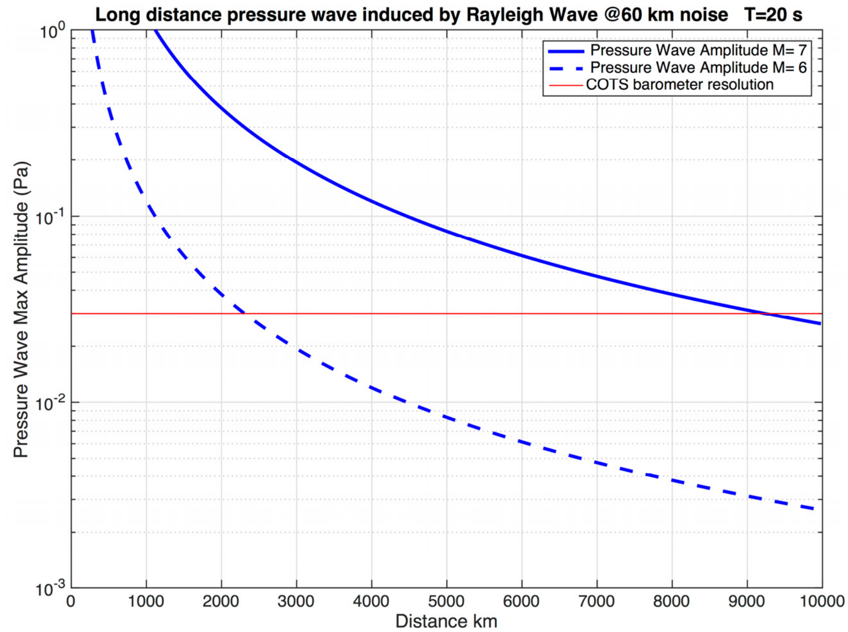


Figure 6-5. Rayleigh wave signal amplitude for ground-earth coupled infrasound from a Venus quake for M=6 and M=7. The horizontal red line represents the sensitivity of a typical cots microbarometer.

delta pressure at 60 km of ~500 Pa for an M=4.5 quake, and a delta pressure at 60 km of ~50 Pa for an M=3 quake, far above the detection threshold. This would enable sensitive monitoring of variations in seismicity as the balloon circumnavigates the planet.

Figure 6-5 represents detection figures given the current state of microbarometer technology in the case of a Rayleigh wave 'far' from the seismic sources. Achieving these goals would require controlling sources of background noise. In the next section, we consider the impact of background noise sources.

6.4 Seismic Background in the Venus Atmosphere

The Venus atmosphere is a very dynamic medium (gravity waves, thunderstorms, and volcanoes) and a lot of background noise is expected. Therefore, it is necessary to first characterize the background noise through a Pathfinder mission, and then expect to make adjustments of the optimal frequency bandwidth or some adapted filtering.

6.4.1 Natural Environment

Some of the same environmental factors considered for a surface experiment must also be considered for a balloon experiment. However, because balloons are in motion and not located on the surface, there are important differences.

6.4.1.1 Wind

Wind effects are a problem for a Venus surface seismic experiment and limit the performance of ground infrasonic arrays. However, for a floating platform, which moves with the wind, noise resulting from the interaction of atmosphere motion with the sensor or with nearby platform elements such as the tether are much less of a problem. In the event, that sensors are deployed on long tethers for background suppression, there will be modest wind background as a result of vertical wind shear. The inlet shape also has to be designed to mitigate part of the wind-induced noise.

6.4.1.2 Pressure Variations

As noted in Section 5.4.1, pressure variations on the surface can be significant on Venus: GCMs indicate they can be up to 1,000 Pa over a Venus day. The models give no direct information on what variations would be expected in the frequency range of interest to this experiment because the typical climate model time step exceeds the periods of interest for numerical efficiency reasons. Smaller timescale 'large eddy simulation' models would be able to model pressure variations below 1 Hz.

6.4.1.3 Temperature Variations

The surface of Venus experiences very little temperature variation with time of day as a result of the small amount of solar radiation reaching the surface. Although no measurements have been made, temperature variations for an atmospheric platform are expected to be much higher, increasing with altitude. Temperature variations would need to be characterized to interpret infrasonic signals.

6.4.1.4 Turbulence

Turbulence in the atmosphere is expected and was observed by the Vega balloons in their trips around the planet (e.g., Linkin[65]). There are many potential sources of infrasonic energy, which could interfere with detection of seismic signals (see **Figure 6-6**). Turbulence is expected to be particularly intense in the convective zone of the cloud layer where most of the solar energy falling on Venus is deposited. According to the analysis of Venera 11 and 12 Doppler tracking data by Kerzhanovich et al.,[66] the turbulence appears to be driven by the energy dissipation rate ($\tilde{\boldsymbol{\varepsilon}}$) according to the following relationship:

$$\tilde{\boldsymbol{\varepsilon}}=C\ (\boldsymbol{\sigma}V)3/L$$

$\boldsymbol{\sigma}$V is fluctuation in speed, L a characteristic length scale, and C a constant. $\tilde{\boldsymbol{\varepsilon}}$ is 50–180 cm^2/s^3 above 40-km altitude, but only 3–9 cm^2/s^3 for the lower troposphere. Less turbulence is expected in the radiative zone above the cloud tops (65 km) where there is little energy deposition.

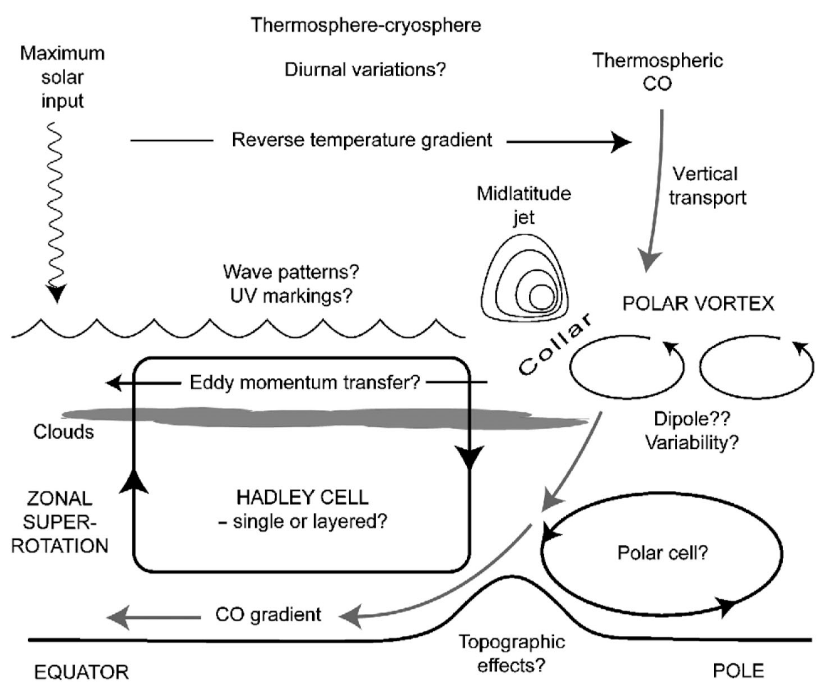


Figure 6-6. Venus has a dynamic atmosphere with many potential sources of infrasonic energy. (Reprinted from Taylor.[64])

6.4.2 Spacecraft Effects

The floating platform makes for an interesting contrast with the surface platform when it comes to dealing with spacecraft effects.

6.4.2.1 Spacecraft Noise—Mechanical or Electromagnetic

For both surface and floating platform, it is desirable to deploy sensors at a considerable distance from other spacecraft systems. With robotic landers, this is complex. A robotic arm can deploy sensors a few meters from the lander. A rover would be required for more distant deployments. For the floating platform, it is much more straightforward since the sensors can be deployed beneath the platform on a tether to distances of tens or even hundreds of meters.

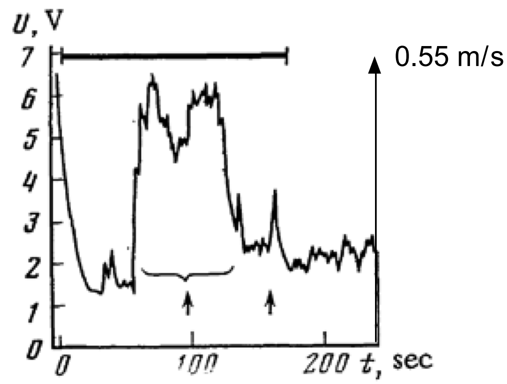


Figure 6-7. Venera—acoustic data interpreted as wind. Lander equipment (pumps, etc.) were operated during the period indicated by the horizontal bar at the top. A wind speed range of 0.35–0.57 m/sec was derived from the record between 180 and 240 sec corresponding to a signal of approximately 2V. (Reprinted from Ksanfomaliti 2001.)

6.4.2.2 Altitude Changes

The floating platform also has a disadvantage. Variations in the altitude of the platform mimic pressure variations. This is the principle of most altimeters, and this signal is expected to be orders of magnitude bigger than the acoustic seismic wave. Any measurement concept will have to therefore compensate for this phenomenon, either by filtering or by removing the altitude variations using inertial measurements.

6.5 Technology Development

The 'sweet spot' altitude for balloon flight will depend not only on background signals in the atmosphere, for which very little is known, but also the capabilities of electronics and the lifetime of the balloon at different flight altitudes on Venus. The status of high-temperatures electronics technology and power generation was coved in Section 5.5. This section discusses the potential for designing balloons for a long-lived seismic network.

6.5.1 Long-Duration Balloon

6.5.1.1 Mid-Cloud Level Balloon

The current status of super-pressure balloon technology for operation in the mid-cloud levels on Venus at 55-km altitude has been described by Hall et al.[67] At this altitude, the nominal temperature is 27^{o}C, pressure is 0.5 bars, and the density is ~0.8 kgm^{-2}. This is an ideal region for operation with conventional electronics. Although there has been considerable progress in extending the lifetime of such balloons by controlling the development of pinholes in the envelope,[68] the lifetime of this type of balloon is inherently limited by diffusion through the plastic membrane. This can be extended somewhat by adding a metal coating. A recent JPL prototype with an 8 micron thick aluminum foil coating reduced the helium permeability below the detection threshold of (<10cm^3/m^2-day-atmosphere). A prototype of a balloon with a 45 kg payload capacity is shown in the left image of **Figure 6-8**.

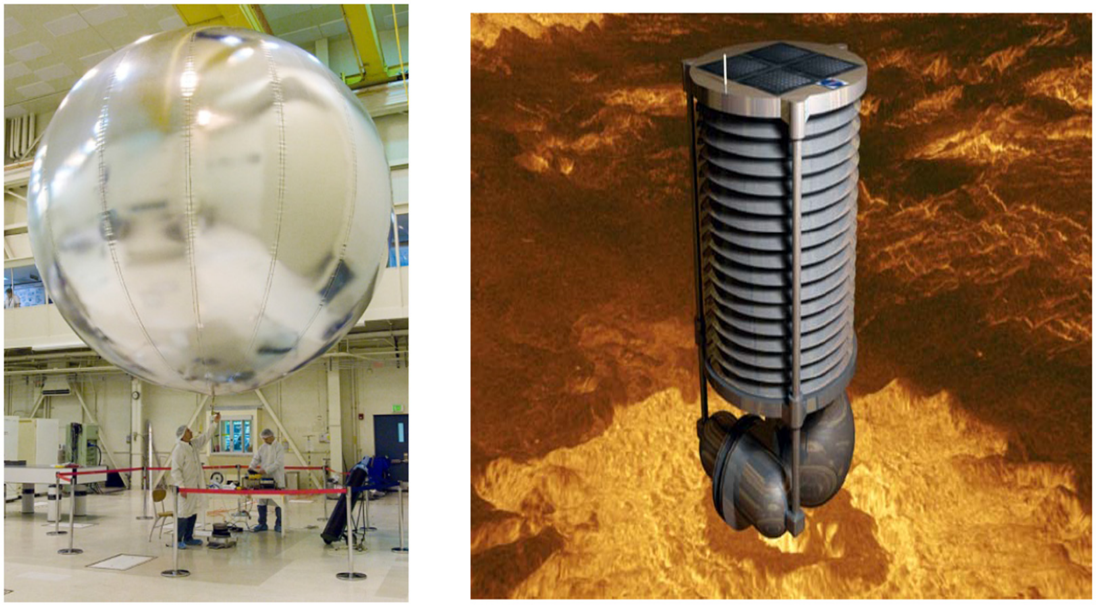


Figure 6-8. Flotation devices for the mid-cloud level on Venus (left) and for near surface operations (right). The two concepts have similar payload capacity but the vehicle on the right has only 2% of the volume of the balloon.

