Progress towards Balloon-Based Seismology on Venus in 2021-2022 (#50)

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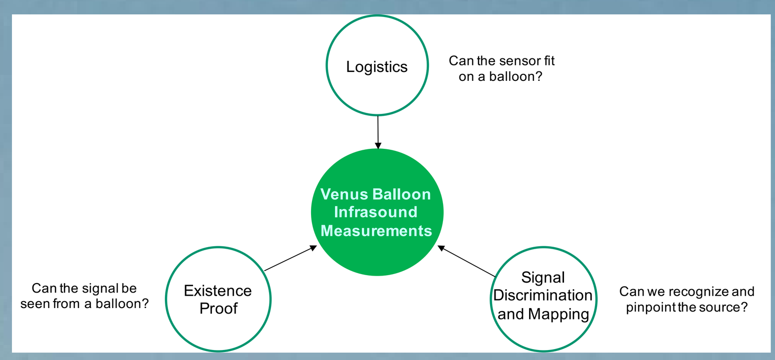
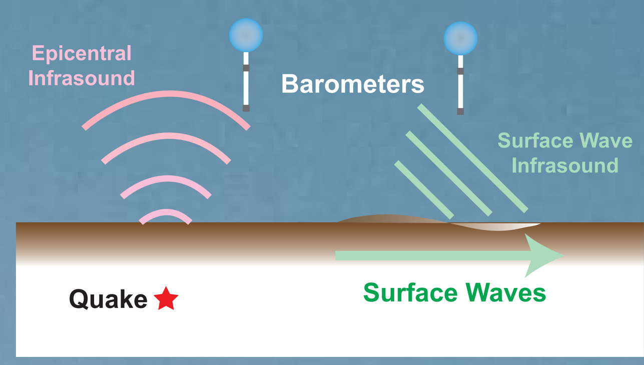
The **evolution and interior structure of Venus remain uncertain** despite half a century of exploration. This is in large part due to the absence of seismic investigations, which have yielded much of the information about Earth's interior. **Extreme surface temperature(>460 C) and pressure (>90 atmospheres)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

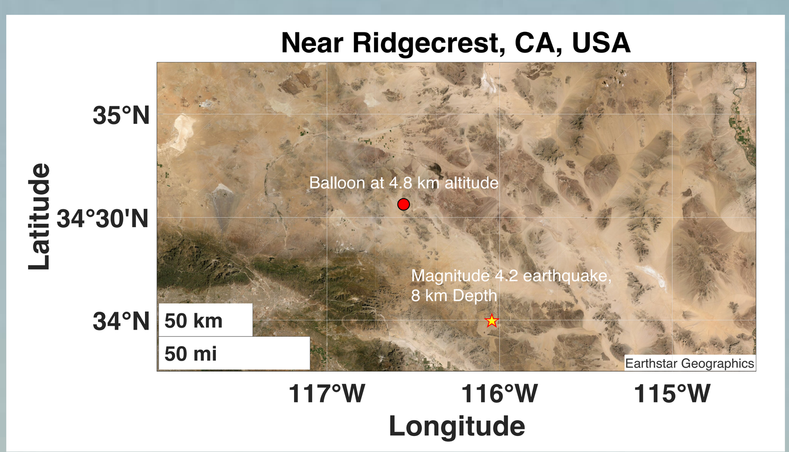
Our development efforts are primarily focused on **three key areas** of balloon-based infrasound seismology: **demonstrating existence proof**, i.e. that the signal can be detected from a balloon; **developing automated signal discrimination and mapping**, so that seismic signals may be distinguished 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.

