Venus Exploration with Infrasound Techniques

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Introduction:
The formation, evolution and structure of Venus remains a puzzle more than fifty years after the first visit by a robotic spacecraft. Radar images have re-vealed 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 un-derstand how Venus works as a planet it is necessary to probe the interior of Venus. This paper describes the application and adaptation of seismic and infra-sonic techniques to exploit and cope with the unique environment of Venus in order to probe its interior and characterize its seismicity.

Background
The Venus environment, with surface temperatures of 460°C, makes conventional seismology using sen-sors in contact with the planetary surface impractical with current technology. However, the dense atmos-phere of Venus, which efficiently couples seismic energy into the atmosphere as infrasonic waves, ena-bles an alternative: detection of infrasonic waves in the upper atmosphere using either high altitude bal-loons or orbiting spacecraft. In June 2014, the Keck Institute for Space Studies (KISS) at the California Institute of Technology sponsored a one week work-shop with 30 specialists in the key techniques and technologies relevant to investigating Venus's inte-rior structure. The report of that study (Cutts, Mimoun, & Stevenson, 2015) identifies the most promising approaches for developing seismic sensors tolerant of the high temperatures as well as means of observing the infrasonic signal.

High Temperature Seismic Sensors
The surface of Venus, with temperatures near 460°C is a very hostile environment for instruments. Con-ventional electronics are out of the question as there are currently, nor are there in prospect, techniques for protecting components from the environment for more than a few hours. Technologies for tolerating the environment involving vacuum electronics and high temperature semiconductors require many years of development (Cutts, Mimoun, & Stevenson, 2015). Work continues on these technologies but alternative techniques are needed for near term mis-sions and that is the focus of this paper.

Infrasonic Techniques

Infrasonic techniques for probing the Venus interior can be implemented without exposing sensors to the severe environment of the Venus surface. This approach takes advantage of the fact that approxi-mately 60X the energy from a seismic event on Ve-nus is coupled into the atmosphere on Venus as would occur for a comparable event on Earth. (Lognonne, Geophysics of the Terrestrial Planets, 2010). The KISS report (Cutts, Mimoun, & Stevenson, 2015) evaluates the possibility of detect-ing seismic events on Venus as infrasonic waves from balloon platforms floating at altitudes where conventional electronics and sensor components can be used and from orbital spacecraft by observing an optical signal produced by the infrasonic wave as il-lustrated in Figure 1. A direct or epicentral wave can be detected where infrasonic energy is generated right above the event by the piston-like motion pro-duced by the quake. An indirect wave produced at distance can be detected where seismic energy propagates through the crust and interior of the planet and vertical motions at the surface atmosphere interface then excite the vertically moving infrasonic wave. Only the indirect wave probes the interior of the planet. However, the epicentral wave can be a sensi-tive detector of seismicity across the planet which is itself a subject of considerable interest.

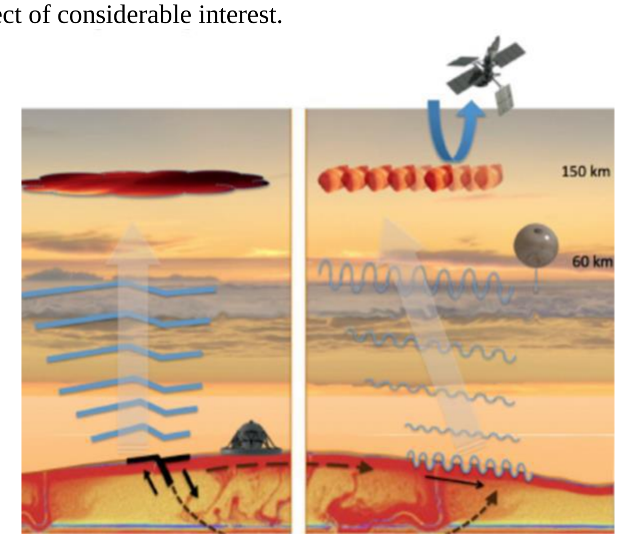

Figure 1 Generation of infrasonic waves by a seismic event on Venus. The direct or epicentral wave (left) propagates vertically above the event. The indirect wave (right) propagates through the planet as a Rayleigh wave and then couples to an infrasonic wave.