6.5.1.2 Deep Atmosphere Balloon

For operation deep in the Venus atmosphere, where the atmospheric density exceeds 50 kg m^{-2}, flotation devices made of thin metal sheet become practical.[69] The bellows-balloon illustrated in **Figure 6-8** has been demonstrated at JPL and is designed to cover the altitude range from 0 to 15 km so that it could descend to and ascend from the surface. However, for the present purpose, a constant altitude balloon of a simpler design without the bellows feature would be adequate. The life-limiting process here will be corrosion from the sulfuric acid environment, but a lifespan of years may be achievable. However, the electronics available for such a system would essentially be the same as those available for surface operations. On the other hand, the low altitude may help with the detection of the atmospheric counterpart of seismic waves.

6.5.1.3 Balloon at the Base of the Clouds

In the assessment of high-temperature electronics technology in Section 5.5, it was noted that 300°C is currently the highest temperature that has been achieved for electronics with a high level of integration. To provide margins for operation of a floating seismic station, designed to operate for years, the temperature to which this SOI technology is exposed to should probably be limited to 250°C. On Venus, this temperature is reached at an altitude of approximately 27 km above the mean Venus surface where the pressure is approximately 12 bars. Would it be feasible to design a long-lived super-pressure balloon for operation at that altitude?

We are not aware of any work on a constant altitude balloon for this altitude region. JPL has studied a concept for a cycling or phase change balloon inflated with a gas that changes phase to a liquid at the upper altitude but cycling is not conducive to extended life. There are two significant advantages to the targeted altitude:

1. This is below the clouds and very little sunlight reaches this level. This means that diurnal pressure cycling of the balloon/flotation device, which drives the design of super-pressure balloons and enhances buoyancy gas loss would be minimal.

2. The density of the atmosphere at this level is approximately 10 kg/m^{-2} or about 12 times that at the 55 km altitude of the mid-cloud level balloon. This would enable a more robust constructions and conceivably using a metallic membrane.

6.5.1.4 Summary: Balloons and Flotation Devices

Balloon technology for operations in the mid-cloud regions (55 km) is available today and missions with an atmospheric focus using this technology have been endorsed by the National Research Council's Decadal Survey.[70] Flotation devices for near-surface operation are largely an engineering challenge; it is the electronics that limit the utility of such a mission at this time. The region of the atmosphere near 27 km altitude may be the sweet spot for operation of a long-duration seismological observatory. The temperatures here would be low enough to permit the use of highly integrated electronics. The dense atmosphere and the low amount of solar radiation should also permit the design of a robust flotation device capable of years of operation without significant leakage. Hence, technology work on a flotation device with high payload capability for this region is needed.

6.6 Roadmap for Seismology in the Atmosphere

Given the maturity of the different technologies a step-wise approach is advocated similar to that adopted for the surface missions.

6.6.1 Generation 1—Pathfinder Mission

The mission would determine the atmospheric seismic background and lay the foundation for the next mission with more ambitious scientific goals. This mission would operate at mid-cloud level where conventional electronics can be used and for which the balloon technology is already developed. The NRC's Decadal Survey has already recommended a super-pressure balloon mission to the middle atmosphere; the Pathfinder mission would logically form a part of such a mission or be deployed as a technology experiment on that mission. The mission concept is illustrated in **Figure 6-9**.

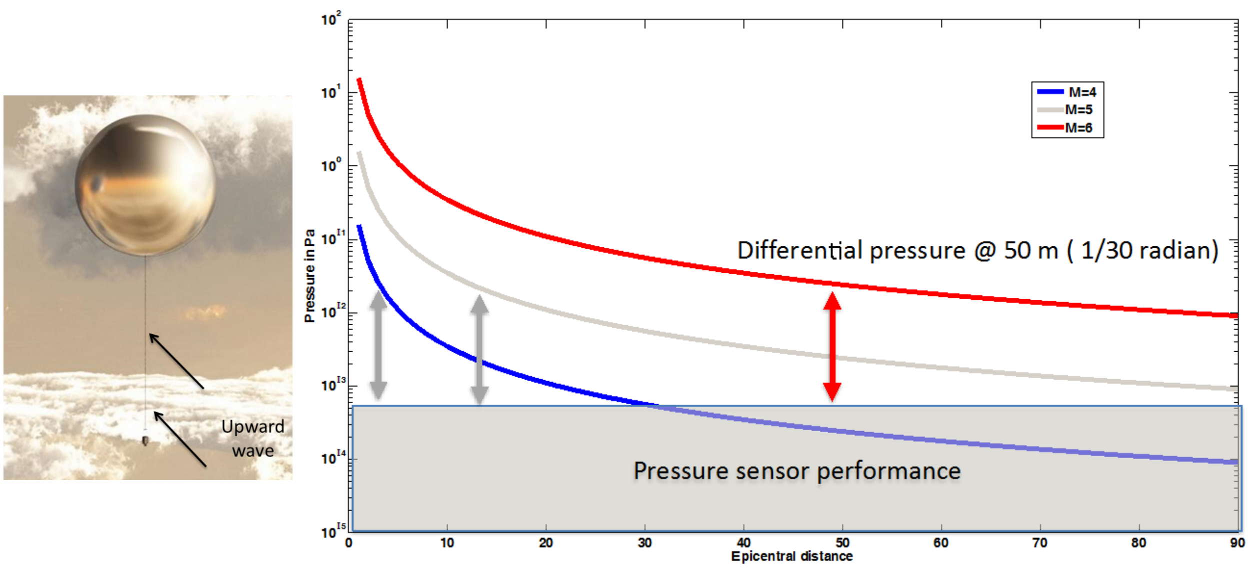


Figure 6-9. *Right:* Use of two barometers enables spatial filtering. *Left:* Differential pressure for a 50 m separation of the two barometers, as a function of the epicentral distance and for various earthquake magnitudes, at an altitude of 60 km. Atmospheric attenuation not taken into account. The shaded gray areais the blind zone of an off-the-shelf differential barometer.

The experiment consists of two barometers deployed from a tether. The purpose of the separation of the barometers is to enable pressure variations from waves propagating up from the surface to be discriminated from the effects of balloon altitude changes and atmospheric disturbances arriving from other directions. The use of two barometers with a vertical separation of a few tens of meters enables to correlate the arrival of a seismic waveform on both sensors (the speed of sound at the surface is 240 m/s) independently of the pressure noise linked to the altitude variation.

Other compensation methods could also be considered for the vertical motion: a radar altimeter or an accelerometer would be, in principle, useful augmentations of the measurement. Careful attention also has to be paid to the inlet. Local effects will include the motion of the gondola and the resulting turbulence, and may be compensated by the inlet. The waveform observed by the barometer in the seismic bandwidth is expected to be very similar to the waveform observed on the ground, but amplified due to the decrease in pressure along the transmission path, as discussed in Section 4.2. Unfortunately, the atmosphere of Venus is very dynamic and several sources of perturbations can be expected.

On Venus (which is here assumed to be close to Earth seismicity), there are about 1,500 M=5 events/yr. A balloon located in the 60 and 150 km altitude range would see ~1/400 of the planet, so about four detections per year. A 90-day mission may therefore record about 1 event (or maybe an order of magnitude fewer). If magnitude 7 quakes exist on Venus, and if their occurrence is monthly (like on Earth), their atmospheric counterpart would likely be seen globally.

A similar experiment on Venus will require either a precursor mission used to ‘tune’ the detection algorithm or a single mission in which an initial operating period would be devoted to tuning the detection algorithm.

6.6.2 Generation 2—Local and Regional Seismicity

This mission would use the same basic platform as the Pathfinder mission tailored for a seismic experiment. The principal differences are:

1. Mission duration: The primary means of extending mission duration would be using solar power on the vehicle so that it is not limited by battery storage. Lifespan would be limited only by the balloon itself; we believe that a lifespan between 3 months and a year is achievable.
2. Number of platforms: Deploying more platforms represents both more observation time and also the opportunity to detect teleseismic events at more than one location greatly simplifying interpretation.
3. Tether length: This was limited on the Pathfinder mission to avoid complexity in the accommodations of what is conceived of as a secondary payload. Increasing the tether length to several hundred meters and deploying an array of sensors along the tether would improve the discrimination of the system for low level signals and primarily benefit detection of teleseismic events.

The mission as conceived can be implemented with existing sensor, electronics, and balloon technology.

6.6.3 Generation 3—Internal Structure and Global Seismicity

This next major step in both the capabilities of the mission and the technology requirements involves deploying the balloon platforms at lower altitudes. Flight below the clouds has a number of advantages:

1. Most of the solar energy falling on Venus that is not reflected is absorbed in the clouds and, as a consequence, there is significant turbulence in the mid-cloud region. This turbulence was observed in situ by the Vega balloons. Deployment of the platform beneath the clouds would access a lower altitude zone that is more stable.
2. Floating below the clouds where the variations in solar heating of the balloon as it moves between day and night are much attenuated and so the balloon does not have to be designed with the extra strength to tolerate pressure cycling.
3. Extending the life of a balloon beyond the 3 months to a year for the Generation 2 vehicles may require floating in a denser part of the atmosphere. If the atmosphere is sufficiently dense, an impermeable metallic envelope can be used to achieve buoyancy with a lifespan of many years.

Any vehicle floating below the clouds will require high temperature electronics and a long-lived power source. These requirements have similarities to those for the long-lived surface stations (see Section 5.6). A key difference is that the temperatures are not as high. Long-lived platforms at 27 km altitude for example would be in a comparatively stable region of the atmosphere and could use SOI technology, which is already available at a fairly high level of integration. Solar power should be practical at these altitudes.[52]

6.6.4 Roadmap Summary

Table 6-1 provides a comparison of all three generations of missions. Note that neither the Generation 1 nor Generation 2 missions require new technology, as the primary sensor properties are based on existing off-the-shelf performance. Generation 3 would likely benefit from electronics technology developed for surface seismology. The development pathway for Generation 3 will, of course, depend on what is learned in earlier stages about Venus and its seismicity as well as the effectiveness of techniques used to discriminate against other acoustic signatures.

Table 6-1. Venus atmospheric seismology experiment roadmap.

	Generation 1 Pathfinder Technology Experiment	Generation 2 Local and Regional Seismicity	Generation 3 Global Interior Structure and Seismicity
Main Science Objectives	Seismic background investigation Seismicity in seismically active regions	Local / regional investigation of crustal thickness & structure)	Global investigation of internal structure
Platform	Balloon at 55 km with 50 m (TBC) tether	Balloon at 55 km with sensor array	Balloon at 27 km (250°C) to 55 km (0°C). Trade study needed
Number of Stations	1	3	5 to 7
Typical Mission Duration	Less than 1 month	3 months to 1 year	5 to 10 years
Sensors and Sensitivity	Microbarometer based payload sensitivity < 10^{-3} Pa + Inertial measurements, complementary atmospheric payload (electric field sensor …)	Microbarometer-based payload sensitivity < 10^{-3} Pa + Inertial measurements, complementary atmospheric payload (electric field sensor …)	Microbarometer-based payload sensitivity < 10^{-3} Pa + Inertial measurements, complementary atmospheric payload (electric field sensor …), imaging radar
Support Electronics	Conventional electronics	Conventional electronics	High temperature electronics may be needed depending on altitude
Balloon Technology	Polymer balloon with Teflon coating (TRL 6)	Polymer balloon w Teflon coating (TRL 6)	Polymer balloon with thin layer of aluminum foil providing low permeability (TRL 3)
Supporting Measurements	Temperature, pressure, wind speed	Temperature, pressure, wind speed	Temperature, pressure, wind speed

7 Remote Detection of Seismic Waves from Orbit

A number of techniques have been used to detect seismic events on the Earth from space (**Figure 7-1**). They may involve active or passive remote sensing of electromagnetic radiation originating from a disturbed layer in the atmosphere or in situ measurement of the ionospheric density. This section provides a review of the techniques that have been used on Earth and their potential application to Venus.

