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Progress towards Balloon-Based Seismology on Venus in 2020-2021

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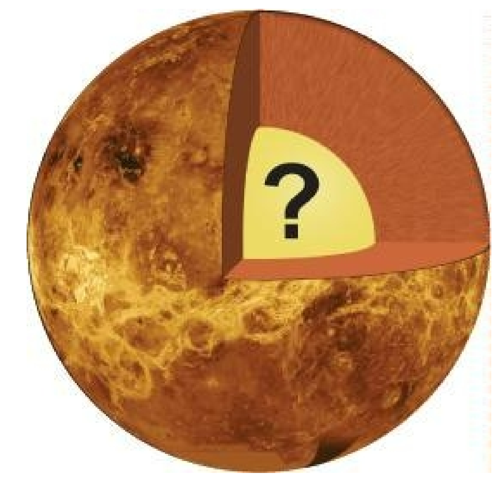
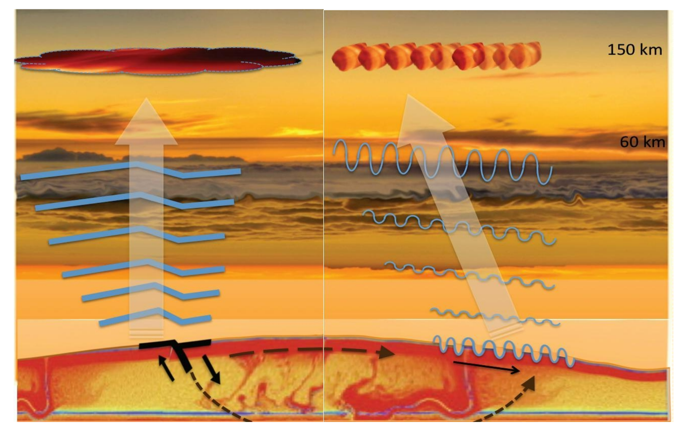
The evolution and interior structure of Venus remain uncertain despite half a century of exploration. This is in large part due to the absence of seismology investigations, which have yielded much of the information about Earth's interior. Extreme surface temperature(>460 C) and pressure (>90 atmospheres) result in extremely limited lifetimes for surface missions.

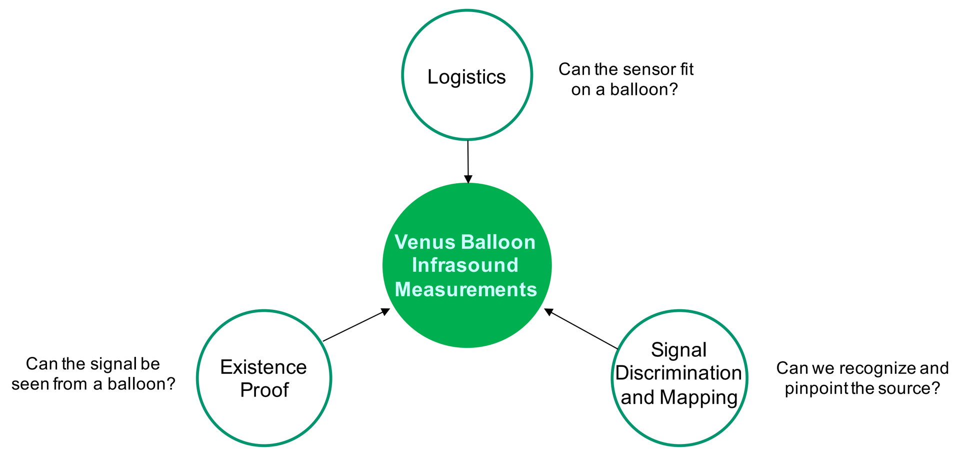


Venus' thick atmosphere allows for the efficient coupling of seismic waves between the solid planet and its atmosphere resulting in low-frequency pressure waves, also known as infrasound. Infrasound travels relatively unattenuated for large distances and may be used to study seismic activity on Venus without needing to land on it. Infrasound barometers may be deployed on balloons floating at 50-60 km altitude on Venus, where the temperature and pressure are much more benign and longer mission lifetimes can be guaranteed.