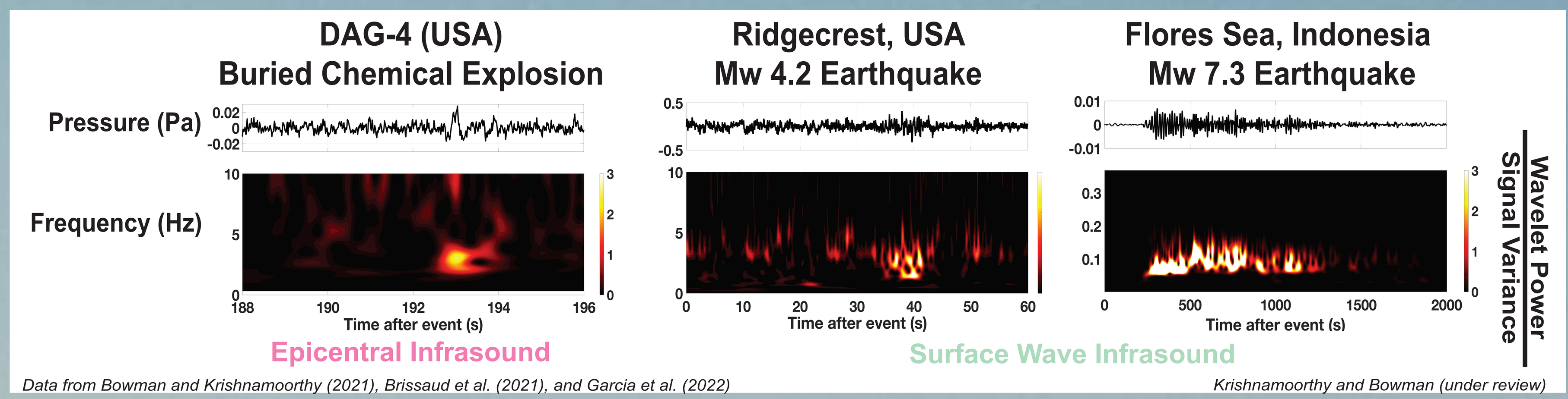


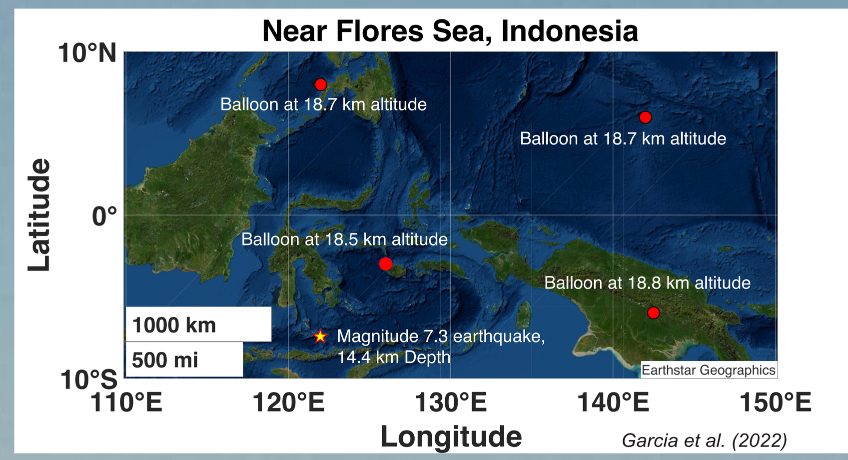
In previous work, we have demonstrated the viability of detecting seismic infrasound from balloons at close range using artificial seismic sources. In this poster, we present recent successful efforts at maturing this technique through the **detection of multiple earthquakes from balloons around the world**. We showcase the Balloon-based Acoustic Seismology Study (BASS) project, which is **flying tens of balloons over areas of high seismicity in the continental US** in a an effort to expand the available detection dataset. Lastly, we discuss the **expansion of modeling tools for predicting signals on Venus**.