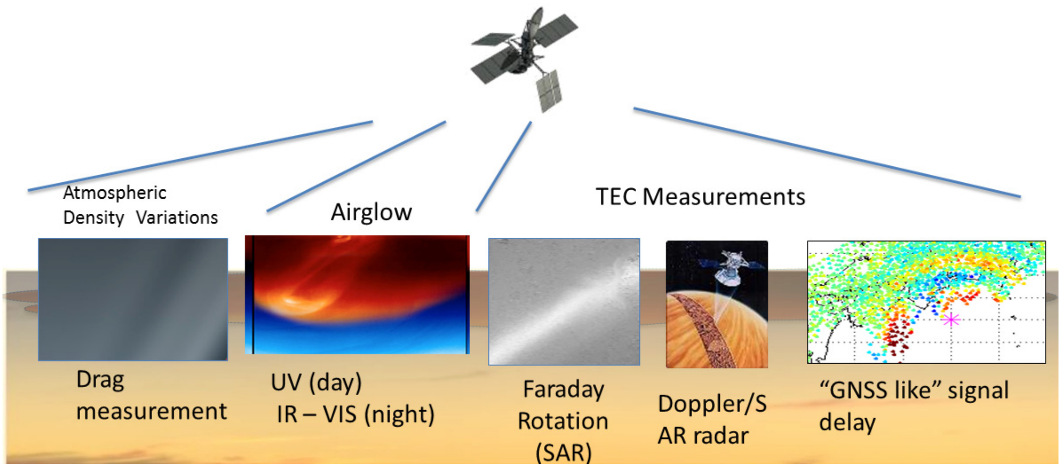


Figure 7-1. Orbital and ground-based observations that have been used for detecting terrestrial seismic events.

7.1 Relevant Terrestrial Measurements

In 1976, Peltier and Hines[71] proposed that tsunamis could excite waves in the ionosphere that would be detectable by the monitoring of the total electron content (TEC) in the ionosphere. Based on the very same principle (and governed by the same equations), the propagation of seismic gravity waves above quakes has been recorded on several occasions (see e.g., Occhipinti et al.[72]). **Figure 7-1** summarizes the various approaches that can be considered to detect those waves.

7.1.1 Total Electron Content—Detection with GPS Stations

When a seismo-acoustic wave arrives in the ionosphere, the large motion of the neutral particles induces the motion of ionic species in equilibrium. The changes in this equilibrium can be monitored through integrated electron densities or TEC values, which reflect the electronic balance resulting from the ion dispersion. The status of the ionosphere is primarily driven by the Earth/Sun interaction, solar wind, and magnetic field. On top of the diurnal pattern, the gravity waves trying to restore the overall balance, therefore sweep all over the planet's atmosphere and reflect these complex solid earth/ magnetic field/ atmosphere-coupling phenomena. However, as described in Lognonné and Clévédé,[73] a very specific time/space filtering can isolate perturbations such as tsunami atmospheric counterparts of seismic–acoustic waves.

Large quakes or tsunamis can therefore modulate the TEC content along a path through the ionosphere and these changes can be measured; GPS measurements are very sensitive to the TEC perturbations, as they induce delays in the propagation, and ultimately errors in precise point positioning applications. Taking advantage of this (e.g., **Figure 7-2**), it is possible to retrieve the ionospheric delay and hence the TEC as it is inversely proportional to the square of the considered frequency integrated along the line of sight. Any 2D or 3D knowledge of the TEC therefore requires numerous line-of-sight measurements requiring dense GPS networks to retrieve 3D information about the TEC value in a dedicated region (see **Figure 7-3**).

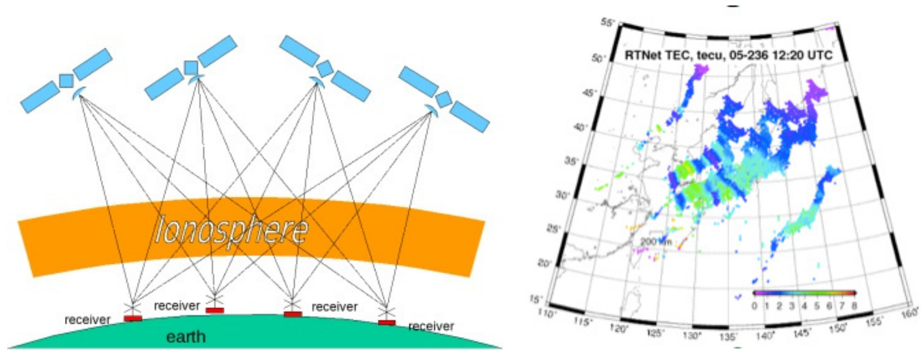


Figure 7-2. Ionosphere tomography measurement principle and resulting TEC map over Japan (http://gpsmet.com/gps_ionosphere_space_weather.php).

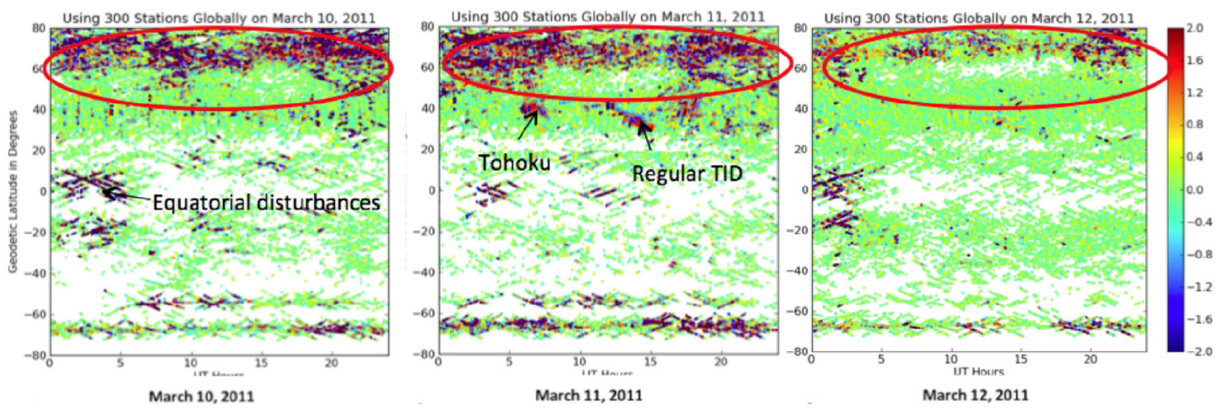


Figure 7-3. Earthquakes and tsunamis recorded by GPS networks—see the signal from the Tohoku earthquake in this record are not the only sources of TIDS on Earth. Methods are needed for discriminating from other kinds of events for accurate tsunami prediction.

For example, a dense network of GPS ground stations has retrieved the great Sumatra earthquake atmospheric counterpart.[74] The ocean height profiles measured directly and obtained from the TEC data (see **Figure 7-4**) are proof that the signal monitored in the atmosphere is in reality a seismic signal, and is not due to another simultaneous perturbation, such as the one linked to geomagnetic activity (At high-altitude, traveling ionospheric disturbances [TIDs] are present frequently). Methods of discriminating seismic events from naturally occurring events are being explored so that this information can be used to reliably predict tsunamis.[75]

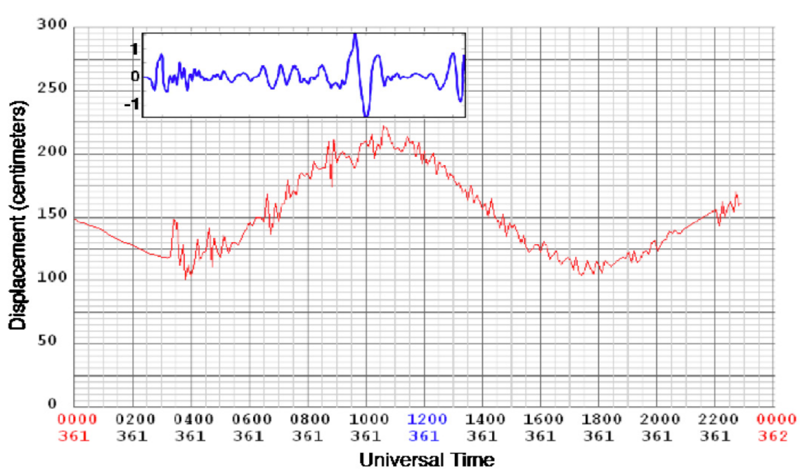


Figure 7-4. Comparison of sea surface variability measured directly (red line) and from TEC measurement during the Sumatra tsunami (blue line).

7.1.2 Total Electron Content—Dual Frequency Sounding

The ionospheric perturbation resulting from the tsunami following the Sumatra earthquake of 2004 was also detected in TEC measurements using dual frequency altimeters on both the Jason and TOPEX/Poseidon spacecraft. These observations were snapshots along a ground-track and did not document the propagating nature of the disturbance. Nevertheless, they provided sufficient information on the nature of the tsunami signal. The signature at right in **Figure 7-5** indicates the TEC of the tsunami. The signature at the left is an estimate of the background signal under these same sunrise conditions. The broken lines represent the TOPEX/Poseidon (left) and Jason-1 (right) trajectories. The blue contours represent the magnetic field inclination.

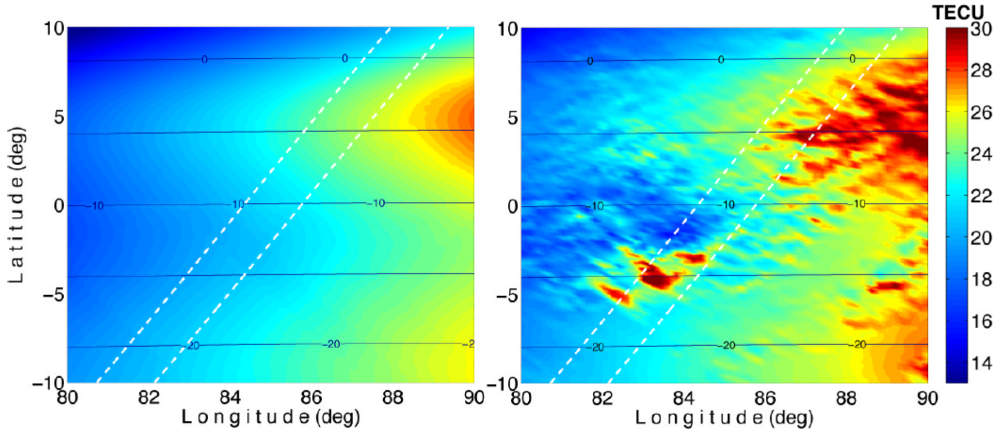


Figure 7-5. Comparison of the unperturbed TEC (left) with that perturbed by the 2004 Sumatra earthquake. The dotted lines are the tracks of the Jason-1 and TOPEX-Poseidon satellite, which acquired the TEC data (Occhipinti et al.[20]).

7.1.3 Total Electron Content—Faraday Rotation

Spaceborne synthetic aperture radar (SAR) systems are used in many planetary missions, often as a proxy for imagers. This is a particular asset when a dense layer of cloud covers the planet's surface, as it is the case on Titan or Venus. As described in Jehle et al.,[76] the use of SAR sensors with lower frequency, which is used in conjunction with higher range chirp bandwidth in order to obtain information with a higher geometric resolution, has a drawback for imaging purposes: the impact of ionosphere propagation delays increases and causes signal degradation within a dispersive medium such as the ionosphere. At L-band frequencies, the Faraday rotation, which causes a change in the polarization of the wave due to the magnetic field, can become significant. In the process of correcting for this effect to produce high fidelity images, the value of the TEC value can be computed quite accurately.

Several images of the same region need to be obtained to retrieve temporal variation of the TEC and this may be impractical for a satellite in the low orbit needed for SAR imaging. Accordingly it may be difficult to apply SAR techniques for retrieving small TEC variations in a feasible mission.

