Balloon-Borne Infrasound as a Remote Sensing Tool for Venus – Progress in 2017

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Outline

- Background
- Earth-based campaign
- Conclusions and future work

Background – Venus Interior and Seismicity

- Venus is similar in mass and volume to Earth, yet very different
- Although there is little evidence of Earth-like plate tectonics, the surface of the planet has its own distinctive tectonic and volcanic character
- Estimates of Venus seismicity vary over a large range
- Detection of seismic activity can establish if tectonism is still active and can be used to probe the crust and interior of the planet
- Surface conditions are harsh, spacecraft lifetime is limited

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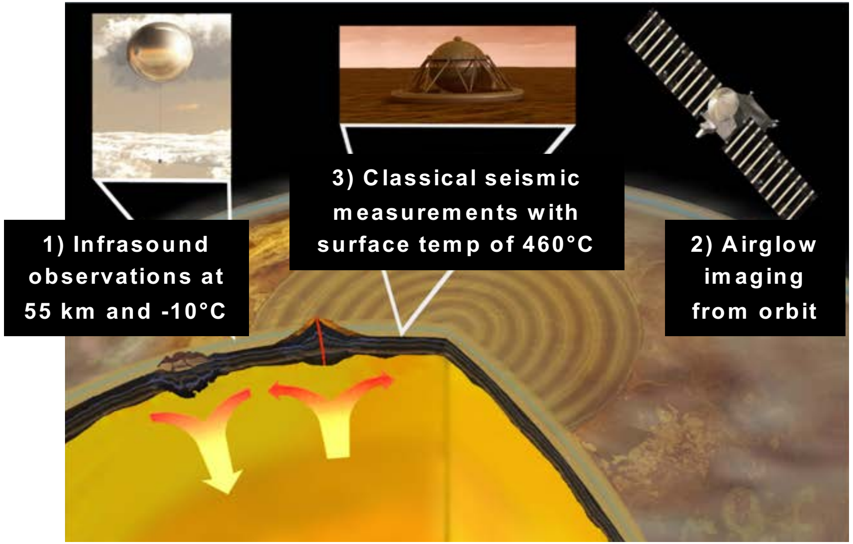
Venera 13, Wikimedia Commons

Background – Options for Seismology on Venus

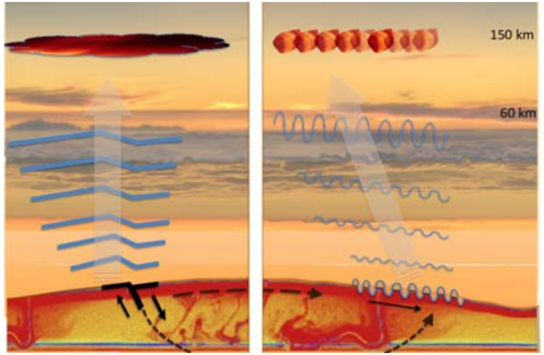


Cutts et al. (2015)

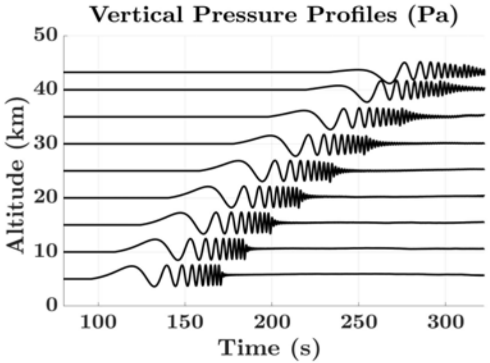
- Surface conditions are harsh – 460°C, 90 atmosphere, sulfuric acid-rich environment, precluding long-term observations with sophisticated seismic sensors
- Infrasound observations from floating platforms in the middle atmosphere and from orbit are practical alternatives

Background – Balloon-Based Infrasonic Remote Sensing on Venus

- Energy from ground motion couples to the atmosphere-thermosphere-ionosphere system
- Ground motion from quakes and volcanic activity produces infrasonic pressure signals (frequency< 20 Hz) at the epicenter and far away (due to Rayleigh waves)
- Infrasound signatures from earthquakes of moderate intensity observed by ground stations over 500 km away
- Venus' thick atmosphere couples with ground motion 60x better than Earth
- Pressure sensors on balloons can detect infrasonic signatures while floating on balloons – benign temperature, global coverage, lower wind noise
- Acoustic remote sensing can also assist in atmospheric science investigations



