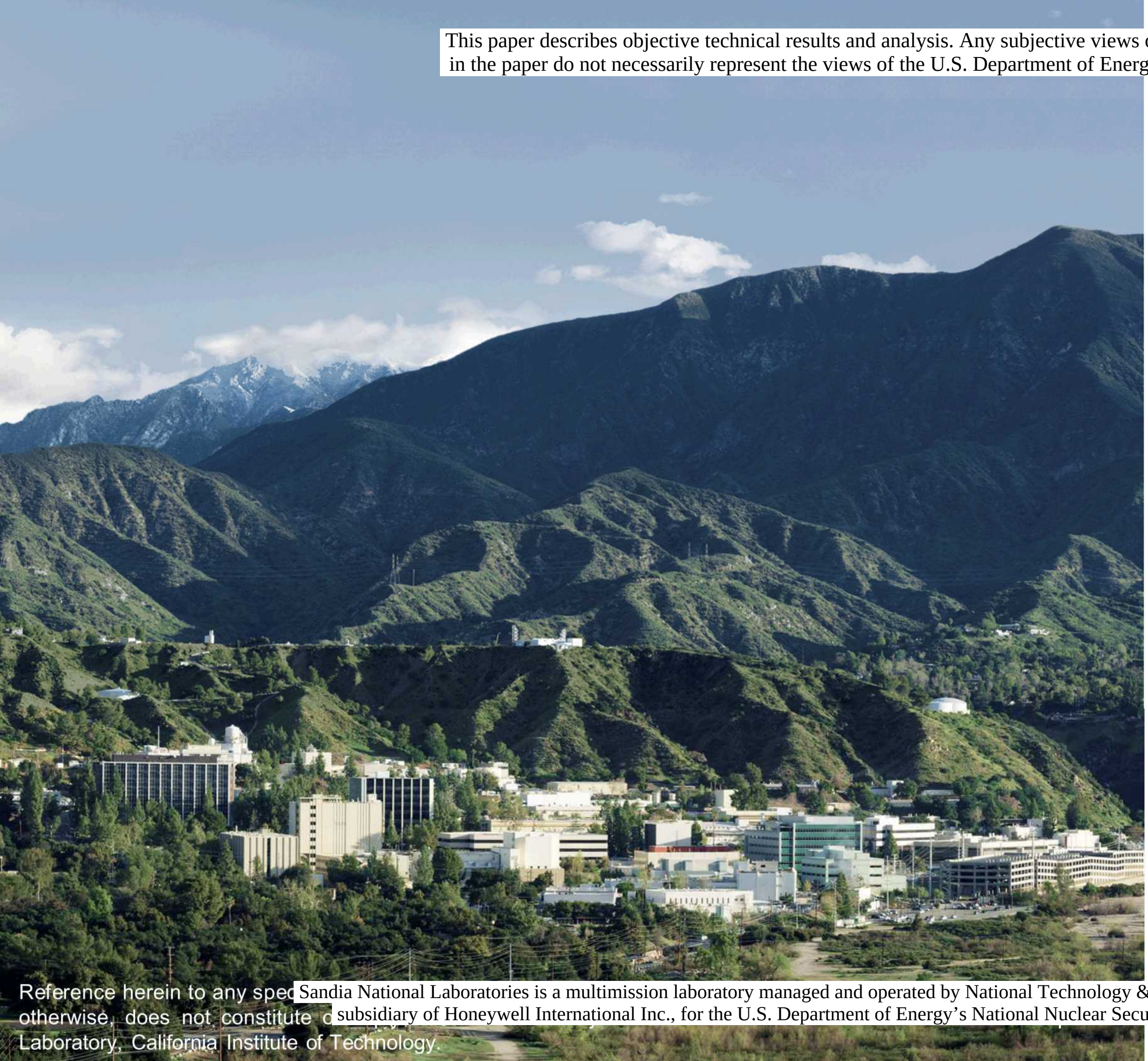


The Road to Venus Seismology via Oklahoma

SAND2018-12673C

Siddharth Krishnamoorthy, Daniel C. Bowman, Leo Martire, Attila Komjathy, James A. Cutts, Michael T. Pauken, Raphael F. Garcia, David Mimoun, Voon Hui Lai, and Jennifer M. Jackson

VEXAG Meeting

November 8, 2018

isae Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO

Sandia National Laboratories

Jet Propulsion Laboratory
California Institute of Technology

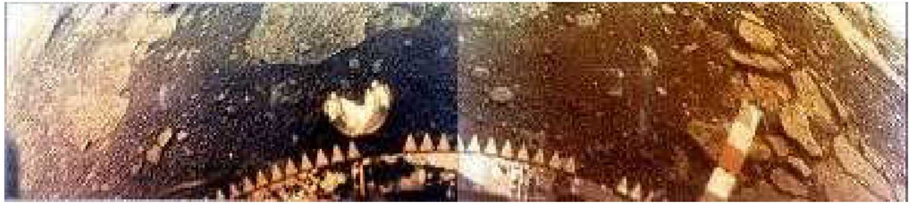
Outline

- Background on infrasound seismology
- Seismic hammer experiment
- Oklahoma earthquake analysis
- Balloon-based seismology demonstration in Oklahoma

