BALLOON INFRASOUND NETWORKS FOR INVESTIGATING THE VENUS INTERIOR: J. A. Cutts[1], S. Krishnamoorthy[1], J. M. Jackson[2], P. K. Byrne[3], A. Komjathy[1], M. Pauken[1], D. Mimoun[4], R. Garcia[4], D. Bowman[5], J. Vander Hook[1], F. Rossi[1] ;[1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov, [2]Seismological Laboratory, California Institute of Technology, [3] North Carolina State University, [4] ISAE-SUPAERO, Toulouse, France, [5]Sandia National Laboratories, Albuquerque NM.

There is growing evidence that Venus is volcanically and seismically active (e.g., [1]), which is motivating efforts to determine how best to characterize this activity and exploit it for investigating the planetary interior. This paper describes a concept for a future mission to investigate volcanic activity, seismicity, and interior structure from infrasound signals with a network of floating stations.

Background: The Venus environment presents both challenges and opportunities for investigating its interior. The principal challenge for missions with surface seismic stations is the high temperature, corrosive environment for which technology is under development but remains immature. An alternative is to employ a network of floating infrasound stations to probe the interior, exploiting the fact that the dense Venus atmosphere couples seismic energy into the atmosphere about sixty times more efficiently than on Earth. Explosive volcanic events may be also be detected from their infrasound signatures in the atmosphere.

Types of Seismic Signals Observable: There are important distinctions between the nature of the seismic signals observed from an aerial platform and those detectable with a lander.

Since the atmosphere is a fluid medium, only compressional waves can be observed. Two primary types of compressional waves result from quakes. Epicentral infrasound is generated by strong vertical displacements directly above the quake (Figure 1) and reaches the sensor directly by propagation through the atmosphere. Surface wave infrasound is initially propagated through the solid planet at the interface

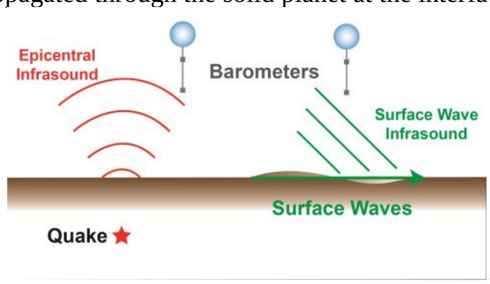

Figure 1. Airborne measurements include the epicentral wave that is activated by strong vertical motions directly above the epicenter, as well as surface wave infrasound, traveling first as a surface wave and then propagating as an infrasound wave when detected by aerial platform sensors

with the atmosphere and then as a nearly planar infrasound wave in the atmosphere (Figure 1).

Sensing Techniques: The detection of the amplitude, frequency, and duration of infrasound waves has been demonstrated on tethered and free floating balloons using very sensitive pressure sensors ([2], [3]). Since pressure is a scalar measurement, arrival direction cannot be determined from a single location measurement. However, an array of two or more sensors on a tether beneath a balloon can measure arrival time differences and the elevation angle of arrival (Figure 2). Concepts for measuring the direction of arrival with inertial sensors at a single location has recently been demonstrated ([5], [6], Figure 2), and are variously referred to as vector infrasound detection, acoustic polarization detection, or aero-seismometry.

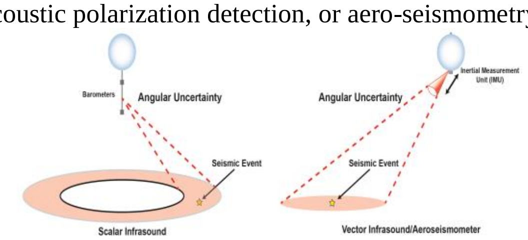

Figure 2. Sensing options for balloon-borne infrasound. Two scalar pressure sensors deployed on a tether can determine the elevation but not the azimuth of arrival of an infrasound wave. Inertial sensors attached to the balloon measure the motion vector induced by passage of an infrasound wave.

In the next two years, these techniques will be demonstrated by observations of terrestrial quakes in field experiments in the United States under NASA's Planetary Science and Technology Through Analog Research (PSTAR) program, and detections by two or more balloons may occur.

This progress is motivating plans to include infrasound sensors on Venus mission concepts, including the recently studied Venus Flagship Mission concept [8]. Measurements of infrasound from a *single* aerial platform will clearly be the first step for applying infrasound techniques at Venus. However, to be sure that we design and implement that first mission optimally, it is important to consider what a *network* mission optimized for seismic and volcanic investigation would look like.

Multi-Station Measurements: What might be accomplished with a network of floating platforms at Venus capable of localized loitering as they drift around the planet in the high-altitude winds? Observations of arrival directions of epicentral waves from two stations alone would establish the source location with sufficient knowledge of the velocity structure of the atmosphere. Measurements of the arrival time differences would validate that calculated source location. Epicentral waves may contain information about the nature of the seismic event, but as they do not propagate through the solid body do not provide information about the interior.

Observations of surface wave infrasound with a single station provides no information about the direction of the source. However, arrival times of the same event at *three* stations can be used to localize events, given knowledge of the seismic velocities. Measurements from additional stations would constrain estimates of those velocities if they were uncertain. Were both epicentral and surface wave infrasound detected from one station, surface wave velocities could be determined with as few as three stations.

Autonomous networks capable of navigating the Venus atmosphere in response to volcanic event detections may also enable high-value, up-close science investigations such as post-eruption imaging and plume sampling [9].

Networked Mission Concept: Our concept is for a network of floating seismic stations that would enter Venus in a single large entry vehicle and be designed to optimize detection of events at multiple station. A JPL internal study has investigated the autonomy techniques for conducting a Venus multiple-balloon mission [9]. Each station requires communication capabilities to relay observations to other stations (possibly through an orbiter relay), and a limited altitude control capability to steer the platforms towards detected events for follow-on, up-close investigations (Figure 3).

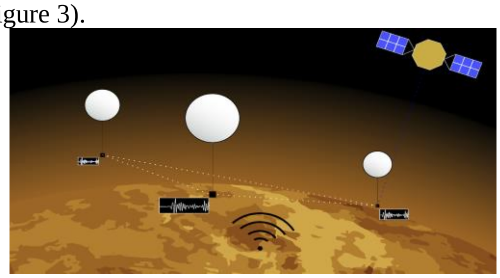

Figure 3. A concept for a Venus Infrasound Network consists of three floating stations and an orbiter.

A mechanical compression balloon architecture for altitude control [10] appears attractive for the purpose for this application. Trade studies are needed to determine the optimal number of balloons, the network architecture, preferred altitude range and the degree of altitude control required.

Summary: A concept for a network of floating stations for investigating the Venus interior has been developed that is keyed to the characteristics of infrasound signals and exploits the comparative ease of deploying multiple floating stations into a planetary atmosphere relative to a landed mission. A single platform equipped with a capable infrasound payload can be implemented with existing technology and would be a key precursor for characterizing the infrasound environment at Venus with a networked mission, and for improving our understanding of the Venus wind structure for optimizing station keeping. The paper will assess seismic sensitivity and compare performance of network options

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