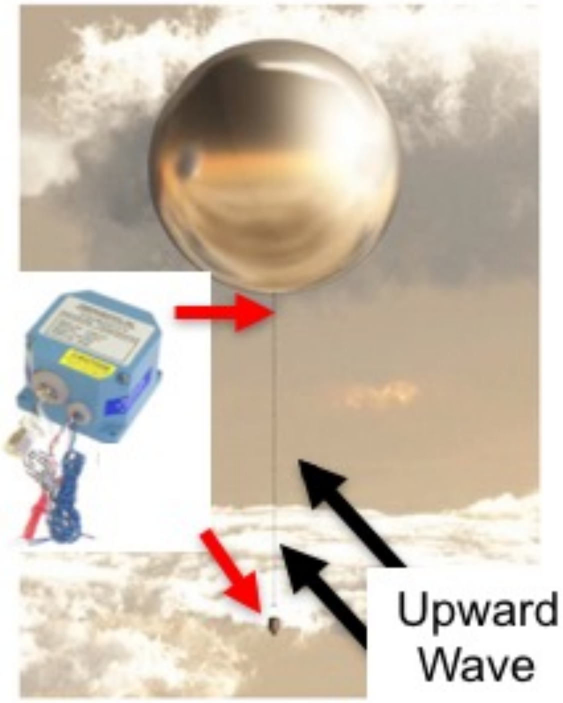
Cutts et al. (2015)



Garcia et al. (2016)

Background – Technical Challenges with Infrasonic Remote Sensing

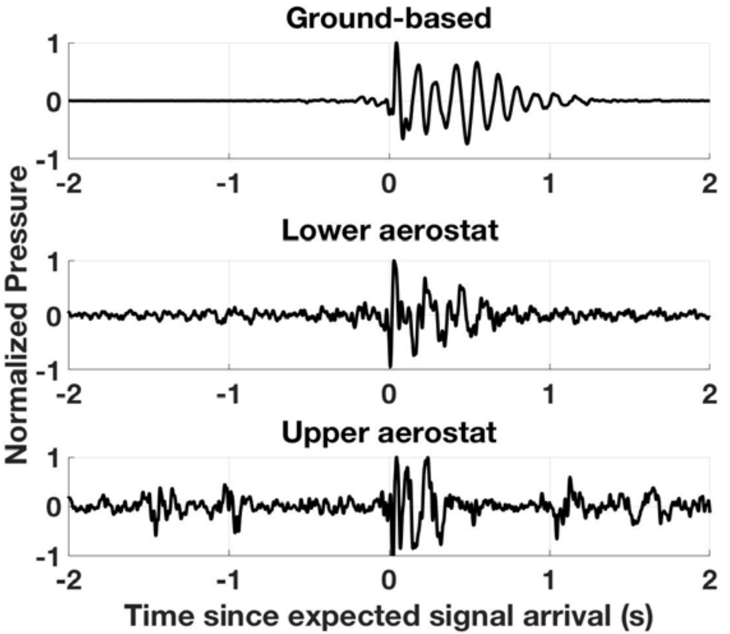
- Detection of seismic infrasound in the atmosphere
- Noise reduction in infrasound signal
- Characterization of infrasound background – avenues for opportunistic Earth and planetary science
- Discrimination of different infrasound sources
- Smart detection of events to reduce data volume – integration of multiple sensors
- Reduction of sensor mass, volume, and power for planetary balloon flight
- Development of robust GCM models for Venus atmosphere