Detections of Earthquakes on Balloons

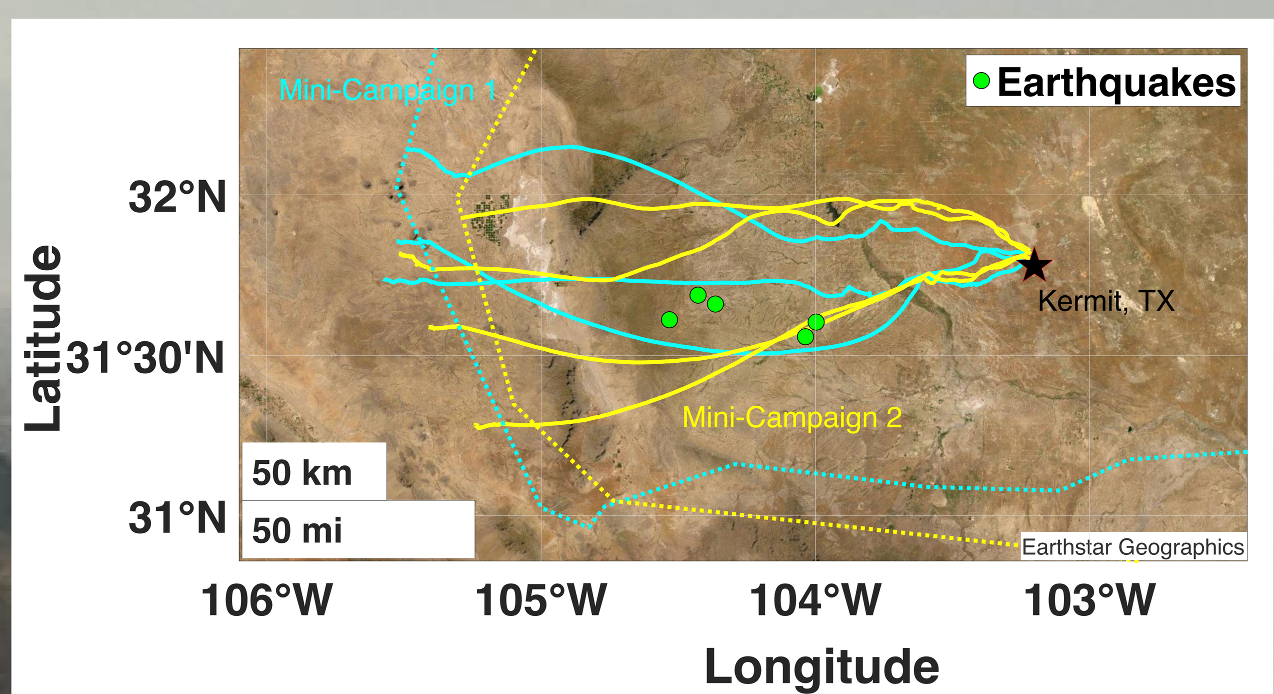


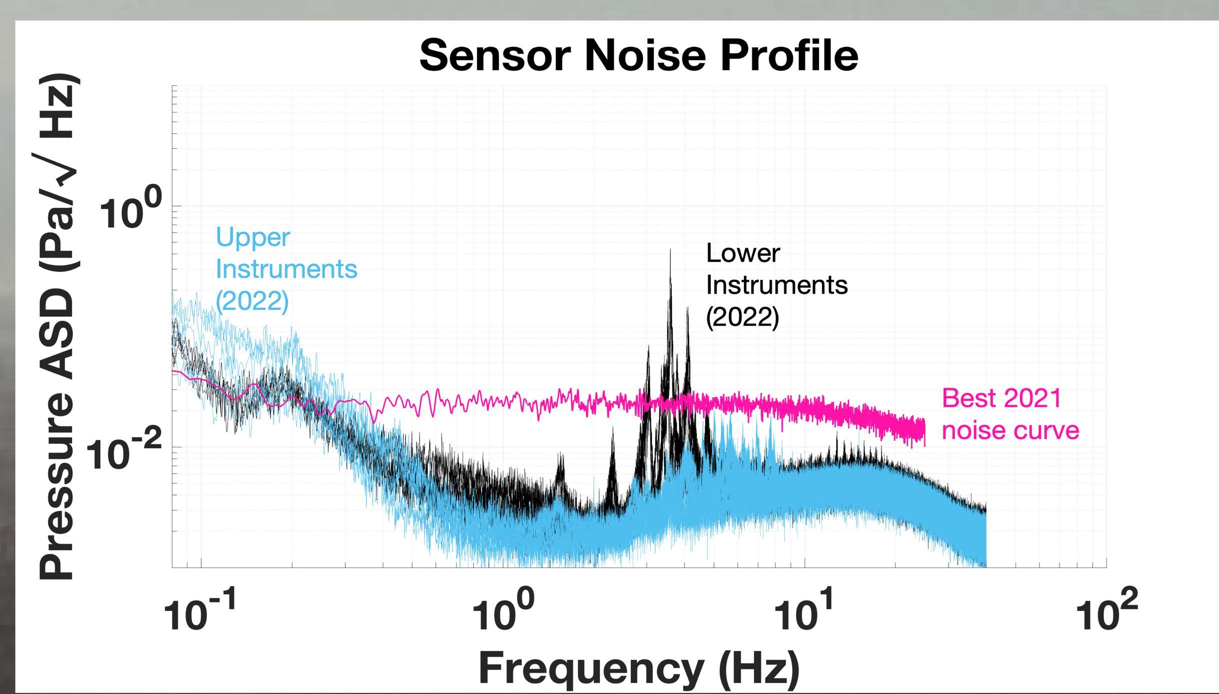




Detecting natural earthquakes from high-altitude balloons on Earth is essential to demonstrate the viability of balloon-based seismology on Venus. In 2019, a JPL team floated four balloons in the vicinity of Ridgecrest, CA after the 2019 Ridgecrest earthquakes. Analysis of these data by a JPL and Caltech team demonstrated the detection of surface wave infrasound from **a magnitude 4.2 earthquake at a distance of 80 km and an