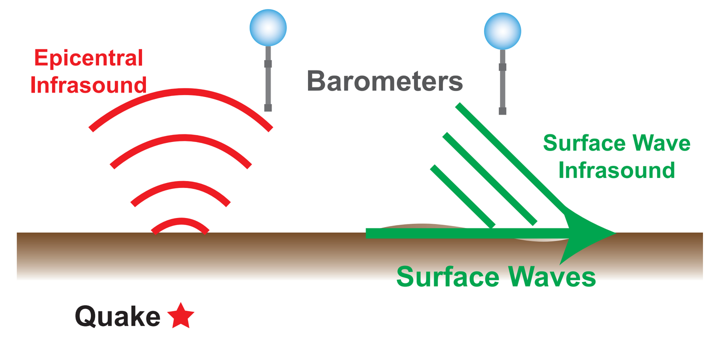


Cutts et al. (2015)

Our development efforts are primarily focused on three key areas of balloon-based infrasound seismology: demonstrating **existence proof**, i.e. that the signal can be detected from a balloon; developing **automated signal discrimination and mapping**, so that seismic signals may be distinguished from the background and transmission data volume may be reduced; and miniaturizing sensor mass, power, and volume so that the **logistics** of infrasound measurement are viable for a Venus balloon.

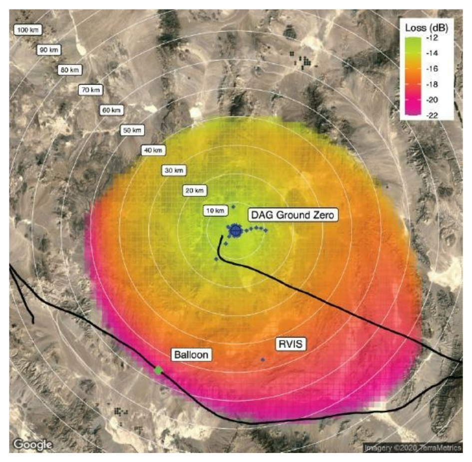


In previous work, we have demonstrated the viability of detecting seismic infrasound from balloons at close range using artificial seismic sources. In this poster, we present recent successful efforts at maturing this technique through the detection of epicentral infrasound from buried chemical explosions and surface-wave generated infrasound from natural earthquakes on high-altitude balloons. In addition, we summarize our recently concluded 2-month long flight campaign in Oklahoma attempting to detect earthquakes from the stratosphere.

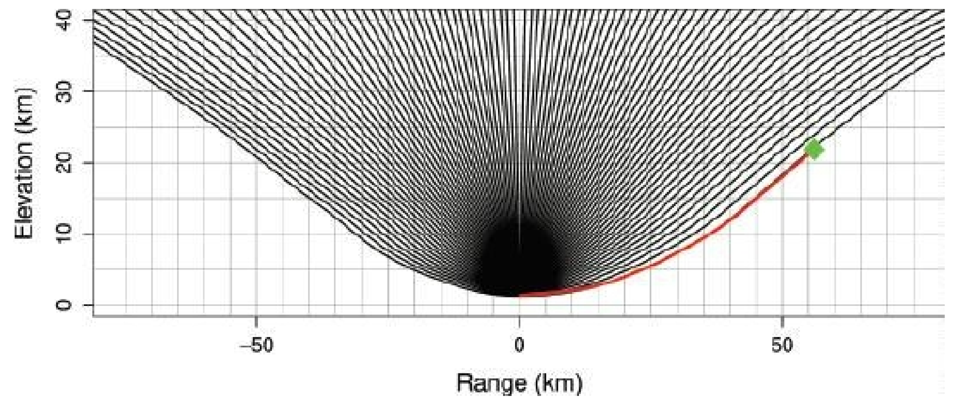


Detection of Epicentral Ground Motion from a Buried Chemical Explosion on a Balloon

On June 21, 2019, the US Department of Energy conducted a buried chemical explosion, with a yield of 10 tons TNT equivalent at a depth of 51.6 meters below the ground. The resulting explosion caused spallation of the ground immediately above the detonation, generating an infrasound pulse. This infrasound pulse is similar to the epicentral signature from a strong earthquake.

