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Progress towards Balloon-Based Seismology on Venus

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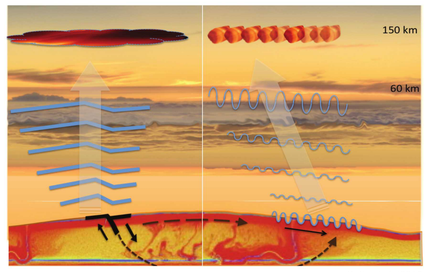
The evolution and interior structure of Venus remain uncertain despite half a century of exploration. This is in large part due to the absence of seismological investigations, which have yielded much of the information about Earth's interior. Extreme surface temperature(>460 C) and pressure (>90 atmospheres) 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 55-60 km altitude on Venus, where the temperature and pressure are much more benign and longer mission lifetimes can be guaranteed.

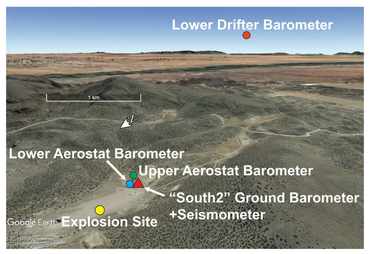


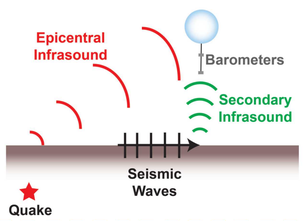
Cutts et al. (2015)

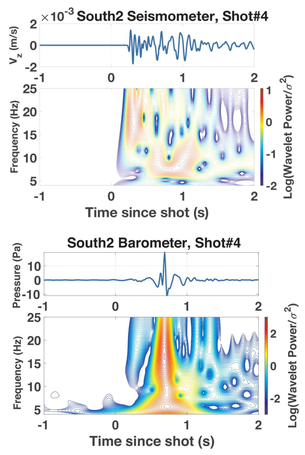
Key Capabilities

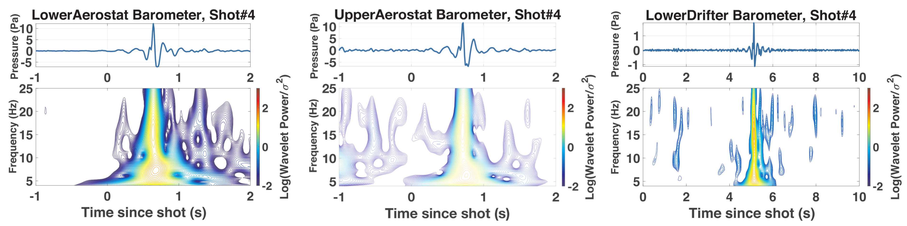
Venus Balloon Infrasound Seismology

Demonstrate Seismic Infrasound Detection and Characterization

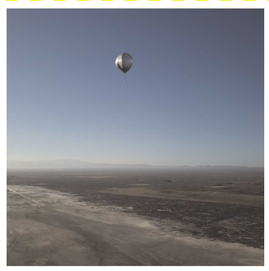


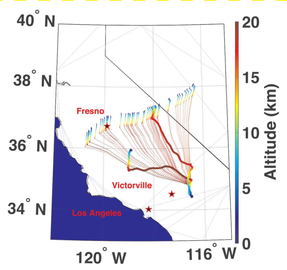


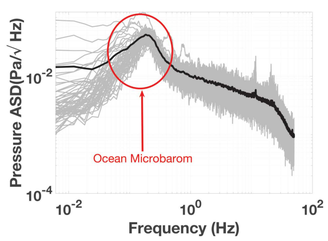


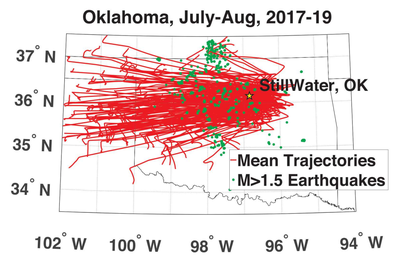


In August 2019, we conducted three buried chemical explosions to generate artifical quakes with multiple detectable seismic phases. The signal was measured by a network of seismometers and ground and balloon-based seismometers. P-waves, blast waves, and surface waves from the largest explosion (50 kg TNT) were recorded and discriminated from balloon-borne sensors using time of flight and spectral analysis. Further analysis is ongoing.