Background – Venus Interior and Seismicity

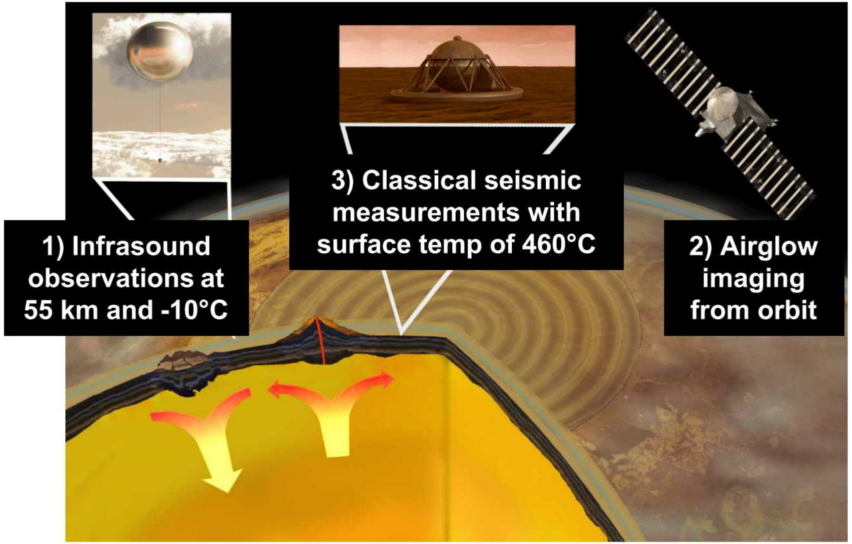
- Little evidence of Earth-like plate tectonics, the surface of the planet has its own distinctive tectonic and volcanic character
- Estimates of Venus seismicity vary over a large range
- Detection of seismic activity can establish if tectonism is still active and can be used to probe the crust and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

Wikimedia Commons



Venera 13, Wikimedia Commons

Background – Options for Seismology on Venus

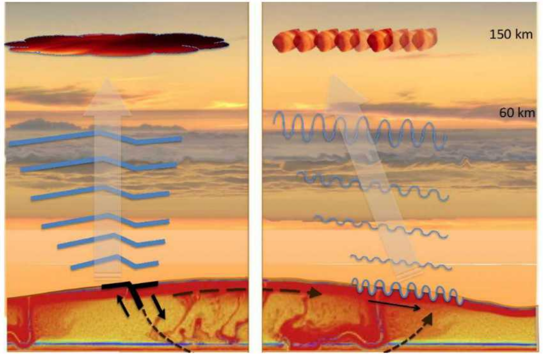


Cutts et al. (2015)

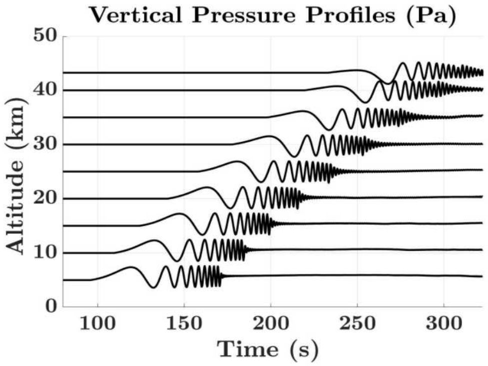
- Surface conditions are harsh – 460°C, 90 atmosphere, sulfuric acid-rich environment, precluding long-term observations with sophisticated seismic sensors
- Infrasound observations from floating platforms in the middle atmosphere and from orbit are practical alternatives

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)