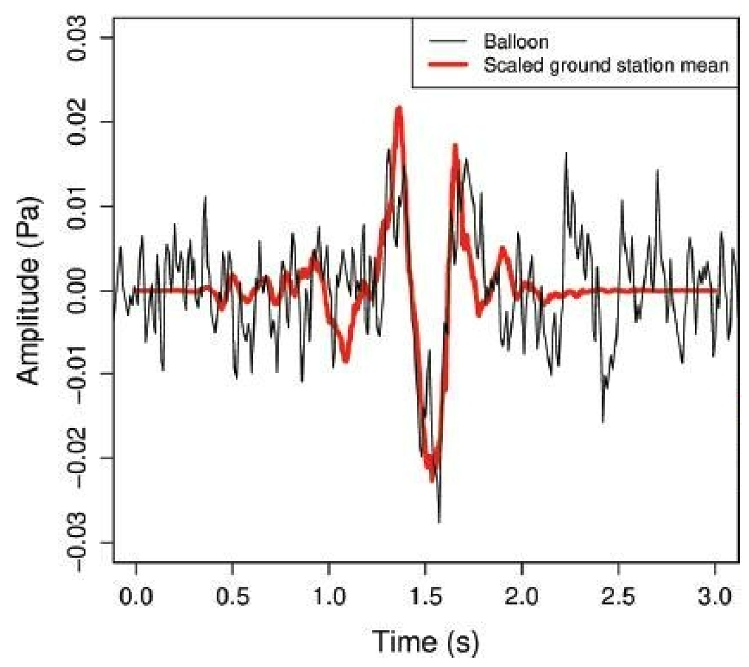


Three"Heliotrope" solar-heated balloons were launched earlier in the day. The structure of the atmosphere creates alternating ensonified and acoustic dead zones as infrasound rays refract and internally reflect, shown by raypaths in the figure on the right. While two balloons were outside the ensonified zone capable of detecting an arrival from the explosion, a third balloon was at the edge of the ensonified zone at 20 km altitude and 56 km away from ground zero.



See also, Bowman and Krishnamoorthy (2021): https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL094861

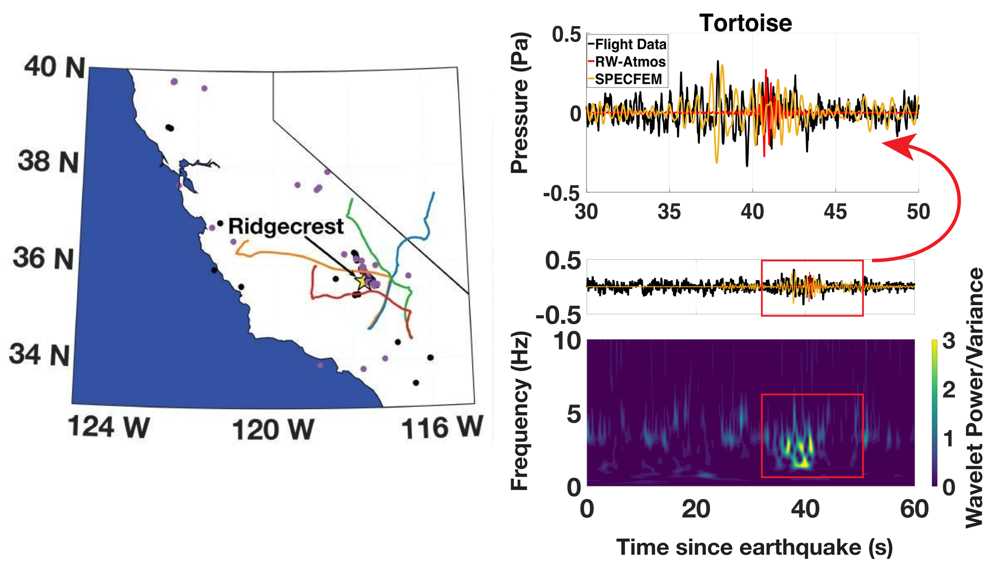
An arrival was detected at the location of this balloon which correlated strongly with a template made using pressure recordings from ground-based barometer arrays near ground zero. The detected amplitude was 3.1 times the expected amplitude from geometric ray tracing, and arrived within 1.1 seconds of the predicted arrival time 188.4 seconds after the explosion. The waveform was preserved extremely well during atmospheric traverse, encoding information about ground motion at the epicenter.



Detection of Surface Waves from an Earthquake on a Balloon

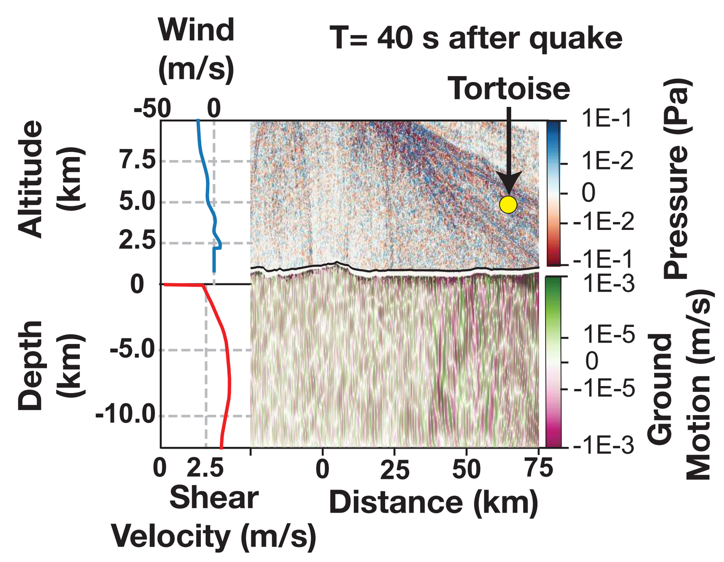
Two major earthquakes of magnitude 6.4 and 7.1 struck Ridgecrest, CA on July 4 and July 6, 2019, unleashing a sequence of over 10, 000 aftershocks of magnitude 1.5 and above over the next 6 weeks. As part of a rapid response campaign, we launched four Heliotrope balloons equipped with barometers in an attempt to measure infrasound from aftershocks of the Ridgecrest earthquakes.