7.1.4 Atmospheric Density Variations through Drag

As the gravity waves propagate up in the atmosphere, they induce variations in atmosphere density that can be measured. The highly drag-sensitive GOCE satellite has therefore recorded the atmospheric counterpart of a tsunami.[77] However, this 'proof of concept' is not yet applicable to the Venus case, as even with a constellation of small satellites, drag measurement would only get local measurement (and not 2D/3D measurements) that are required to retrieve the potential seismic profile.

7.1.5 Airglow Detection on Earth

A more promising approach involves the imaging from orbit of the airglow generated by the local thermal perturbation. In particular, dissociative recombination of O_2+ with ionospheric electrons produces emission at 630.0 nm at an altitude of approximately 250 km. Modulation of the light from the airglow layer, resulting from the tsunami caused by the March 11, 2011 Tohoku earthquake, was observed with mountain-top cameras on the island of Maui and observed to be propagating from the direction of the earthquake epicenter with a velocity that matches that of the ocean tsunami (**Figure 7-6**). The 2D measurement is intrinsically provided by these images; image sampling every few seconds is also feasible.

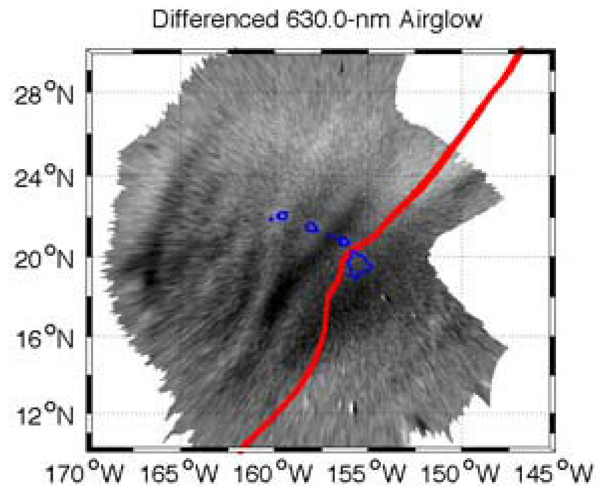


Figure 7-6. Airglow signature of the March 2012 tsunami of which at this point is propagating to the southeast in the vicinity of the Hawaiian islands shown in blue (Reprinted from Makela and Lognonné.[78])

7.2 Key Constraints for Orbital Seismic Techniques on Venus

When considering the application of techniques that have been applied on the Earth, it is essential to recognize some key differences.

7.2.1 Lack of Independent Means of Identifying a Seismic Event

Most of the terrestrial investigations of space detection of seismic events have been enabled by an independent determination of the time and location of seismic events by the terrestrial seismic network. Consequently, techniques with the potential for autonomously detecting event time and location are going to be of much greater interest. In this context, the method should allow discrimination between infrasonic acoustic signals and others signals coming from the atmosphere dynamics.

7.2.2 Mission Lifetime

Unlike the surface and atmospheric techniques, mission lifetime for an orbital mission is typically limited more by financial rather than technical considerations, typically through the choice of electronics parts and components, and by redundancy strategy (and therefore mass). In the next section, we consider the lifetime that is required to perform the needed measurements.

7.2.3 Orbital Considerations

Any orbital monitoring system faces the tradeoff between investigating small areas in detail and having a synoptic view of the planet. To this, we must add the specific constraint of a time sampling sufficient to record the propagation in the ionosphere of any seismic artifacts, and to filter the signal of interest from the background. This implies a sufficient coverage of the globe to see enough of the wave propagation, and therefore, a high altitude (a half globe view would be optimal), but, as a result, this also implies sufficient spacecraft stability and resolution to resolve the propagating wave resolution, very similar in principle to Earth geostationary high-resolution imagers.

In addition, as explained in more detail in Section 9, Venus presents some unique challenges. Because of its slow rotation, there is no ground synchronous orbit. Therefore, measurements requiring a constant local hour observation are difficult to achieve.

7.2.4 Sensitivity

A useful technique and its practical implementation must not only be sensitive enough to detect a seismic signal but also incorporate methods for discriminating that signal from not only instrumentation and spacecraft noise but also non-seismic–related events in the Venus atmosphere.

7.3 Performance Requirements

When considering the application of terrestrial methods, one should remember that on Venus, the position and time of a particular seismic event will not be known by other means.

The infrasonic signal generated by seismic waves at greater distances from the epicenter initially travels through the solid planet as a Rayleigh wave before propagating vertically in the atmosphere and producing thermal, airglow, and TEC signatures in the upper atmosphere. From the standpoint of a spacecraft orbiting Venus, a wave appears to propagate horizontally in the atmosphere from the epicentral location with the speed of seismic waves (~4 km/s). Since atmosphere waves generated entirely within the atmosphere cannot attain such high velocities, this offers a means of isolating and extracting atmospheric wave motions of seismic origin. By acquiring repetitive images of the upper atmosphere at a rate commensurate with the spatial resolution and horizontal propagation speed of the seismic waves, the seismic waves can be separated from slower moving atmospheric waves. Similar techniques have been applied in helio-seismology methods to discriminate acoustic waves and normal modes from the background noise without quakes.

Because of the transient and infrequent occurrence of seismic events, the field of view of the orbital sensors should cover as large a part of the planet as is practical. Ideally, observations should cover the full disk enabling over half the planet to be monitored with a second and possibly a third spacecraft covering the remainder of the planet to ensure coverage with acceptable observing geometry. However, truly global coverage may be impractical in practice since some techniques are not as effective during daytime because of the background of solar reflected light.

7.4 Signal Background

As described by Lognonné and Clévédé[73], the acoustic seismic waves propagating in the atmosphere can be seen as a particular case of general coupling between ‘solid’ Venus modes and atmospheric modes. Among those coupled modes, one can also find solutions that imply gravity waves, which are expected to be one of the main sources of ionospheric airglow (as an example), as they also generate local heating. It is also important to note that the ionosphere, being (by nature) a very dynamic medium due to the interaction of the solar wind and planetary atmosphere, is expected to have a significant amount of perturbations (this can be seen in airglow images measured by Venus Express, see, e.g., Muñoz et al.[79]).

In order to discriminate the signal of interest from these sources, a study of all possible perturbation sources is expected, but, as in the case of tsunami signal detection, a filtering adapted to the spatial and temporal properties of these modes can be envisioned.

7.5 Techniques and Technologies

This section presents various possible techniques and technologies for space detection of infrasonic waves and their feasibility with respect to discriminating seismic sources from other mechanisms.

7.5.1 Infrared Signatures

Two airglow emissions are good potential candidates for a marker of infrasonic post-seismic waves: O_2 night side airglow at 1.27 µm and CO_2 Non-LTE (local thermodynamic equilibrium) dayside emissions at 4.3 µm. The O_2 night side airglow presents an emission peak around a 96-km altitude. Preliminary instrument sizing and Venus Express observations demonstrate that this emission can be observed with a good signal-to-noise ratio in the near infrared. However, the background signal observed at nadir presents two important drawbacks. First, at this wavelength, there is some signal coming from the surface that generates signal intensity variations as a function of position. But more importantly, the background emission varies quickly in space and time depending on the upper atmosphere dynamics. The separation between wave like-features and these variations of the background can be very difficult, even with fast imaging capability.

The other interesting airglow emission is the day-side CO_2 Non-LTE emission at 4.3 µm. Many arguments point in favor of using this emission for the detection and analysis of infrasonic post-seismic signals:

- The emission peak is at 130 km in the proper altitude range.
- The background signal is coming only from the upper atmosphere because below 110 km the CO_2 absorb at this wavelength. Consequently, 1% perturbation induced by acoustic or gravity waves would create 1% variation of the emission observed at nadir.
- The background signal is varying smoothly with solar zenith angle, and will vary in time only with the solar radiation.
- Background signal is properly quantified by Venus Express observations.
- These emissions are sensitive to temperature and density perturbations (Lopez-Valverde[80]), with sensitivities of the order of 1% variations for 1K temperature or 1% density variations.
- Gravity waves have been already identified on top of the 4.3 µm background emission on Venus.[81]
- Preliminary instrument sizing suggest that a SNR larger than 10 can be achieved for a 1% perturbation of background, even at very short integration times (less than 1 second).

As already explained above, the observations imply an observation of the full-day side disc during the majority of the orbit. So, such an instrument would present an important thermal challenge because the focal plane and the optics should be maintained at low temperature whereas the planet, on one side, and the Sun, on the other side, are heating the spacecraft. Despite this technical limitation, the CO_2 day side non-LTE emissions are the best possible markers of post-seismic infrasonic waves on Venus.

7.5.2 Ultraviolet Signatures

A good candidate marker for acoustic and gravity waves is the CO Cameron band UV emission (at 220 nm) because these emissions observed at nadir present a peak around a 140-km altitude. However, the thermosphere emissions represent only about a percent of what is observed at nadir. So, assuming that the infrasonic post-seismic waves generate 1% of the thermosphere emissions, it would be only 0.01% of the background observed at nadir. In addition, the nadir background signal at these wavelengths presents strong lateral variations due to the unknown UV absorber at the cloud top. Because the signal is very weak compared to background at nadir, the preliminary instrument sizing would not allow a SNR larger than 1 for infrasonic waves.

The only opportunity would be a fast imaging instrument at 220 nm looking at the day side limb, but it put severe constraints on the orbit of the mission if long observation times are requested. In particular, it seems difficult to reconcile these constraints with other observations.

7.5.3 Drag Measurement

The detection of acoustic and gravity waves from satellite drag was demonstrated on Earth,[77,28] but also on Venus with the recent air drag measurements by Venus Express spacecraft.[82] So, the concept is feasible, but accelerometer measurements give only a drag profile at a time, a sort of cut in the propagating wave. In order to reconstruct the wave propagation, a constellation or a swarm of satellites, each measuring the drag properties, would be needed.

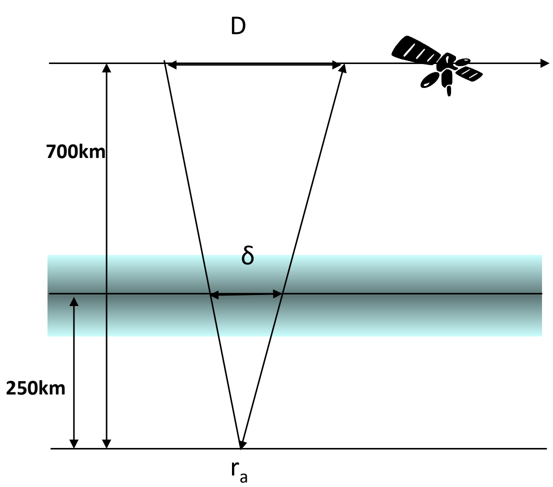
7.5.4 Total Electron Content Signatures

7.5.4.1 TEC Variations through SAR

One of the last remaining options for detecting acoustic seismic waves is to monitor the TEC in the Venus ionosphere. On Earth, such detection can be made through the use of dense GPS networks, which monitor the GPS constellation (see e.g., Rolland et al.[83]). At each ionospheric 'piercing' point, the delay in the propagation can be tracked and a tomography of the ionosphere can be performed.

Such measurements require many ground stations to make regional measurements, and a similar-sized constellation of spacecraft is out of reach for a mission. However, a preliminary demonstration could be made by an orbiting SAR, associated with a ground reflector, which would ensure a 'permanent scatterer' on the surface of Venus (**Figure 7-7**). Several SARs would be better, in order to have a better width of measurement, but the existence of acoustic waves in the ionosphere could likely be inferred from the measurements.

Such a strategy would require a good knowledge of the natural scattering properties of the Venus surface, or the help of a few artificial, passive reflectors spread on the ground to multiply the known reflections (**Figure 7-8**). Such reflectors could also be deployed by a short-lived lander.



r_a	δ	D
10m	8.5 km	23.8 km @ 3.4 s
50m	1.7 km	4.76 km @ 0.68 s
100m	850 m	2.38 km @ 0.34s
300m	283 m	0.8 km@ 0.11 s
500m	170 m	476m @ 0.068s

Figure 7-7. A resolution of a few km for the wave detection can be achieved with a meter-scale reflector.