Earth-Based Campaign – Seismic Hammer Experiment

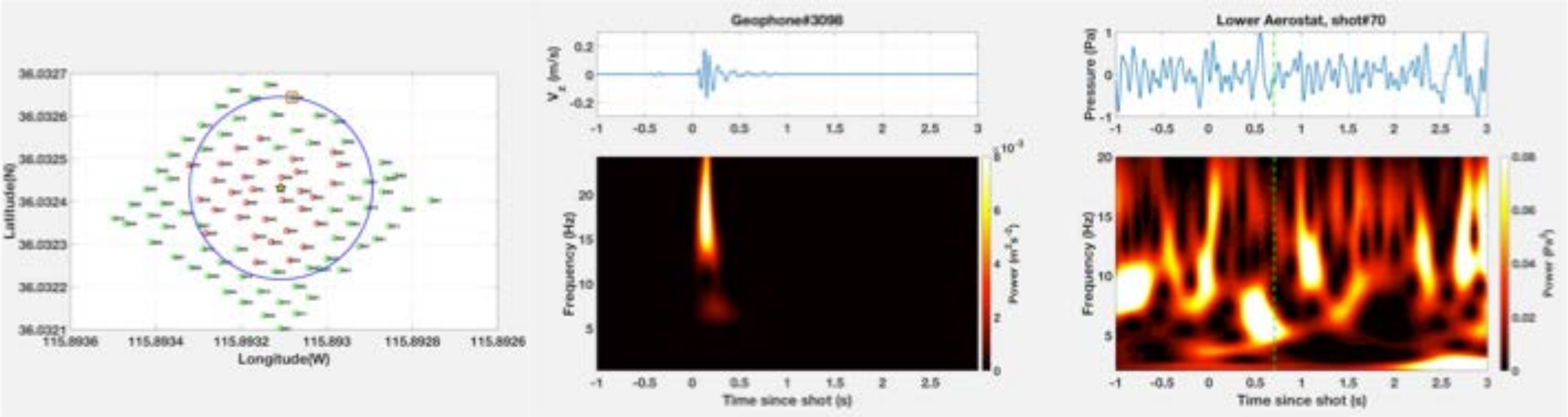
- Objective – use a small but repeatable seismic source to produce artificial earthquakes, demonstrate detectability using aerial platforms at low altitude
- Sensor network included sensitive barometers, broadband seismometers, IMUs, microphones, and geophones
- A total of 108 shots from the hammer over a period of 4 hours

Earth-Based Campaign – Seismic Hammer Experiment



Stacked time-domain signal shows the arrival of seismic infrasound at exactly the expected time

Earth-Based Campaign – Seismic Hammer Experiment

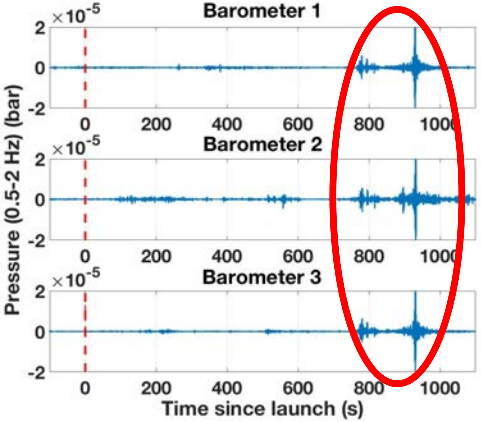


Krishnamoorthy et al. (in preparation)

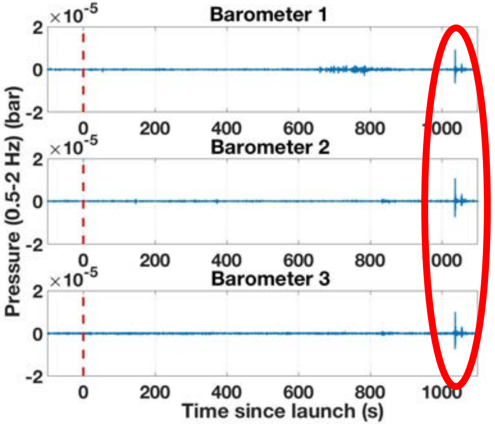
- Frequency content of pressure signal matches that of the ground motion signal near the epicenter
- Pressure signal is able to track the inhomogeneity in ground motion

Earth-Based Campaign – Rocket Infrasound Recordings

- Rockets are comparable to inverted moving volcanoes – signal is Doppler-shifted but has similar signature to explosive volcanism
- Rocket launches from Vandenberg are inexpensive to record compared to deploying near a volcano
- Successfully recorded infrasound from 7 launches at a distance of over 200 km away
- Signals typically arrive from various stages 10-20 mins after launch
- Data will allow us to develop source inversion algorithms