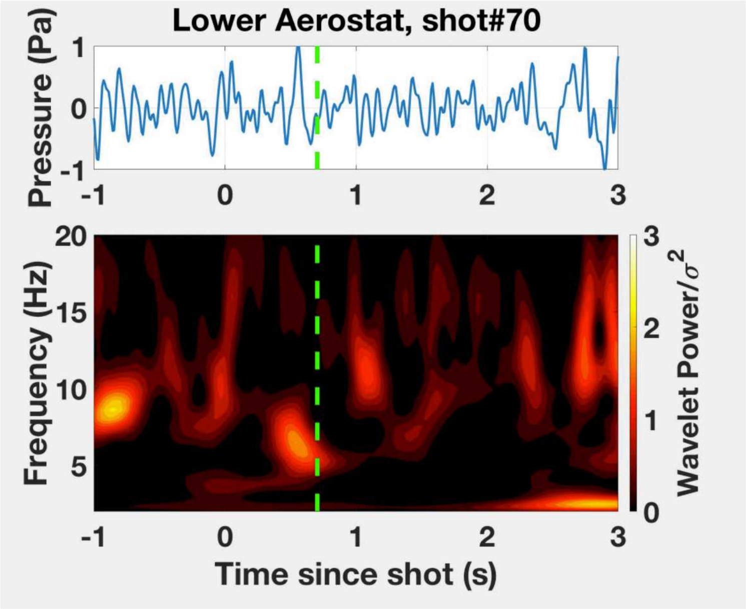
Seismic Hammer Experiment

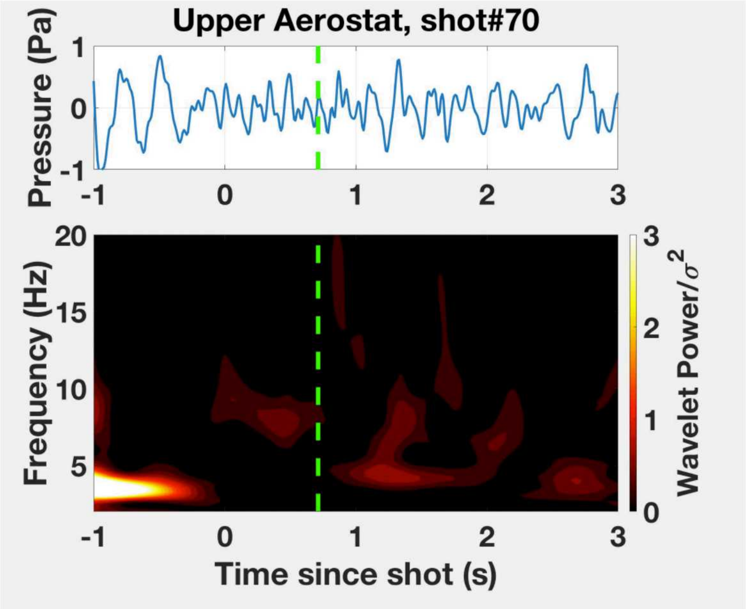
- Objective – use a small but repeatable seismic source to produce artificial earthquakes, demonstrate detectability using aerial platforms at low altitude

- 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

Seismic Hammer Experiment

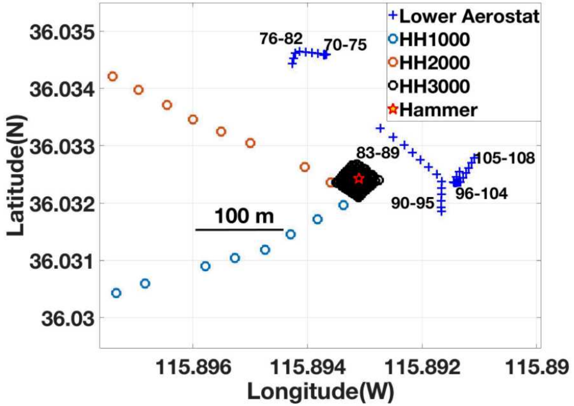


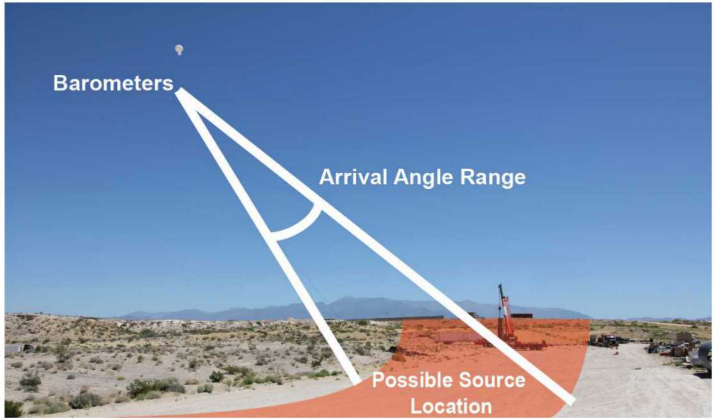


Krishnamoorthy et al. (under review)

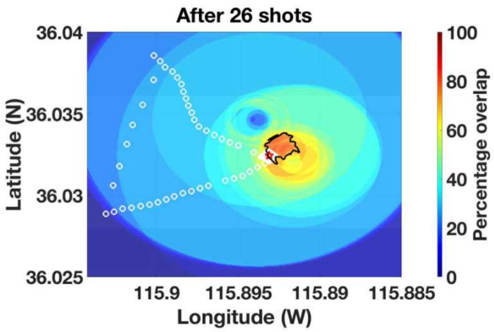
- Balloon-borne barometers detected > 80% of the shots
- Barometer signal showed similar frequency content as ground motion measured by seismometers
- Repeatable shots and two barometers on a tether were used to geolocate the seismic source