Figure 7-8. Orbital observations. *Left:* deployment of a radar reflector. *Right:* Reflectors seen from orbit.

7.6 Roadmap for Orbital Observations

Given the maturity of the different technologies a step-wise approach is advocated similar to that adopted for the surface missions. At our present stage of understanding, the only practical techniques for independent detection and discrimination of seismic events are those that involved some kind of imaging capability with high spatial and temporal discrimination. At this stage, the infrared technique is best understood and the ultraviolet technique shows promise and should be looked at in more detail. There may be ways to generate sufficiently detailed images of TEC with sufficient spatial and time resolution but at this time we have not identified them.

7.6.1 Generation 1—Pathfinder Experiments

As with the surface and atmospheric experiments, the concept here is to exploit opportunities on orbital missions with other primary science goals to determine the feasibility of such a mission. The most important accomplishment of such a mission will be to obtain a comprehensive characterization of the backgrounds so that a mission could be designed with a high probability of discriminating signals from noise.

The first such experiments have already been conducted from the Venus Express mission and have revealed something of the wave motions that exist there.[28] The concept here as on Venus Express is to take advantage of an instrument included on the payload for atmospheric investigations, which can obtain information of adequate sensitivity, spatial resolution, and temporal coverage. A major challenge for the experiment is the large data demands, and a suitable orbit.

A proof of concept could be conducted during an orbiter's aerobraking phase, which could offer extended observations of the entire Venus nighttime. These observations would enable the space-time filtering necessary to the removal of the atmospheric background noise. Even if not optimum, the near–IR nightglow at 1.27 µm, observable in most of the existing spectral imaging instruments, can also be used to identify crustal surface waves from shallow quakes, which typically have periods of 20-30 sec. In contrast to nightglow at other wavelengths (Herzberg I&II, Chamberlain bands), the 4460-s radiative lifetime of the 1.27 µm nightglow is large, and the signal is generated by transport of O_2 by the seismic waves, in contrast to the shorter radiative lifetime airglows, such as at 4.3 µm where the seismic signal is associated with density variations.

A simulation has been done by fully modeling the Rayleigh seismic waves using a Venusgram atmospheric model that takes into account all dissipation effects, including CO_2 (the most critical molecular relaxation), following the approach of Lognonné et al.[84] and Artru et al.[85] The simulation (**Figure 7-9**) is based on an Ms=6.5 quake, at several epicentral distances, assuming a 9-sec integration time. Seismograms are low-pass filtered at 1/25 Hz. Amplitudes have a SNR>2 for the 1600 Rayleigh detection threshold (threshold dashed line) of up to 60° of epicentral distance by increment of 15°. In **Figure 7-9**, each 'airglownogram' is shifted by 30° (Δ–15°), where Δ is the epicentral distance. The simulations assumes that Venus has properties identical to those in the Preliminary Reference Earth Model (PREM) for the upper mantle and crust[86] with Qs=600, but with the Venus radius.

This simulation demonstrates that a magnitude 6.5 event can be observed at up to 60° of epicentral distance with a SNR>2 at the pixel level, large enough for all further processing necessary for the measurement of the phase or group velocity of the seismic waves.

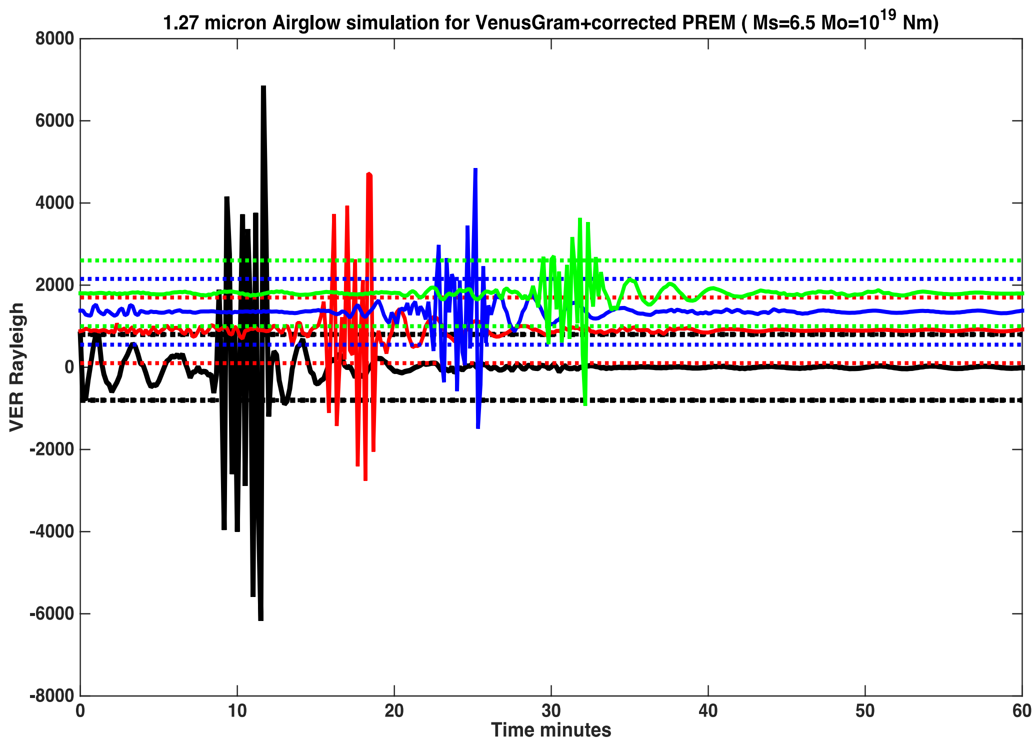


Figure 7-9. Simulation of the volumetric emission rate generated by an Ms=6.5 quake on Venus at several epicentral distances.

7.6.2 Generation 2—Local and Regional Seismology

The concept of this mission would be to observe a limited region of the planet at resolution high enough to detect the signal from the epicentral wave from a Venus quake. This would be a single hot spot emerging directly above the event. Our analysis indicates that events as small as magnitude 3 could be detected in this way. In addition to the thermal sensor, for event recognition, ultraviolet and other sensors should be considered to both confirm the validity of the thermal seismic signature and potentially provide other information about the event.

The sensor would generate approximately 10 megabytes of data per second. Although techniques for recognizing events may ultimately be implemented on board, we believe it is prudent to take advantage of the optical telecommunications capabilities that NASA has developed to return the data to Earth for processing. That way a variety of algorithms can be evaluated and the likelihood of detecting false positive reduced.

7.6.3 Generation 3—Regional and Global Seismology

This mission would provide synoptic coverage of the entire planet with a constellation of at least three spacecraft. The basic measurement technique would be the same as in the Generation 2 mission. However, this system would be equipped to detect and observe the global propagation of large events. As such, it would involve scaling up the second generation mission in terms of the size of the staring focal plane arrays, and the volume of data to be acquired, communicated and processed. Onboard processing of much of this data would be considered if this proved to be a favorable trade with the use of optical telecommunications.

Table 7-1. Roadmap for orbital seismological investigations.

	Generation 1 Pathfinder Technology Experiment	Generation 2 Local and Regional Seismicity	Generation 3 Global Interior Structure
Main Science objectives	Seismic background investigation Seismicity in seismically active regions	Local and regional seismicity local / regional investigation of crustal thickness & structure)	Global investigation of internal structure
Platform	Orbiter with ability to image the planet in infrared wavelengths of interest	Orbiter with enhances telecommunications capability and dedicated sensors	Orbiter with enhanced telecommunications and powerful on board signal processing
Number of Spacecraft	1	1	3
Typical Mission Duration	2 years	2 to 5 years	5 to 10 years
Sensor Complement	Infrared Imaging	Infrared and UV imaging	Infrared and UV imaging TEC measurements
Observational Strategy	Sampled coverage of 1% of the planet at one second intervals	Continuous coverage of 5% of the planetary disc at second intervals	Continuous global synoptic imaging at second intervals
Data Acquisition and Processing Requirements	Modest. Compatible with mission with other primary objectives	High. Requires optical communications	Very high. Requires optical communications and on board processing
Supporting Measurements	TBD	TBD	TBD

8 Surface, Atmospheric, and Orbital Techniques—Synthesis

In this section, the information on seismic techniques implemented on the surface, in the atmosphere, and from orbital techniques, which were discussed in Sections 5–7, are compared and contrasted. By comparing what can be accomplished, by each type of technique in each 'generation' of capability, we are laying the groundwork for defining a path forward in Section 9. For the Generation 2 and 3 implementations, we also discuss the synergies that exist between techniques.

8.1 Generation 1—Pathfinder Missions

A comparison of the Generation 1 Pathfinder concepts appears in **Table 8-1**. The information is derived from the roadmaps for Pathfinder missions presented in Sections 5.6.1, 6.6.1, and 7.6.1. All three concepts involve experiments conducted on a Venus mission with different but compatible primary scientific objectives.

Table 8-1. Comparison of Pathfinder mission concepts for surface, atmosphere, and orbit.

	Surface Platform	Atmospheric Platform	Orbital Platform
Science and Technology Objectives	Seismic backgrounds in the 1 to 5Hz and 0.01 to 1 Hz frequency ranges	Seismic backgrounds in the 1 to 5 Hz and 0.01 to 1 HZ frequency ranges	Seismic backgrounds in the 0.01 to 1 Hz frequency range
Platform and Sensors	Short duration lander, which deploys seismic sensor to the Venus surface	Balloon at 55 km with 50-m tether and two microbarometer sensors	Orbiter with infrared imaging or scanning array
Number of Platforms	1	1	1
Number of Observation Points	1	1	N×N, where N is determined by the actual sensor payload
Frequency Range			
1 to 5 Hz	Yes	Yes	Not feasible
1 to 0.01 Hz	Yes	Yes	Yes
0.01 to 0.001 Hz	Not feasible today	Not feasible	Not feasible
Platform Lifetime - target	2 to 3 hours	30 days	1 year
Technology Readiness	TRL 4. Requires several years of development	TRL 6. Mature	TRL 6. Mature
Supporting Measurements	Temperature, pressure, wind speed	Temperature,	TBD
Infrastructure Needs	Allocation of 5% of payload mass and data resources	Allocation of 5% of payload mass and data resources	Allocation of 5% of observing time and data resources

8.1.1 Science and Technology Objectives

As Pathfinder experiments conceived in a situation where there is a great deal of uncertainty about Venus seismicity and backgrounds, all three concepts are targeted at improving basic knowledge about Venus seismicity: what are the backgrounds that seismic investigations have to contend with, can certain techniques reduced interference from non-seismic events, and can we obtain concrete evidence that there is seismic activity on Venus. Learning anything about Venus's crustal structure would be a bonus.

8.1.2 Platform and Sensors

Each concept requires a different platform but all of these platforms are well within the scope of existing technology. The sensor complement for the lander mission is based on technology that could be available within 5 years. The sensors for the atmospheric platform are available today.

For the orbital techniques, we envisage the use of an imaging infrared sensor already included in the scientific instrument payload.

8.1.3 Number of Stations and Observation Points

Only one platform is required for each of the technology experiments. For the surface and atmospheric platforms where measurements are made in situ, this is also the location of the single observation point. The orbital platform, on the other hand, uses remote sensing techniques (probably infrared) and, in this case, the number of observation points corresponds to the number of resolution elements in the observing sensor. We have indicated this in **Table 8-1** as N×N, where N is in the range of 100 to 500.

8.1.4 Frequency Range

The surface and atmospheric platforms incorporate both a high frequency range (1 to 5 Hz) and moderate frequency range (1 to .01 Hz) sensors. The orbital platform only observes in the moderate frequency range. There are no low frequency observations.

8.1.5 Platform Lifetime

Platform lifetime ranges from 2 to 3 hours for the lander to 30 days for the balloon to more than one year for the orbiter.

8.1.6 Technology Readiness

Both the atmospheric and orbital platforms require no new technologies. Sensor for the surface platform will require some development but this is mitigated because most of the electronics can be operated at near-Earth ambient temperatures during the very limited lifetime of the Pathfinder mission.