altitude of 4.8 km**. In 2022, ISAE-SUPAERO demonstrated the detection of two earthquakes of magnitude 7.3 and 7.5 from the stratosphere. The **magnitude 7.3 earthquake in the Flores Sea was simultaneously detected by four balloons at distances ranging from 684 km to 2832 km away**. Together, these detections showcase two opposite regimes for this technique: weak earthquakes at a regional distance and strong earthquakes at continental distances.

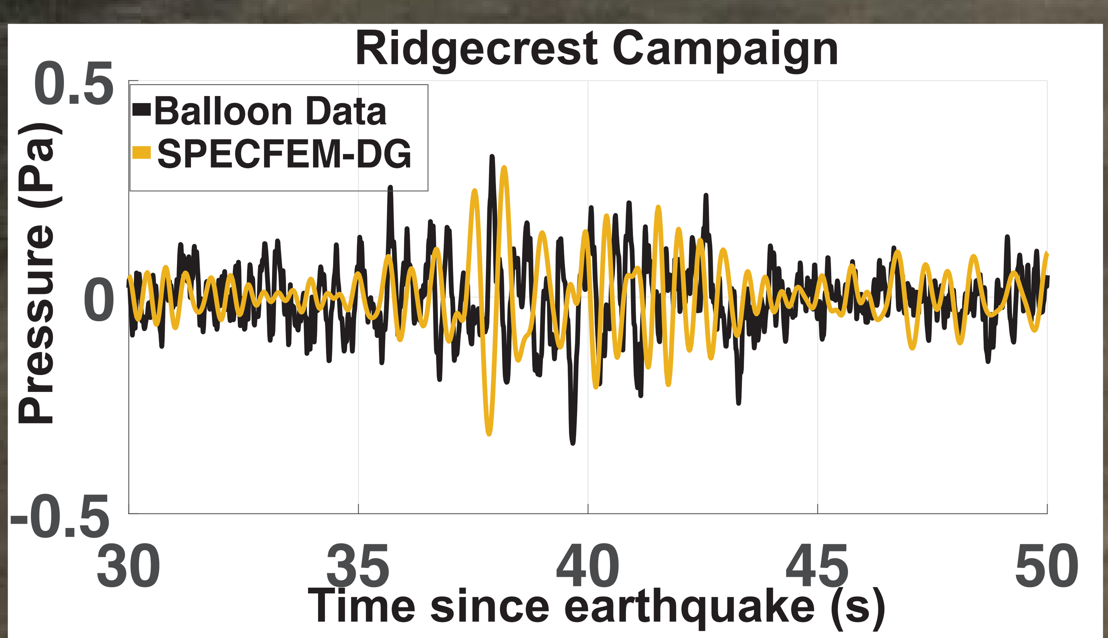
Balloon-based Acoustic Seismology Study (BASS) Flight Campaign