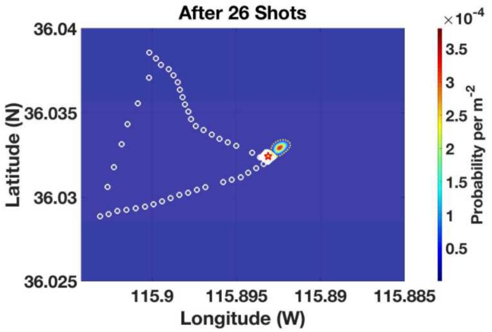
Seismic Hammer Experiment





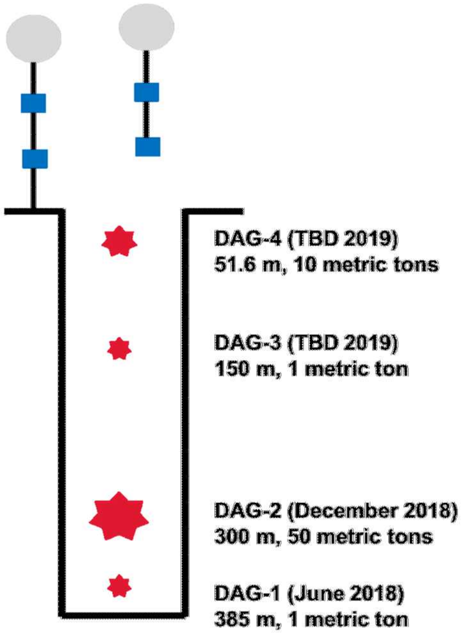
Krishnamoorthy et al. (under review)

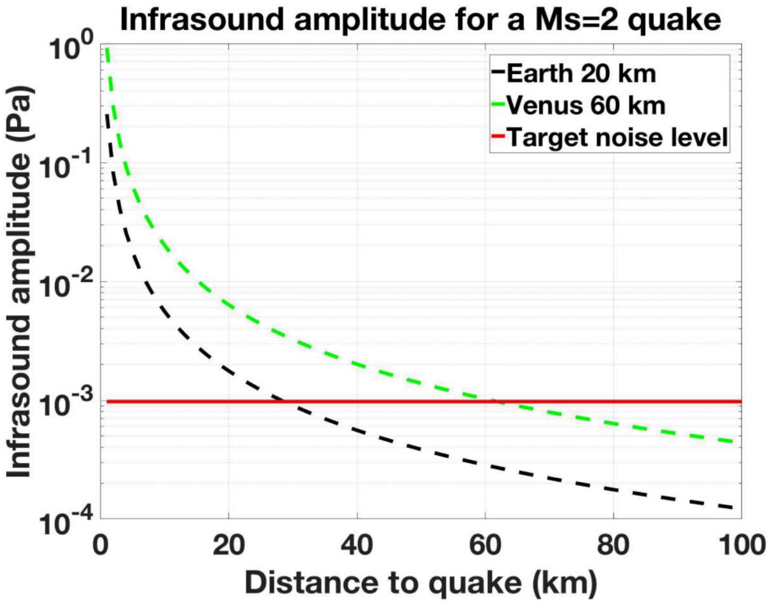




- Balloon-borne barometers detected > 80% of the shots
- Barometer signal showed similar frequency content as ground motion measured by seismometers
- Repeatable shots and two barometers on a tether were used to geolocate the seismic source

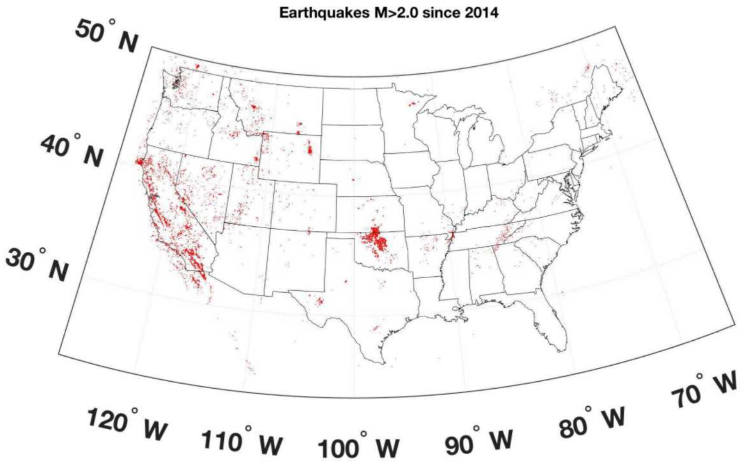
What's Next?