8.1.7 Supporting Measurements and Infrastructure Needs

Some of the supporting measurements specified here may be part of the baseline payload. Temperatures and wind velocity for the in situ measurements are vital. All of these Pathfinder experiments are envisaged as demonstrations of a technique and may not contribute in any way to the primary scientific objectives. However, they will require spacecraft resources. The target for the Pathfinder missions is to employ no more than 5% of the resources (payload mass, power, telecommunications etc.) allocated to the primary science objectives.

8.2 Generation 2—Local and Regional Investigations

Generation 1 Pathfinder mission concepts are exploratory—characterizing backgrounds and validating techniques and technologies while creating the opportunity for obtaining some science results but using only a fraction of mission resources. Generation 2 mission concepts (see **Table 8-2**), on the other hand, are primarily science missions with substantial resources dedicated to the seismology objectives.

8.2.1 Main Science Objectives

The goals of all three Generation 2 concepts are to characterize seismicity and to investigate crustal thickness and regional structure. Since the atmospheric platform circumnavigates the planet every few days and the orbital platform can observe different regions, both have the potential for detecting global variations in seismicity.

Table 8-2. Comparison of Generation 2 concepts for surface, atmosphere, and orbit.

	Surface Platform	Atmospheric Platform	Orbital Platform
Main Science Objectives	Local/regional investigation of seismicity	Local / regional/global investigation of seismicity crustal thickness	Local regional global investigation of seismicity and crustal thickness
Platform and Sensors	Lander with HF and VBB seismic sensors	Balloon at 55 km with 500-m tether and microbarometer array	Orbiter with infrared staring array for regional monitoring
Number of Observation Stations	1	1 to 3	1
Number of Observation Points	1	1 to 3	512×512 (infrared staring array)
Frequency range			
1 to 5 Hz	Yes	Yes	Not feasible
1 to 0.01 Hz	Yes	Yes	Yes
0.01 to 0.001 Hz	Yes	Not feasible	Not feasible
Platform Lifetime – target	3 months to one year	3 months to one year	5 years
Technology Readiness	TRL 3. 5–10 years to technology readiness	TRL 6. Mature	TRL 6. Mature
Supporting Measurements	Temperature, pressure, wind speed	Temperature, TBD	TBD
Infrastructure Needs	Relay orbiter	Relay orbiter	Optical telecom

8.2.2 Platform and Sensors

The platforms for both the atmospheric mission and the orbital mission are broadly similar in capability and technology to those discussed for the Pathfinder missions. However, for Generation 2, they are dedicated to the seismology investigations and sensors and deployment devices can be tailored and optimized to the seismology objectives. The platform for the surface mission on the other hand requires new technology in order to operate for 90 days to 1 year needed to achieve Generation 2 science objectives. This is a formidable challenge (see Section 8.2.6).

8.2.3 Observation Stations and Observation Points

As with the Pathfinder experiments, for the two in situ experiments, the number of observation points corresponds to the number of stations—one for the lander and up to three for the atmospheric platform. For the orbiter, which uses remote sensing, there is a very large number of observation points. We envisage a 512×512 grid for this Generation 2 experiment. It may be feasible to make it much larger.

8.2.4 Frequency Range

With a stable point on the surface, the landed sensor can, in principle, conduct measurements in all three frequency bands of interest. Technological feasibility in the high temperature environment is the controlling practical consideration discussed in Section 8.2.6.

Measurements from the atmospheric platform can be conducted in two frequency bands. The high-frequency band presents the least difficulty. The mid-frequency band will be more challenging because of the difficulty of compensating for altitude changes in the platform, which cause spurious pressure changes. Very low frequencies are impractical for the same reason.

For the orbital platform, the low frequency range is not accessible because of absorption effects in the high atmosphere. The mid-frequency is the prime target. Low frequencies are not detectable because the wavelengths are longer than the field of view of the sensor and sensor stability issues become important on these long time scales.

8.2.5 Platform Lifetime—Target

Both the surface and the atmospheric platform are of limited lifetime (3 months to 1 year) although for different reasons. The surface platform is limited by the lifespan of the high-temperature electronics, and the atmospheric platform by the lifespan of the balloon as a result of diffusion or pinholes. In contrast, the orbital platform would have inherently a longer lifespan limited primarily by station-keeping requirements (see **Table 8-2**).

8.2.6 Technology Readiness

The technology for both the atmospheric and orbital platform is ready today. The technology for surface seismology, specifically the high-temperature electronics and power technology, is at least 5 years away depending on the approach taken (e.g. analog or digital).

8.2.7 Supporting Measurements and Infrastructure Needs

Supporting measurements are needed to discriminate events of seismic origin in a background dominated by other natural and spacecraft sources. The ability to capture large amounts of data through an enhanced communications infrastructure plays a key role in this process.

8.2.8 Synergies between Atmospheric and Orbital Platforms

The atmospheric platforms, depending on the ultimate sensitivity that can be achieved will be able to detect events as small as magnitude 2 or 3 within a radius of a few hundred kilometers of the platform. The orbital platform is less sensitive but can observe events over a much larger area. There should be a significant number of events observed by both observation times in year that are in the magnitude 3.5 to 4 range that can be detected by both platforms. Direct observation of the infrasonic signals at a range of frequency will provide much more information on the source mechanisms for confirming models of event generation. Since both platforms can be implemented with existing technology, it is reasonable to consider a mission with these synergies. Since the technology for Generation 2 surface measurements is less mature, we consider these synergies in Section 8.3.

8.3 Generation 3 Global Investigations

The goal of the Generation 3 mission concepts is to perform comprehensive investigations of the seismicity and interior structure of Venus. The goal is to improve sensitivity, spatial coverage, and lifetime relative to the Generation 2 concepts. This section provides a comparison of surface, atmospheric, and orbital approaches and discusses the synergies between the techniques.

8.3.1 Main Science Objectives

The science goals are to characterizing seismicity and interior structure on a global basis. Specifically, the missions will attempt to map the spatial distribution of seismic events and characterize at least 10 teleseismic events of magnitude M>6 in order to probe the deep structure of the Venus interior. With our seismic activity assumptions, this may require a lifespan of about 1 terrestrial year.

Table 8-3. Generation 3 comparison of surface, atmospheric, and orbital platforms.

	Surface Platform	Atmospheric Platform	Orbital Platform
Main Science Objectives	Local/regional investigation of seismicity and for probing the deep interior	Local / regional investigation of seismicity crustal thickness	Global investigation of seismicity and crustal thickness
Platform and Sensors	Lander with HF and VBB seismic sensors	Balloon at 27 to 55 km with 500 m tether and microbarometer arrays	Orbiter with infrared staring arrays for **global** monitoring
Number of Observation Stations	1 to 3	3 to 5	3 to 4 for continuous global coverage
Number of Observation Points	1 to 3	3 to 5	Infrared staring arrays or mosaicked array with 10 to 100 megapixels
Frequency range			
1 to 5 Hz	Yes	Yes	Not feasible
1 to 0.01 Hz	Yes	Yes	Yes
0.01 to 0.001 Hz	Yes	Not feasible	Not feasible
Platform Lifetime - target	3 months to one year	3 months to one year	5 years
Technology Readiness	TRL 3. 5–10 years to technology readiness	TRL 4. 5 years to technology readiness	TRL 4. 5 years to technology readiness
Supporting Measurements	Temperature, pressure, wind speed. Altimeter and inertial measurements	Temperature, background pressure, wind speed, Altimeter and inertial measurements	TBD
Infrastructure Needs	Relay orbiter	Relay orbiter	Optical telecom

8.3.2 Platform and Sensors

The platform for the surface mission represents a significant advance over that described for the Generation 2 mission. Rather than the analog approach adopted for Generation 2 this would involve a fully digital approach implemented with high temperatures electronics for multiyear operation at 500°C. The atmospheric platform is also an advance over Generation 2 since it would be designed for a five year lifetime. This may require operation lower in the atmosphere and hence operation at higher temperatures but it should still be possible to operate with solar power. There is no major technical advance required for the orbital platform. However, it would be equipped with much larger staring arrays than needed for the regional investigation.

8.3.3 Observation Stations and Observation Points

For the global investigations, more platforms are needed than for the regional investigations in Generation 2 missions. For the in situ platforms the number of observation points corresponds to the number of stations – one to three for the lander and up to five for the atmospheric platform. Synergies among the platforms and the orbiter may reduce the number that are needed (see Section 8.3.9). For the orbiter, which uses remote sensing, there is a very large number of observation points. We envisage a 10 Megapixel grid for this Generation 3 capability.

8.3.4 Frequency Range

With a stable point on the surface, the landed sensor, is unique in that it conduct measurements in all three frequency bands of interest. It also can make measurements in all three degrees of freedom.

Measurements from the atmospheric platform can be conducted in two frequency bands. The mid-frequency band will be more challenging because of the difficulty of compensating for altitude changes in the platform. Very low frequencies are impractical for the same reason.

For the orbital platform, the low frequency range is again not accessible because of absorption effects in the high atmosphere. The mid frequency is the prime target. Although, in principle, low frequencies could be accessible with the very large staring sensors envisaged here, it might prove impossible to achieve the sensitivities needed at these low frequencies.

8.3.5 Platform Lifetime—Target

For Generation 3, the goal is at least 3 (terrestrial) years. This will ensure a sufficient margin with respect to the expected seismic activity. For the surface platform, the technology driver is the electronics and the pathway is likely the use of vacuum electronics rather than semiconductors. For the atmospheric platform, it is the balloon. Flight at lower altitudes is the chosen approach. The orbital platform would have inherently a longer lifetime although it may be limited by station-keeping requirement.

8.3.6 Technology Readiness

The most challenging technology is for the lander and this will involve a stretch beyond the Generation 2 mission because of the additional lifetime and the need for digital electronics operating at 500^{o}C. The atmospheric platform requires advances balloon technology and electronics for up to 250^{o}C. This is an advance beyond the Generation 2 platform where no new technology is needed. No new technology is needed for the orbital platform.

8.3.7 Supporting Measurements and Infrastructure Needs

The supporting measurements needed are similar to those for Generation 2. There is a major advance in telecommunications infrastructure needed to support the global monitoring of the planet in the infrared. If it is not practical to return all the data to Earth, there will be a requirement for onboard processing of the orbital data and candidate events detected by both surface and atmospheric sensors may be used in selecting the data to be returned.

8.3.8 Synergies between Surface and Orbital Platforms

Observations from the surface and orbit can provide an investigative capability that is much more powerful than either of these techniques implemented alone. It may also obviate the need for multiple surface stations for locating a large Venus quake. The orbital platform can, in some respects, emulate the capabilities of a very large network for characterizing interior structure.

Consider a large seismic event detected by the surface station. There will also be a near-synchronous infrared enhancement due to the epicentral wave propagating vertically into the Venus upper atmosphere and depositing energy. Localization of the epicenter from orbit means that the surface seismic signature can now be interpreted much more specifically in terms of the Venus internal structure using only a single surface station.

The Rayleigh wave will also produce an infrared signature. If the location of the surface sensor is within the field of view of the orbital data, the Rayleigh wave as observed at the surface site can be compared to the temporal variation in the infrared signal at that same location in order to confirm modeling of the propagation of surface displacements into the atmosphere.

If the signal to noise is adequate, and it can be enhanced if necessary by integration of the signal along small circles centered on the epicenter, a synthetic profile can be developed as if there were seismic detectors all along the great circle arc connecting the epicenter with the surface station.

Finally, in the event that an extremely strong signal is observed it may be possible to detect deviations from spherical symmetry in the structure of Venus. If this occurs to any significant extent, the Rayleigh waves radiating out from the source would no longer be small circles on the sphere and would be distorted as a result of internal structure.

8.3.9 Synergies between Surface and Atmospheric Techniques

Observations from surface and atmospheric platforms are valuable in terms of enhancing the utility of the data from both kinds of platform. We examine here what could be accomplished with one surface platform and several floating platforms.

Consider a teleseismic event that is first detected by the surface platform. This could initiate a search for near synchronous event in the datasets transmitted from the floating platforms. If identified, then arrival time information could be used to locate the event, greatly enhancing the value of the surface seismograms. In addition, the source characteristics can be investigated with information from the infrasonic traces.