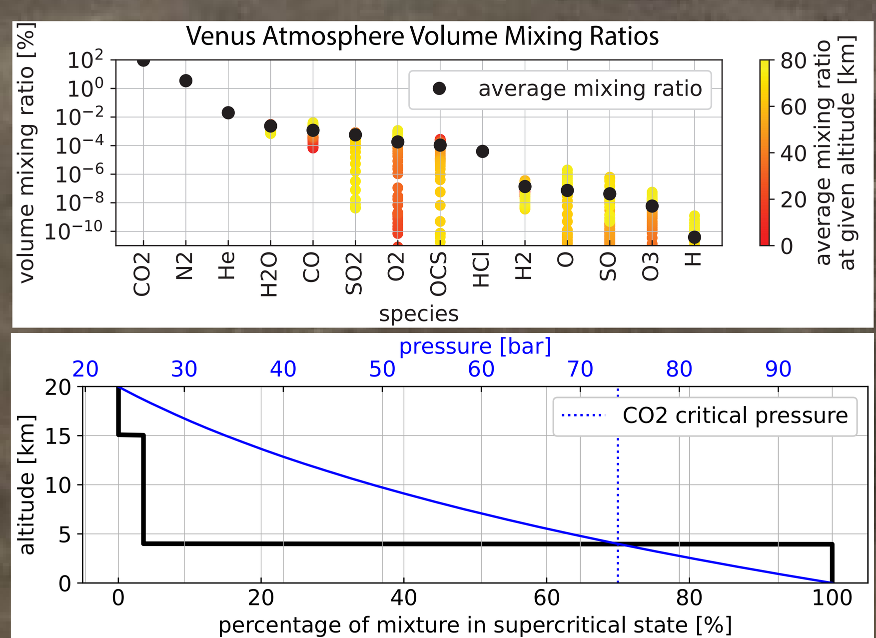


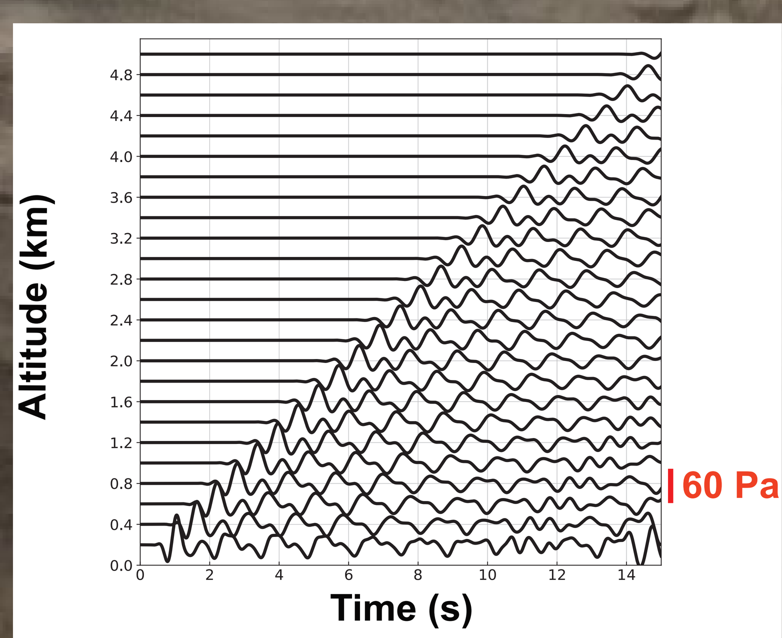


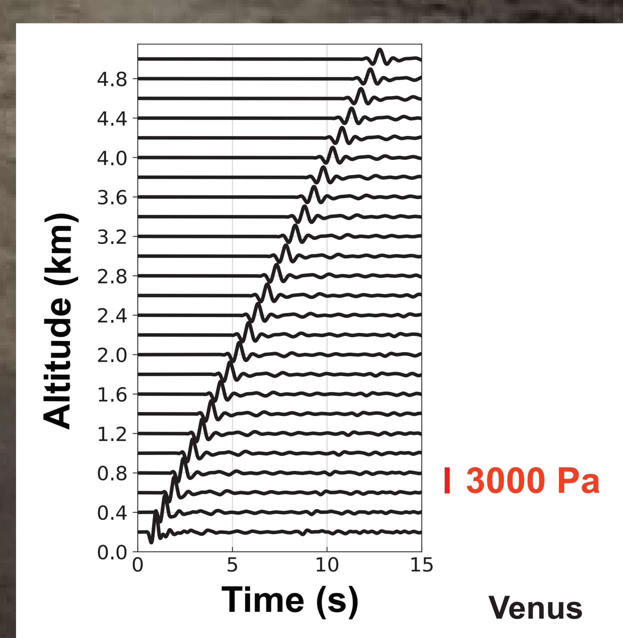
The BASS project is an effort funded by the NASA Planetary Science and Technology through Analog Research (PSTAR) to carry out overflights seismically active areas in the US to detect earthquakes from stratospheric balloons. The successful collection of many seismic infrasound signatures will result 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 first campaign in 2021 conducted 39 flights in the State of Oklahoma**. However, high instrument noise levels and low seismicity hindered earthquake detections. In 2022, we reconfigured sensors for lower noise and adopted a new strategy of targeting a highly active and localized earthquake swarm in the Permian Basin in Texas in three one-week-long mini-campaigns. **The 2022 campaign has conducted 5 flights (total of 7 flights by end of campaign) and has flown within 50 km of 5 earthquakes of magnitudes 2-3 with multiple barometers.** Data analysis is ongoing.

Venus Infrasound Modeling









Simulated Magnitude 1.0 event

Ground truth data is abundant on Earth but scarce on Venus. **What signal levels do we expect on Venus? How do we identify signals within the recorded dataset? How different do signals look on Venus with a 98% CO_2 atmosphere compared to Earth? Infrasound modeling helps us understand these questions.** We are using our Earth-based flight data to validate the SPECFEM-DG seismo-acoustic simulation tool developed at ISAE-SUPAERO and enhanced at JPL, and integrating models of the Venus atmosphere and subsurface to forward model signals from potential Venus seismic events.

Key Takeaways

- Several (3 earthquakes, 6 detections so far) natural earthquakes (magnitudes 4.2 to 7.5) have been detected from high-altitude balloon platforms across the world at tropospheric and stratospheric altitudes from as far as 2800 km away. Seismo-acoustic coupling on Venus is 60x stronger than Earth. **If Venus is seismically active, then the signals from venusquakes are likely detectable from balloons even very far away.**
- Additional detections of different types of earthquakes will help algorithms for automatic earthquake identification without ground truth. The detections of weak quakes help quantify the lower detection limit of the balloon infrasound technique.
- Forward modeling of signals using simulation software can help create signal catalogs for Venus, which will help determine expected signal strength.

 The authors acknowledge support from the JPL Strategic Initiative for Research and Technology Development, and the NASA Planetary Science and Technology through Analog Research (PSTAR) program. Part of this work was performed at California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.