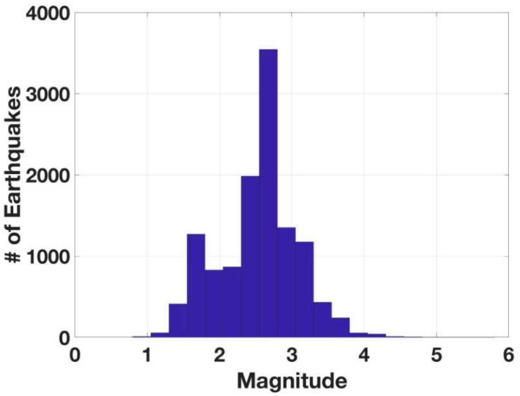


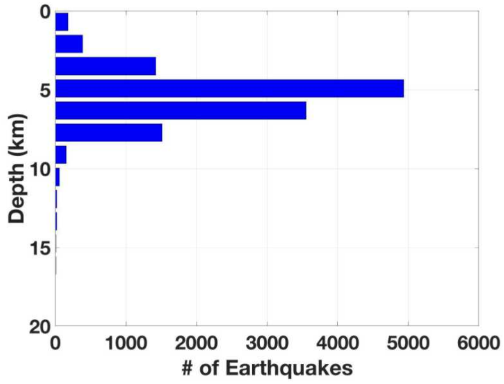


- Balloon infrasound overflight of sub-surface chemical explosions by the DoE in December 2018
- We hope to be able to distinguish seismic phases from each other
- Stratospheric overflight of Oklahoma natural earthquakes

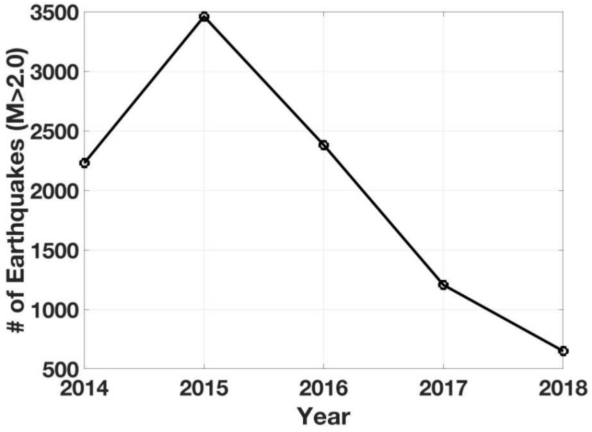
Oklahoma Earthquake Analysis



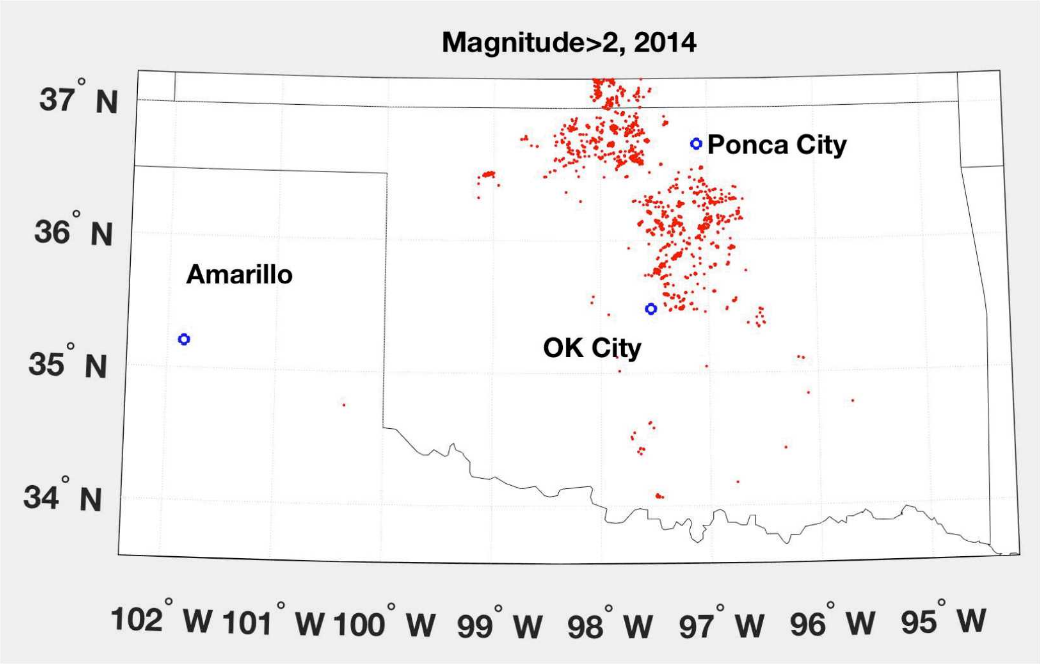




- 9798 quakes with magnitude> 2.0 since 2014
- Quakes are very shallow – high ground motion near epicenter
- Reducing in number but still >1 per day