The balloons floated to altitudes between 18 and 25 km, and self-terminated at sunset, landing over a wide region ranging from California's Central Valley region to north of Las Vegas, Nevada, as shown by the figure on the right. Each colored line is the trajectory of a balloon launched during this campaign. Two balloons were launched on July 22, 2019, shown by red and green lines. Two additional balloons were launched on August 9, 2019, with their trajectories represented by orange and blue lines.



See also, Brissaud et al. (2021): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GL093013

On July 22, a balloon nicknamed "Tortoise" detected an arrival approximately 40 seconds after a magnitude 4.2 aftershock from an altitude of 4.8 km approximately 80 km away from the epicenter. The arrival showed strong spectral correlation when compared to seismometers near the balloon's location, which showed the arrival of a surface wave from the earthquake 25 seconds after it occured. Numerical simulation tools "RW-Atmos" and "SPECFEM-DG" also showed expected arrivals at the balloon's location close to when it was detected.



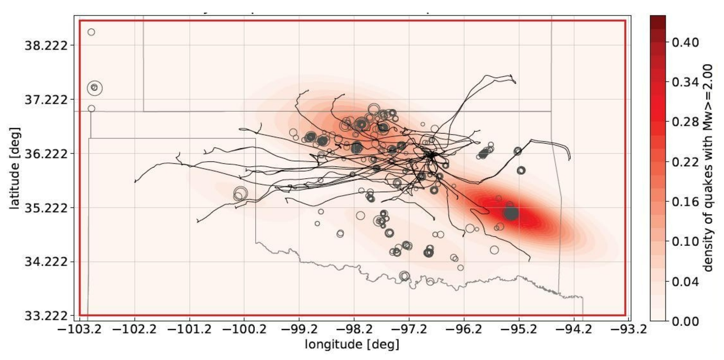
SPECFEM-DG Simulation

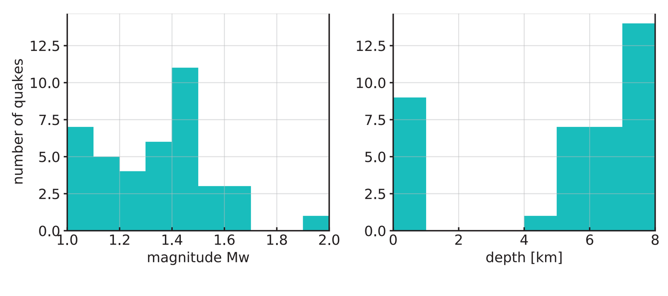
Balloon-based Acoustic Seismology Study (BASS) 2021 Flight Campaign in Oklahoma

The BASS project is an effort funded by the NASA Planetary Science and Technology through Analog Research (PSTAR) to carry out overflights of the State of Oklahoma to detect earthquakes from stratospheric balloons. The successful collection of many seismic infrasound signatures will result in a better understanding of seismic infrasound, determination of the detection limit of the balloon infrasound technique and the development of an algorithm for the automated detection of seismically induced signatures in balloon infrasound data.

The 2021 BASS campaign was conducted between July and September. A total of 38 heliotrope balloons were launched, 26 of which reached float. The balloons were equipped with two barometers on a tether. This configuration allows for signal stacking and time-of-flight correlations to determine the arrival direction of the signal. The entire campaign was student-led and operated under the guidance of staff from JPL, Sandia National Laboratories, and Oklahoma State University.

In the plot on the right, all balloon trajectories are overplotted with all earthquakes with magnitude > 1.0 that occured during the full duration of the campaign. Over the course of 26 flights, the balloon was within 100 km of 41 of these earthquakes, all between magnitude 1.0 and 2.0. This is significantly weaker than the earthquake detected during the Ridgecrest campaign. Data analysis is currently ongoing to search for signatures of earthquakes. A second balloon campaign is also planned as part of the project.





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