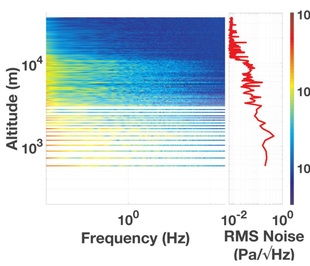


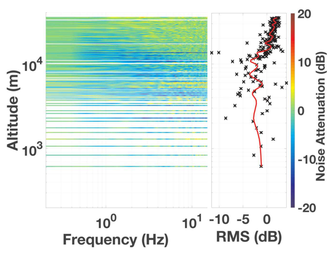


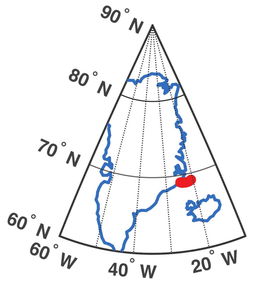
We wish to demonstrate infrasound detection and characterization from natural quakes. We are proposing daily flights in the summer over earthquakes in Oklahoma by "solar balloons" equipped with barometers on a tether. Our analysis shows that one earthquake every two days may be detectable at 20 km altitude with a noise level 0.005 Pa.

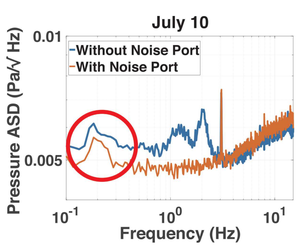
In July and August 2019, we conducted test flights of solar balloons in southern California at 20-25 km altitude with barometers in different configurations. We used our trajectory simulator to select flight days, coordinated with several airspace agencies, and tracked and recovered all payloads successfully. The average noise level recorded was 0.005 Pa in the 1-10 Hz band.

Discriminate Seismic Signals from the Background





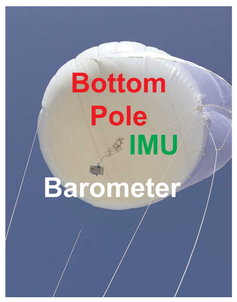


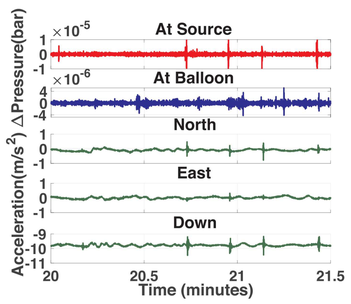


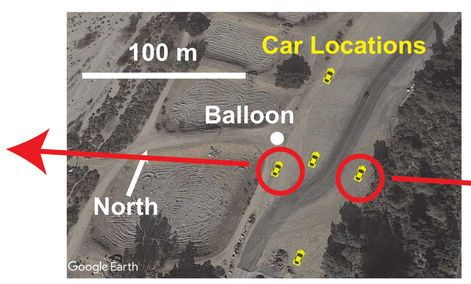
We have been collecting valuable infrasound background data on Earth by flying as a secondary payload on NASA Long-Duration balloons. Large datasets will allow us to train algorithms to identify different geophysical infrasound signals autonomously and map results to Venus. These flights also generate important science results. For instance, our July 2018 overflight of the arctic demonstrated that wind noise mitigation systems are not needed on drifting balloons, saving mass. We also detected coastally reflected infrasound from the ocean near Greenland's east coast - a first from a balloon.

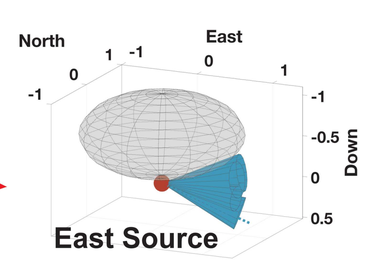
Sensor Miniaturization

We completed the first demonstration of the "vector infrasound" instrument concept – by measuring a neutrally bouyant balloon's acceleration in response to an infrasound wave (using a high-precision IMU) along with the pressure, **a single station can determine the direction and magnitude of an incoming infrasound wave**, circumventing the need for balloon-borne arrays.









Infrasound was generated by slamming a car door. The signal from the barometer and the IMU was combined to generate a direction estimate for the source. **The correct octant was predicted 75% of the time.** Further development of this conecpt involves testing with larger sources on freely-floating tropospheric and stratospheric superpressure balloons.

Key Takeaways

- Performing balloon-based seismology on Venus can happen with technology of today
- The ability to detect and discriminate seismic infrasound signals from balloon-compatible sensors must be demonstrated
- We are making steady progress in demonstrating these key capabilities using the Earth as a Venus analog

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Additional Reading

- Krishnamoorthy et al. (2019), "Aerial Seismology Using Balloon-Based Barometers", *IEEE Trans. Geosci. and Remote Sensing*, doi:10.1109/TGRS.2019.2931831
- Krishnamoorthy et al. (2018), "Detection of Artificially Generated Seismic Signals using Balloon-Borne Infrasound Sensors", *Geophysical Research Letters*, doi:10.1002/2018GL077481

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