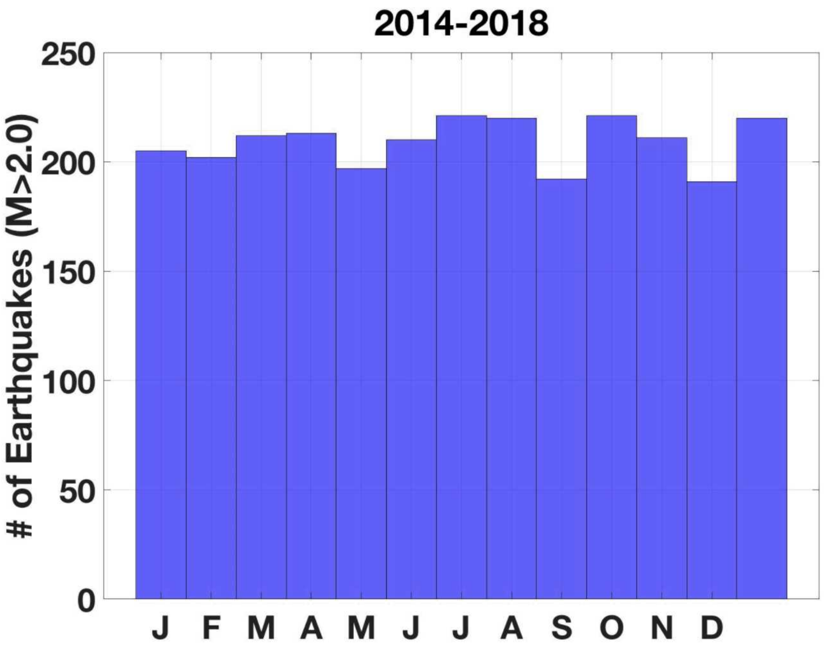


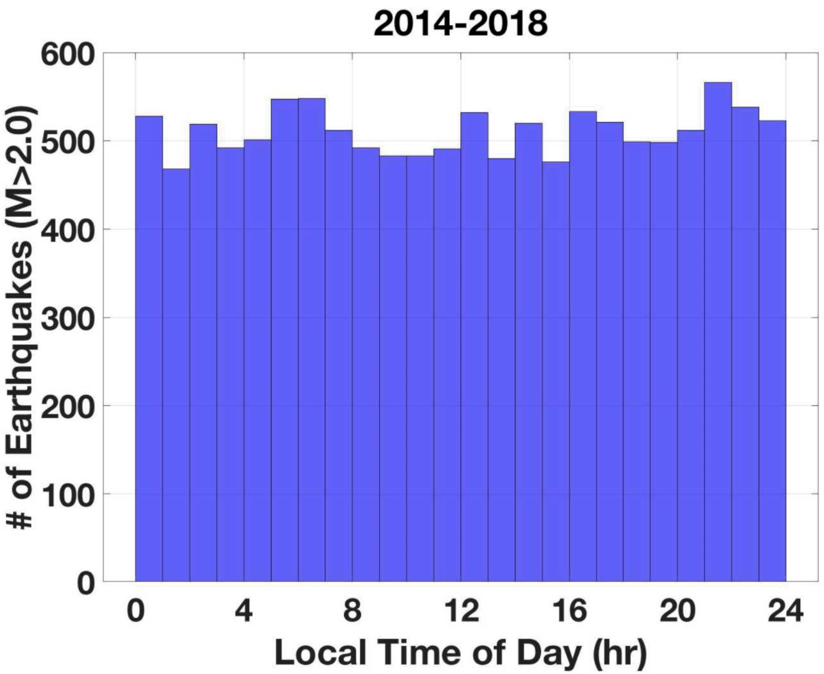
Oklahoma Earthquake Analysis



- Quake activity shifts with year, new hot spot has emerged south of Oklahoma City

Oklahoma Earthquake Analysis

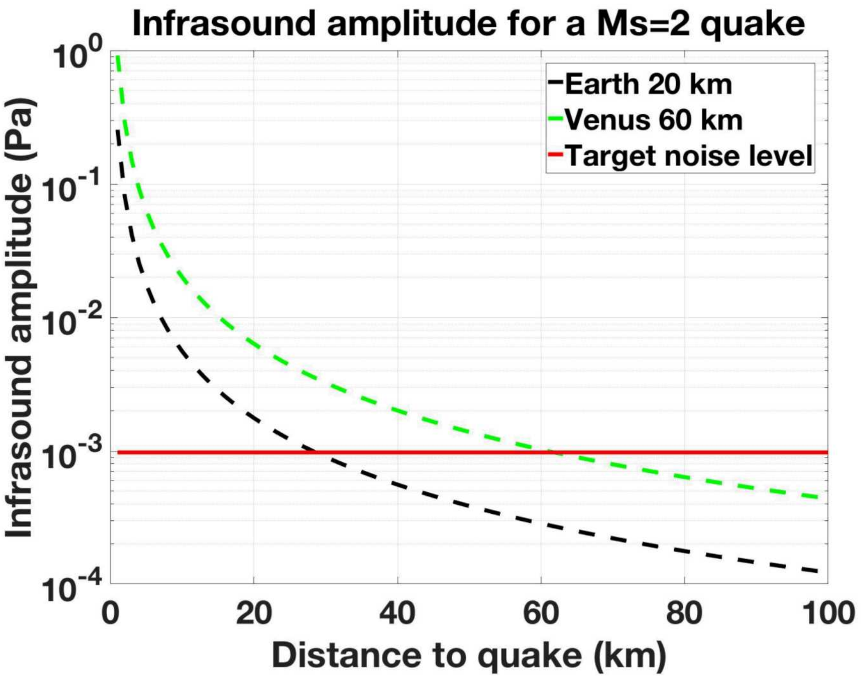




- Earthquakes are relatively uniform over the year and during the day (generally true across 2014-2018)