Balloon Infrasonic Detection – Sensitivity

Despite the much larger losses at the ground-atmosphere interface on Earth quite small earthquakes can be detected. For example, (Arrowsmith, et al., 2011) report the detection of a magnitude 4.7 quake in Utah across a statewide network of ground based infrasonic stations.

In addition to the fact that more seismic energy will be communicated into the atmosphere on Venus, the balloon station is moving with the medium which will substantially reduce the wind noise which gener-ally determined the threshold of detection for quakes on Earth. This sensitivity advantage of a balloon plat-form was recently established by comparison of infra-sonic measurements from a stratospheric balloon on earth with nearby ground stations as shown in Figure 2 (Bowman & Lees, 2016).

The instrumental limits for detection of seismic events on Venus are likely to be well below the Earth and may be determined by the background for other types of infrasonic source. While no inventions are needed at the component level, developments of ex-perimental techniques are needed and these should in-volve terrestrial flights on both tropospheric and strat-ospheric balloons. During the last two years, one of us (Bowman) conducted two stratospheric flights from New Mexico and demonstrated that the background noise levels were lower than for simultaneous meas-urements made at infrasound networks on the surface of the Earth (Bowman & Lees, 2016). Further meas-urements from balloon platforms are planned to de-velop and refine techniques for identifying quakes on Venus as well as to learn more about the Earth's in-frasound signature including both naturally occurring and anthropogenic events.

Relevance to Future Missions:

The great advantage of the infrasonic approach to studying the Venus interior is that the basic technol-ogy is ready today. While independent balloon and orbital missions could contribute valuable infor-mation, the real strength of this technique will involve the synergies between them as shown in Figure 3. The balloon technique provides a synoptic view but there is less energy particularly at the higher frequencies that propagates to the top of the Venus atmosphere and will be visible from space.

Opportunities for a mission with multiple platforms are currently being considered for Russia's Venera D but the baseline mission does not currently include balloons. The U.S. National Research Coun-cil's Planetary Science Decadal Survey of 2011 advo-cated a Venus Climate Mission which did feature a synoptic orbiter and balloon platforms but focused ex-clusively on atmospheric objects. The same flight el-ements could be employed to extend the capabilities of that mission as a Venus Climate and Interior Mis-sion. As NASA prepares for its next decadal survey this option should be considered.

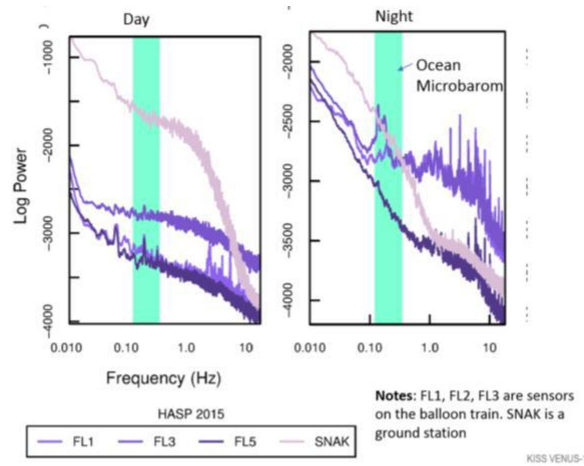

Figure 2. Comparison of acoustic signatures from a strat-ospheric balloon platform with a ground station during day and night time in the same location.

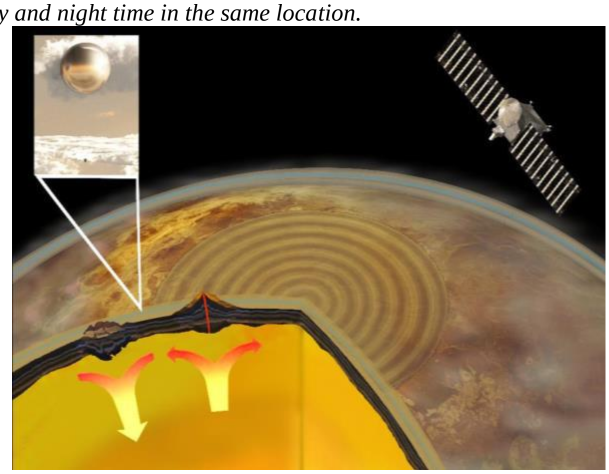

Figure 3. Coordinated observations of the infrasonic sig-natures from an orbital spacecraft and a balloon platform could provide confirmation of seismic event detections and complementary information