Finally, if the floating platforms traverse the same region of the planet as where the surface platform is located, independent measurements of seismicity can be made and the orbital measurements can be better calibrated. Meridional drift of a balloon platform could be as little as 0.5 degrees for each circumnavigation of Venus by the balloons so if this did occur, it would have to occur within 5 to 10 days of initial deployment. This is assuming that surface and floating platforms are deployed from the same entry vehicle.

8.3.10 Synergies between Surface, Atmospheric, and Orbital Techniques

In Section 8.2.8, synergies between atmospheric and orbital techniques were covered; this section expands to cover surface techniques. In Sections 5–7, we have examined how these techniques can be explored pairwise to extract information that any single technique would not provide. We have not identified any unique measurement that could be made by applying all three techniques in combination. Of course, there are clear technical synergies where relay communications would be implemented with similar protocols and in some instances similar protocols for communications from lander and balloon platform. Correspondingly, the orbiter is a shared resource for sending data from all three platforms on a ‘trunk line’ back to Earth.

9 The Path Forward

This report, up until this section, has been primarily a scientific and technical assessment. It has focused on devising experimental approaches and mission concepts for seismology objectives without consideration for the strategic plans that are already in place for planetary exploration. In considering how to accelerate the investigation of the Venus interior with seismology, we now consider what those existing plans are, assess their compatibility with the concepts developed in Sections 5 through 7, and develop a path forward that exploits synergies with existing concepts and requires modest modifications to enhance seismic investigations. Our goal is a series of missions during the next 10 to 15 years.

9.1 Plans and Opportunities for Venus Exploration

Finding a path forward requires consideration of the current plans and strategies for exploring Venus developed by nations with the capability to explore Venus. Here we review the plans of four space agencies that have carried out missions to Venus—NASA, ESA, JAXA, and RFSA.

9.1.1 NASA's Planetary Science Decadal Survey

In 2012, the NRC completed a Planetary Science Decadal Survey (PSDS) laying out a strategic vision for planetary exploration for 2013 to 2022, including three mission classes: small (Discovery class), medium (New Frontiers [NF]), and large (Flagship). The following subsections present the current status of Venus opportunities in each of these classes.

9.1.1.1 Discovery Program

Venus missions including probe, balloon, and orbiter missions have been proposed in the past to the Discovery program, although none have been selected, and such missions continue to be within the scope of Discovery. An announcement of opportunity for Discovery 2014 was issued on November 5, 2014, with proposals due on February 18, 2015. Discovery proposal opportunities typically occur every 2 years.

9.1.1.2 New Frontier Program—Venus In Situ Explorer

VISE was one of the original missions recommended for the competitive NF program in the 2003 PSDS. Its importance was reaffirmed in the 2013 PSDS. VISE is envisaged as a short-duration lander with a lifetime measured in hours, similar in concept to the Soviet Venera missions of the 1970s and 1980s but with vastly enhanced instrumental and communications capabilities. However, other implementations accomplishing the designated science, which included geochemistry of the surface and surface atmosphere interaction, are not precluded.

9.1.1.3 Venus Climate Mission

The VCM was the top and only priority of the Inner Planets panel of the PSD whose scope was Venus and Mercury. Two of the flight elements of the VCM are an orbiter with a 24-hour period and a super-pressure balloon to be deployed near 55 km. While VCM was prioritized below missions to Mars, Europa, and Uranus by the Executive Committee of the PSDS for the 2013–2022 decade, two of the higher ranked missions are already going forward and so the prospects of a Venus Climate Mission for the subsequent decade are enhanced.

9.1.2 ESA Cosmic Vision Program

The ESA Venus Express ended its 8-year mission on December 16, 2014. The primary future opportunities for new Venus missions are through ESA's competitive Cosmic Vision program.

There are two parts to the Cosmic Vision program: the Medium Class or M-class missions and the Large or L-class missions.

9.1.2.1 M-Class Opportunities

Venus missions including both orbiter and balloon missions have been previously proposed as M-class missions. ESA recently issued an Announcement of Opportunity for M4 in August 2014 with proposals due in January 2015 and selections by March 2015. M-class opportunities are planned for 3-year intervals.

9.1.2.2 L-Class Missions

L-Class missions are in the same class as a small NASA Flagship mission. ESA selected the Jupiter ICy Moons Explorer (JUICE) mission in May 2012 as the first L-class mission within the Cosmic Vision 2015–2025 program with a planned launch in mid-2022. ATHENA, a large X-ray telescope was selected as the L2 mission with a planned launch in 2028. The L3 mission has not yet been selected but its launch will not be before 2034. Prospects for a Venus mission within L-class category program are distant.

9.1.3 Russian Federal Space Agency and Venera-D

With at least 27 missions launched in the 25-year period between 1961 and 1985, the Soviet Union is the only agency to have conducted investigations of the Venus surface from landed platforms—the Venera and Vega series, which survived for about 2 hours on the surface. The RFSA has not conducted a Venus mission since the dissolution of the Soviet Union but it is now planning the Venera D mission, which includes a lander with a lifespan of about 5 hours, a lander with a lifespan of 24 hours, an orbiter, and a subsatellite. Although a scientific collaboration on Venera D between RFSA and NASA was announced in December 2013, it was suspended following the events in Crimea in the spring of 2014. Russian interest in the mission continues and was reported at the August 2014 COSPAR meeting in Moscow.

9.1.4 Japanese Space Agency—JAXA Akatsuki

The JAXA spacecraft Akatsuki is currently on its way to Venus. After its main propulsion system failed when it attempted to enter Venus orbit on December 10, 2010, it remained in a heliocentric orbit. There will be an attempt to inject Akatsuki into a highly eccentric Venus orbit on November 10, 2015, using attitude control thrusters alone. Akatsuki is equipped with a capable scientific payload focused on atmospheric observations but it is not clear how much science can be obtained even if the spacecraft succeeds in entering Venus orbit. JAXA has not announced any plans for future Venus missions and does not operate the same kind of open competitive programs like NASA and ESA.

9.2 Technology Demonstration Opportunities

To strengthen the case for a dedicated scientific mission to investigate the interior of Venus with seismology, demonstrations of Venus specific techniques in currently planned or prospective Venus missions would be highly desirable. Useful information about signal backgrounds can be gained from missions that are short in duration or, in the case of orbital missions, which can allocate only a limited portion of resources to this task. The primary goal of the demonstrations would be validation of these scientific measurement techniques. Here we consider the opportunities for these demonstrations among the NASA, ESA, JAXA, and RFSA missions discussed above.

9.2.1 Surface Seismology

NASA's proposed New Frontiers VISE is likely to have a surface lifetime of less than 5 hours and the main lander in RFSA's Venera D has a similar operating lifetime. Venera D may also include a lander with a 24-hour mission and NASA has been performing technology work on such a capability but it is technically immature. As discussed in Section 5, the technology for missions that can operate beyond one day is many years away.

A seismology instrument on a short-duration lander such as VISE or Venera-D would nevertheless be a critical step forward. It could establish the key components of the ambient noise background that would be experienced on the surface of Venus. The Venera 13 and 14 experiments provide intriguing indications of a relatively low noise Venus surface environment. However, the performance characteristics of the Venera 13/14 instruments were not well enough understood for the data to be interpreted with confidence. Also, the fact that the sensor was mounted on the spacecraft instead of being deployed to the surface, suggests that it may have been sensing spacecraft vibrations rather than those intrinsic to the Venus environments and so the natural background may be even lower.

The technology demonstration instrument envisaged here would include some high-temperature electronic components. The sensor head would include an amplifier capable of operating at Venus ambient conditions and would ideally be deployed to the surface from the robotic arm, drill, or digging device. The acquisition of signals and processing of those signals and their communication and relay to Earth would only last for a few hours. However, in that time, it would be possible to measure the signal levels when there is no mechanical activity on the lander. These backgrounds could arise from a number of sources as described in the paper by Lorenz,[35] including wind motions, turbulence, and thermal equilibration of the sensor and the lander. Such a mission could establish definitively the sensitivity threshold attainable with a future long-duration surface seismic mission. It could also establish the feasibility of using ambient noise tomography for studies of the Venus subsurface. Use of an active source, deployed from the lander during descent, should also be considered for studies of the subsurface to shallow depths of a few hundred meters to 1 km.

In parallel with such an initiative, we recommend that NASA initiate development in high-temperature electronics and power technologies for a long-duration surface station or stations in the lower atmosphere. Both semiconductor and vacuum electronics approaches need to be pursued.

9.2.2 Seismology within the Atmosphere

The first balloon mission to Venus in 1985 included two balloons each lasting for 48 hours limited by battery storage. Balloon missions that have been proposed for past NASA Discovery and ESA Cosmic Vision opportunities have envisaged operating lifetimes of no more than a few weeks. Although longer-duration missions with multiple balloons have been contemplated, the next balloon mission at Venus is likely to be a single balloon designed to last for a few weeks at most.

There is considerable merit in conducting a technology demonstration experiment to study the seismic backgrounds relevant to the ultimate sensitivity of a dedicated balloon seismic experiment. However, with a lifetime of several weeks instead of just a few hours for a lander experiment, there is also the possibility with a balloon experiment of detecting seismic events. The balloon seismic experiment would consist of two microbarometers taking time-correlated measurements deployed on a tether beneath the balloon and separated by several tens of meters.

By differencing the signals from the microbarometers, signals propagating vertically upward from seismic Rayleigh waves could be isolated from atmospheric waves originating within the atmosphere as well as the effects of the small balloon altitude changes on the pressure signal. A particularly attractive feature of this demonstration is that it can be implemented with existing component technologies; it is the technique that is being validated.

Prior infrasonic measurements from a balloon in the Earth's atmosphere would also have merit. All existing earthquake data have been obtained from infrasonic observations from stations on the Earth's surface. Signal backgrounds are commonly established by wind noise. A comparatively short-duration terrestrial balloon mission would be able to identify what atmospheric backgrounds look like on Earth and tests with active sources might also be conducted. However, this latter concept requires further study.

9.2.3 Seismology from Space

Precursor technology demonstrations would also be valuable for measurements from the orbital vantage point. These could be implemented with only modest interference with the primary scientific objectives of mission that were planned with some other primary scientific goal involving radar observations of the surface or passive remote sensing of the atmosphere. While the orbits selected for these missions are not necessarily optimal for a long-duration monitoring station, they may be adequate for background characterization. For ongoing missions, such as Akatsuki, it would, of course, be necessary to use science instruments in the existing payload complement. For future missions, dedicated instruments might be considered so long as these were compact and had a minor impact on resources.

One such experiment has already been conducted: the use of the VIRTIS instrument on Mars Express to test predictions of a possible thermal signature in the 4.3 μm band.[25] It did provide extremely useful information on the wave motions. However, the orbital dynamics of the Venus Express spacecraft would not allow a successful detection of seismic waves. A future experiment might use instruments on the Akatsuki spacecraft if orbital insertion is successful.

Although no future orbital mission is approved, both NASA and ESA scientists are interested in opportunities in connection with the upcoming Discovery and Cosmic Vision M4 opportunities. The Russian Venera-D mission also includes an orbiter with a payload dedicated primarily to atmospheric signatures, which may present opportunities. Venera-D is planning a 24-hour orbit and an instrument suite complementing that of Venus Express including a UV imaging spectrometer.[87] The proposed ENVISION mission described by R. Ghail et al.[88] as a Cosmic Vision M4 candidate is primarily focused on radar imaging of the surface conducted from a near circular orbit. However, it will be initially inserted into an elliptical orbit; the proposed payload includes IR and UV imagers and would provide opportunities for conducting precursor observations. According to the analysis presented in this report (see Section 7.6.1), detection of the 1.27 μm nightglow, which is generated by transport of O_2 by the seismic waves, may result in a more easily detectable signal than shorter radiative lifetime airglows, such as at 4.3 μm, where the seismic signal is associated with density variations. Sensor performance is also generally better at the shorter wavelengths.

9.3 A Dedicated Science Mission

While technology demonstrations are both a desirable and an effective way of moving forward the investigation of Venus's seismicity and interior structure, a dedicated science mission will be needed. A mission that combines balloon-borne and orbital observations and is feasible with technology that either exists today or is achievable within 5 years is the logical next step. Long-duration measurements from the surface would hinge on the success of the technology developments described in Section 5 and appear at this point to be a longer-term prospect.