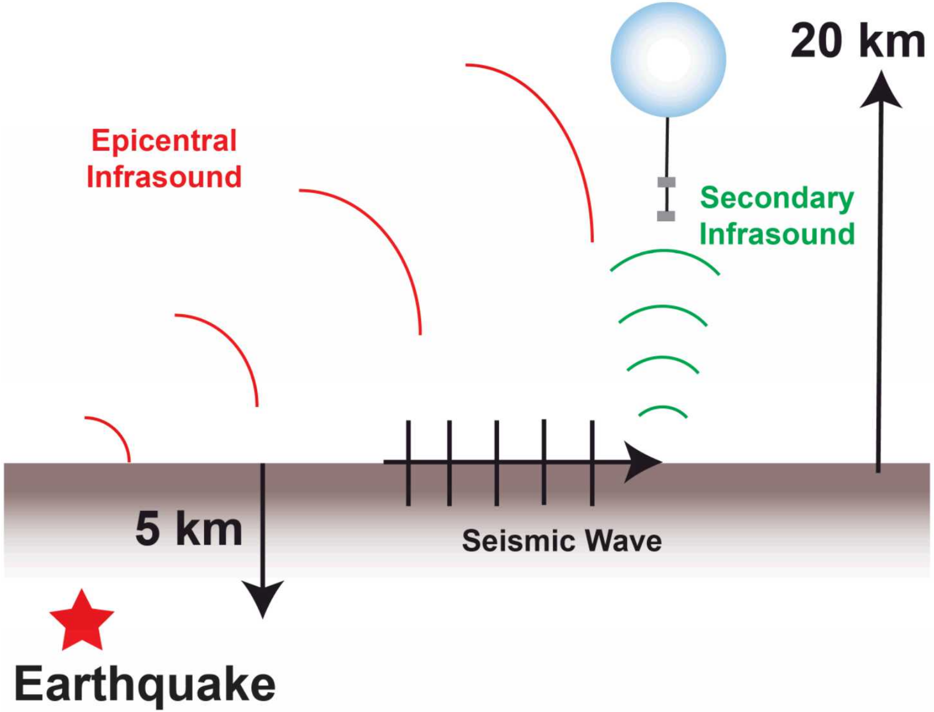
Balloon-Based Seismology Demonstration in Oklahoma

- Zero pressure balloons at 20 km altitude
- Summer-long campaign with daily flights
- Each balloon equipped with two barometers on a tether
- Launch in Eastern Oklahoma, recovery in the West
- Approximately 8-hour overflights of the seismically active zone
- Ground truth provided by the Oklahoma Geological Survey's seismic network



Balloon-Based Seismology Demonstration in Oklahoma

- Infrasound produced at the epicenter is the strongest – ground motion decays with distance from the source
- Large quakes will produce significant low-frequency surface waves, which may have high amplitude



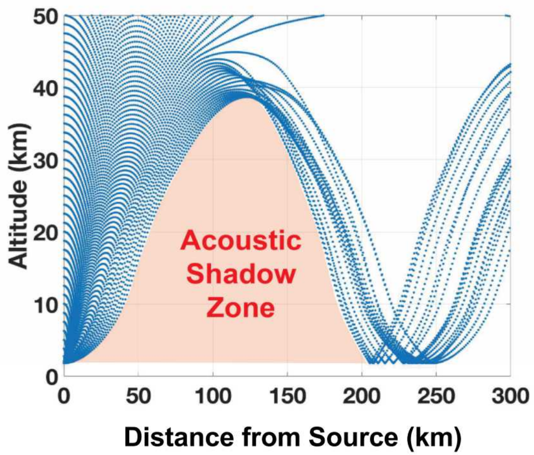
Balloon-Based Seismology Demonstration in Oklahoma – Signal Levels

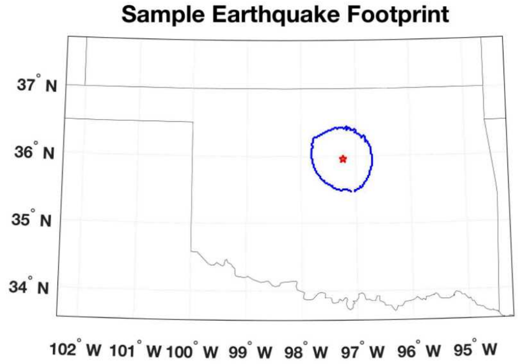
- Convert epicentral ground motion to infrasound amplitude based on magnitude