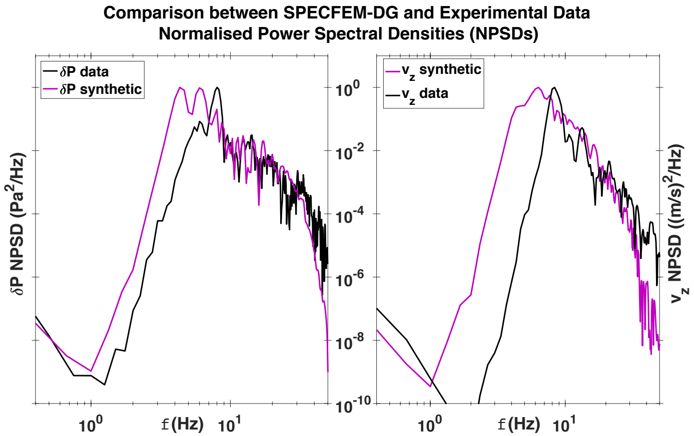
Falcon-9 Iridium, Dec. 22, 2017

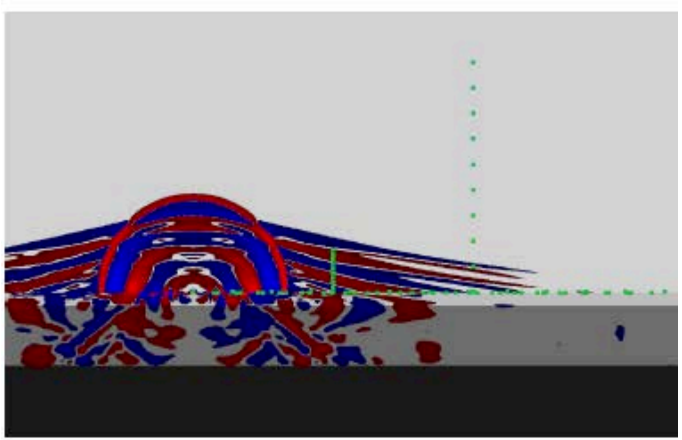


Atlas-V InSight, May 5, 2018

Earth-Based Campaign – Simulations

- Simulations performed using the SPECFEM-DG simulation tool (Brissaud et al., 2017) developed at ISAE
- Simulation tool solves elastodynamics equations for the ground coupled with the Navier-Stokes equations for the atmospheric signature
- Simulated waveforms agree well with data from the seismic hammer experiment
- SPECFEM-DG to be developed further to predict pressure signatures for natural quakes

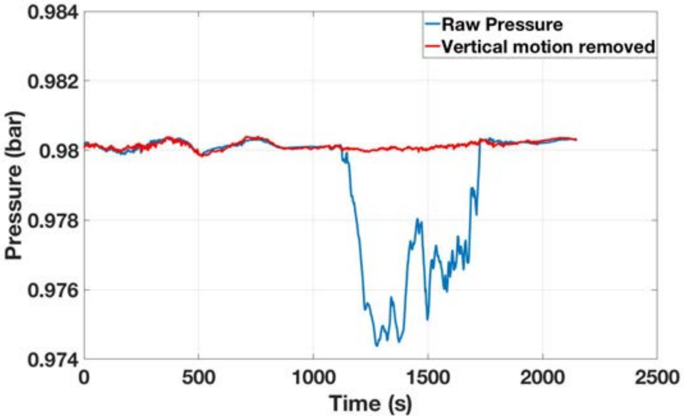




Martire et al. (under review)

Earth-Based Campaign – Noise-Reduction by Motion Tracking

- Pressure fluctuations due to vertical motion of the barometers cause noise in the signal
- Using an IMU, the vertical motion can be tracked and the pressure fluctuation can be removed
- Conducted two experiments in December 2017 and May 2018 to demonstrate this capability
- May 2018 experiment conducted during Grace-FO launch – rocket infrasound to provide the reference signal for comparison



Conclusions

- Infrasound signals can act as proxies for ground motion signals from seismic events
- Signals can be detected a large distance away from the originating event
- Noise mitigation and signal differentiation are big challenges

Future Work

- Sensors will fly in the stratosphere on a NASA balloon from Sweden to Canada in June 2018
- Balloon-borne sensors will be deployed over sub-surface chemical explosions conducted by the US Department of Energy in 2018-19
- We hope to fly loitering balloons in the stratosphere over areas with high natural seismicity to demonstrate natural earthquake detection from a distance
- We are continuing to develop methods for noise mitigation and signal differentiation using additional sensors and simulations

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