The Venus Climate Mission, the top priority Flagship mission of the PSDS Inner Planet's panel, consists of an orbital platform in an eccentric 24-hour orbit equipped with infrared imaging sensors designed for atmospheric observations. A single balloon platform is deployed into the atmosphere and is designed to operate at an altitude of 54 km for 21 days. A mini-probe and balloon dropsondes complete the payload complement. As the name implies, the objectives of VCM are focused on the Venus climate. It is intended to investigate the greenhouse effective on Venus, the source of the Venus super rotation and surface and atmospheric exchange in the lower atmosphere.

We envisage a modified form of VCM that would greatly augment the science that this Flagship mission can accomplish without a commensurate increase in cost. In a minimal configuration, this would involve equipping the balloon platform with infrasonic sensors and the orbiter with a more capable infrared imaging system so that to give it the capability of investigating the interior structure of Venus. In this role, its capabilities would be further expanded if the lifetime of the balloon was extended and if one additional balloon platform were included. We are calling this concept the Venus Climate and Interior Mission (VCIM). Interior investigations would not be limited to seismic methods. Measurements of the Venus magnetic field and Schumann resonances from the balloon platform should also be implemented.

The study team recommends investigation of the VICM concept including an assessment of payload options, communications, and onboard computational needs including opportunities for international collaboration. We believe VICM is a scientifically credible, technically feasible, and programmatically achievable pathway to investigating the Venus interior with seismology. It is also a mission that can be accomplished within the professional lifetime of most study participants. It's high time to go back to Venus and this is a compelling reason to do it.

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11 Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
A/D	analog to digital
ADC	analog-to-digital converter
ADEPT	Adaptable, Deployable Entry and Placement Technology
ALSEP	Apollo Lunar Surface Experiments Package
ASRG	Advanced Stirling Radioisotope Generator
AU	astronomical unit
BJT	bipolar junction transistor
Caltech	California Institute of Technology
CND	carbon nanotube device
CNT	carbon nanotube
CTBT	Comprehensive Test Ban Treaty
EMC	electromagnetic compatibility
ESA	European Space Agency
GCM	general circulation model
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
HEEET	High Energy Entry Environment Technology
HIAD	Hypervelocity Inflatable Atmospheric Decelerator
I/O	input/output
IMS	Infrasound Monitoring Station
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
IPGP	Institut de Physique du Globe de Paris
IR	infrared
ISAE	Institut Supérieur de l'Aéronautique et de l'Espace
JAXA	Japan Aerospace Exploration Agency
JFET	junction field effected transistor
JPL	Jet Propulsion Laboratory
JUICE	Jupiter ICy Moons Explorer
KISS	Keck Institute for Space Studies
LANL	Los Alamos National Laboratory
LTE	local thermodynamic equilibrium
MERMAID	Mobile Earthquake Recorder in Marine Areas by Independent Divers
MMRTG	Multi-mission Radioisotope Thermal Generator
MOS	metal oxide semiconductor

MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
NF	New Frontiers
NRC	National Research Council
PREM	Preliminary Reference Earth Model
PWM	pulse-width modulated
PSDS	Planetary Science Decadal Survey
RF	radio frequency
RFSA	Russian Federal Space Agency
RPS	Radioisotope Power System
S/N	signal to noise
SNR	signal-to-noise ratio
SAR	synthetic aperture radar
SEIS	Seismic Experiment for Interior Structure
SiC	silicon carbide
SOI	silicon on insulator
SP	short period
STMD	Science Technology Mission Directorate
TEC	total electron content
TID	traveling ionospheric disturbance
TNT	trinitrotoluene
TPS	thermal protection system
TVD	thermionic vacuum device
UCLA	University of California, Los Angeles
UHF	ultra high frequency
UV	ultraviolet
VBB	very broad band
VCIM	Venus Climate and Interior Mission
VCM	Venus Climate Mission
VEXAG	Venus Exploration Analysis Group
VIRTIS	Venus Express Visible and Infrared Thermal Imaging Spectrometer
VISE	Venus In Situ Explorer
VISM	Venus Interior Structure Mission
WTS	wind and thermal shield

Appendix A Mission Architectural Issues

A.1 Introduction

Several kinds of observational platform are considered in this report. Landed platforms are fixed to the surface of the planet. Balloons drift with the prevailing easterly wind, which changes with altitude. The space platforms view the planet from an orbital vantage point. This appendix deals with the challenges of delivering the in situ payloads (landers and orbiters) to Venus and the selection of orbits for the space platforms. Orbiters serve not only as communication relay systems for landed and balloon platforms but they also have an independent role for sensing seismic events either by remote sensing or in situ sensing. The unique characteristics of Venus place constraints on what kinds of orbits are available.

A.2 Unique Characteristics of Venus

For mission designers familiar with designing orbital missions at Earth or Mars, Venus presents some very different challenges. The slow retrograde rotation of Venus imposes certain constraints on operations at Venus. The absence of satellites, also limits some of the orbit design and scientific opportunities that might be created by the perturbing presence of even very small satellites such as Phobos and Deimos. The key gravitational, rotational, and orbital parameters for Venus appear in **Table A-1**.

Table A-1. Venus key parameters.

Bulk Characteristics		
	Gravit'l parameter (GM)	324827 km^3/s^2
	Avg radius (Solid surface)	6051.84 km
	Sidereal rotation period	243.02 days (retrograde)
	Obliquity	2.64 deg (or 177.36)
Heliocentric Orbit		
	Period	224.70 days
	Avg radius	108,209,000 km
	Eccentricity	0.006793
	Inclination	3.394 deg

A.3 Venus-Unique Mission Constraints

There are a number of Venus-unique mission constraints, which appear surprising at first to those familiar with orbit designs for orbiters of the Earth and Mars:

1. As a result of the very low rotational rate of Venus, there are no stable synchronous orbits analogous to Earth geosynchronous orbits.
2. Because J_2 for Venus is so small, a consequence of the low rotational rate, there are also no Sun synchronous or frozen orbits that enable sustained observations under the same illumination conditions.
3. Because there is no large satellite, there are no Venus–satellite Lagrange points.
4. The Venus-Sun Lagrange points are too distant for utility in an observational mission.

A.4 Effect of Dense High MW Atmosphere

The dense atmosphere, comprised primarily of CO_2 has a significantly higher molecular weight than the Earth's atmosphere. As a result, the scale height is not only smaller than that of Mars but also smaller than that of Earth, which has a comparable gravity field. Key orbital parameters are as follow:

1. The minimum circular orbit altitude for low drag is 350 to 400 km.
2. The minimum periapsis altitude for a highly eccentric orbit is ~300 km.
3. The typical atmospheric interface altitude for atmospheric entry is about 200 km.

A.5 Utility of Eccentric Orbits

Eccentric orbits with a line of apsides close to the equator with any inclination appear to have most utility.

1. They are useful for both science observations and data relay.
2. They have a relatively low Delta-V for orbit insertion ~1.3 km/s, which is easily performed with a standard solid rocket motor.
3. There is an easy transition using aerobraking or electric propulsion to a 12-hour orbit, which is useful for SAR observations.

A.6 Delivering Landed and Balloon Missions

For a direct Venus atmospheric entry from a hyperbolic approach trajectory, the velocity of the spacecraft towards Venus before it experiences Venus' gravitational field (V-inf) is typically 4.5–6 km/s. The actual entry speed as the probe accelerates in towards the planet varies with V-inf but is typically 11–12 km/s. Because of the slow rotation speed of Venus and despite the high wind speeds, there is almost no difference among prograde, retrograde, and other kind of entry trajectory.

A.6.1 Conventional Entry Systems

Entry systems with conventional aeroshells small enough to be accommodated within the shroud of the aeroshell experience high heating and large decelerations because of the high velocity of entry and the small scale height of the Venus atmosphere. The small scale height also means that entry corridors are extremely narrow imposing navigational demands. Large temporal variations in the atmospheric density revealed by the Venus Express aerobraking tests during 2014 may create even greater uncertainties for shallow entry corridors.

The carbon phenolic thermal protection system (TPS) technology that was used by NASA on the Pioneer Venus mission as well as the even higher energy entry of the Galileo probe is no longer available. NASA's Space Technology Mission Directorate (STMD) is developing an alternative approach based on woven carbon fabrics infused with high temperature resins. The High Energy Entry Environment Technology (HEEET) project expects to bring this technology to TRL 6 by 2017 in time for its use by a potential Venus Discovery mission.

Communications with an entry probe is a vital part of mission design. A co-delivered relay spacecraft could provide entry monitoring and immediate data relay (see **Figure A-1**). However, this is only useful for confirming the success of entry and for science that can be executed in minutes to hours. It is not useful for a seismic experiment lasting weeks, months, or longer.

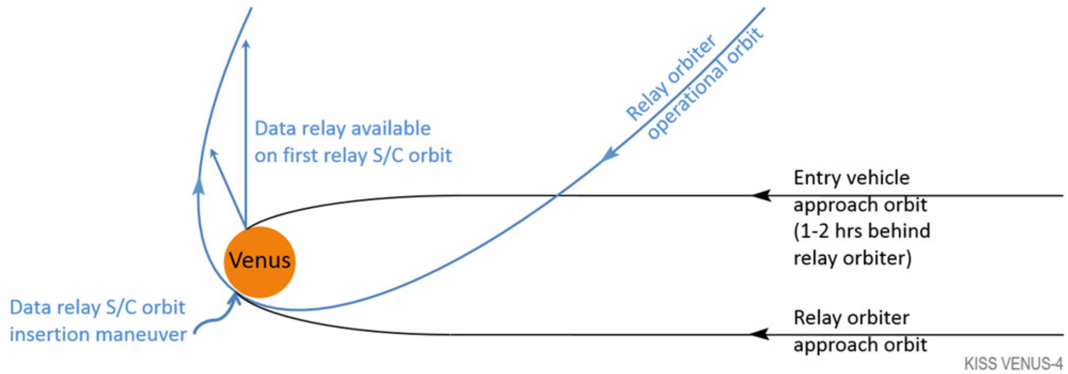

Figure A-1. Data relay approach for Venus entry spacecraft.

A.6.2 Deployable Entry Systems

In order to mitigate the entry loads and to lessen the requirements on entry systems, NASA's STMD has been developing deployable entry systems. The purpose is to reduce the ballistic coefficient of the entry vehicle so that much of the deceleration occurs higher in the atmosphere. A deployable is needed because the diameter of a conventional aeroshell is limited by the shroud diameter of the launch vehicle. In the HIAD (Hypervelocity Inflatable Atmospheric Decelerator) project this is achieved by inflating a series of toroidal structures supporting a thin flexible heat shield. In the ADEPT (Adaptable, Deployable Entry and Placement Technology), a mechanical umbrella-like deployment scheme is employed. Only ADEPT is currently being equipped with a high-temperature–tolerant supporting structure needed for the entry environment of a Venus mission. Some seismic investigation approaches may involve sensitive mechanisms that would sustain damage if used in conventional entry systems. However, others may be quite compatible with these entry loads.

A.7 Trades in the Selection of Orbits for Science and Communications

An ideal vantage point for an observational platform for observing seismic-induced disturbances in the upper atmosphere would have the following features:

1. At a constant altitude, so that the sensitivity and discrimination techniques can be standardized and do not have to be tailored for different ranges from the planet;
2. High enough in altitude to provide a synoptic view but low enough to provide the spatial resolution needed for detection; and
3. Synchronous with the Sun in order to conduct observations only on the dark side of the planet, which requires that the platform orbit Venus each Venus solar year.

Such an orbit is impractical for reasons already discussed. One compromise would be to drop the sun-synchronous requirement. This would mean a reduction in the temporal and spatial coverage from a single orbiter, which might be in an orbit of between ½ and 2 Earth days. The spatial and temporal coverage problem could be mitigated with the additional of two additional circular orbiters 120° apart.

From the standpoint of relaying data from both landers and balloons, no single orbiter can be synchronized with their motions. Neither would these orbiters be close enough to the planet for minimizing power usage during transmissions. In the case of the balloon, there would be periods between ½ and 2 days when the orbiter would be out of view. Additional orbiters would remove this restriction.