$$v_z = 0.01\ 10^{-4.151+1.762M-0.09509M^2}$$

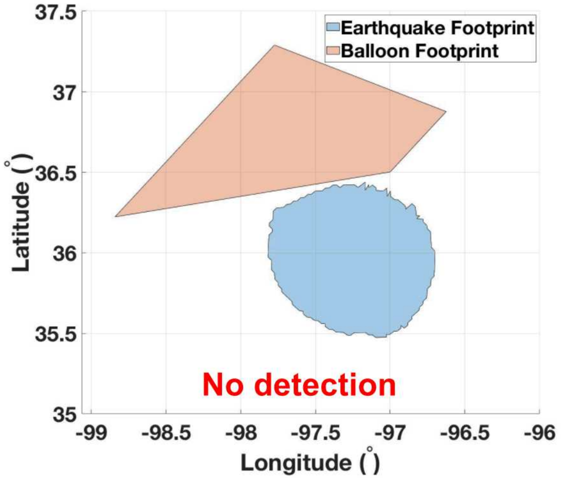
$$p = \rho_0 c_0 v_z$$

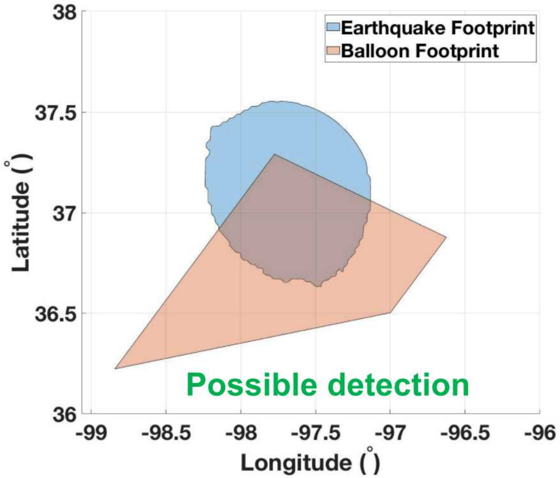
- Use GeoAc raytracing to compute 3-D attenuation and propagation characteristics of infrasound rays
- Propagate up to 20 km
- Obtain the 10^{-3} Pa contour – detection footprint of the quake





Balloon-Based Seismology Demonstration in Oklahoma – Detection Stats

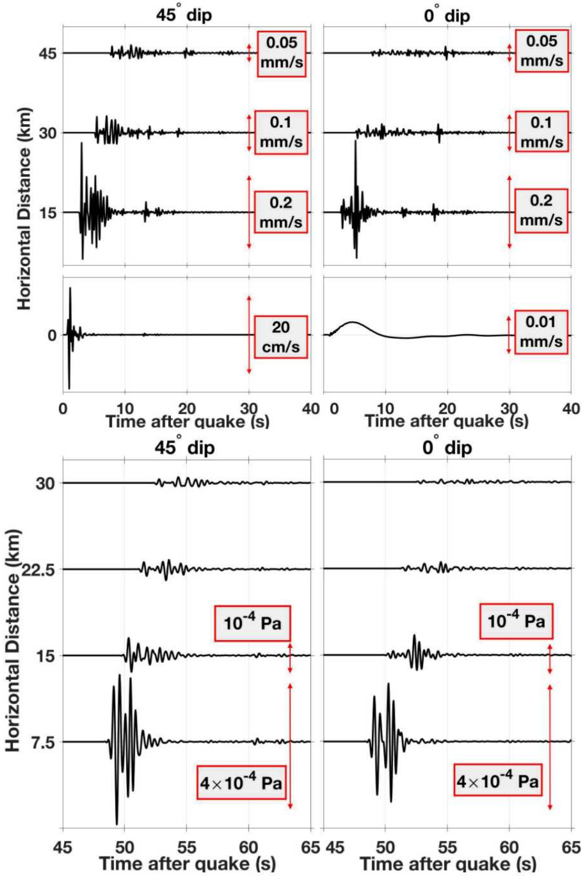




- Balloon trajectories for the June-August 2015 and 2016 with 8 hour float times at 20 km
- Mean plus 1 standard deviation float trajectories computed for balloon footprint
- Possible detections in June-August – 2014: 372, 2015: 848, 2016: 438, 2017: 259, 2018: 131

Balloon-Based Seismology Demonstration in Oklahoma – Simulation

- Mw 2.5 quake at 5 km depth modeled
- Elastodynamics equations coupled with Navier-Stokes equations solved for ground motion and infrasound footprint
- Signal levels shown at ground level and 15 km altitude
- 2-D simulations with amplitude scaled down by a factor of 1000 to account for 3-D spreading
- Simulations show pressure signature much lower than previously predicted – work in progress



Ground Motion

Pressure Signal

Martire et al., 2018

Conclusions and Takeaways

- Balloon-based infrasound is a potentially game-changing technology for Venus exploration
- We have demonstrated the detection, characterization and geolocation of seismic signals using their acoustic signature in the seismic hammer experiment
- We hope to identify different seismic phases in the upcoming Dry Alluvium Geology experiment
- Estimates for Oklahoma predict a good chance of demonstrating the first recording of a natural earthquake from the stratosphere

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov