EARTH-ANALOG EXPERIMENTS FOR DETECTING SEISMICITY ON VENUS USING BALLOONS. S. Krishnamoorthy[1], Q. Brissaud[2], A. Komjathy[1], J. A. Cutts[1], M. T. Pauken[1], D. C. Bowman[3], J. M. Jackson[4], B. R. Elbing[5], A. Vance[5], J. Jacob[5], R. F. Garcia[6], and D. Mimoun[6]
[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[2] Norwegian Seismic Array (NORSAR), Olso, Norway
[3] Sandia National Laboratories, Albuquerque, NM
[4] Seismological Laboratory, California Institute of Technology, Pasadena, CA
[5] Oklahoma State University, Stillwater, OK
[6] Institut Supérieur de l'Aéronautique et de l'Espace (ISAE), Toulouse, France

Introduction: Seismological investigations are essential for understanding the internal structure of a planet. Tectonic and volcanic structures on Venus [1], [2] suggest recent deformation and potential for ongoing seismic activity. The presence of shield volcanoes, coronae and domes, in conjunction with simulation studies [3] and numerous instances of circumstantial evidence suggest present-day volcanism as well. Extremely high temperature and pressure conditions on the surface of Venus [4] present a significant technological challenge to performing long-duration seismic experiments similar to those being performed by the InSight lander on Mars. Therefore, despite multiple visits from several landers, basic knowledge of the internal structure of Venus is still lacking.

Earthquakes are known to generate acoustic waves by coupling energy from ground motion into the atmosphere. Low-frequency (< 20 Hz) acoustic waves known as infrasound have been detected from earthquakes and volcanic activity from terrestrial stations on Earth [5], [6]. Seismic infrasound generated from artificial seismic sources has also been detected from balloon-borne pressure sensors [7]–[9]. The amplitude of infrasound generated from seismic activity depends strongly on the relative density of the atmosphere and the planet's crust. On Venus, energy from seismic activity couples with the Venusian atmosphere up to 60 times stronger than Earth [10] due to its dense atmosphere, which offers a unique opportunity to explore the internal structure of Venus using balloons floating in the mid and upper atmosphere.

Earth-Analog Experiments: In order to achieve the aim of performing geophysical experiments from an atmospheric platform, we have been conducting an Earth-based campaign to detect seismic infrasound in the Earth's atmosphere as an analog for Venus. By closely studying infrasound generation and propagation in the Earth's atmosphere, we can develop tools and methods that will allow for the detection, location and characterization of venusquakes from a balloon floating in the relatively benign conditions in its upper atmosphere.

The earthquakes in Ridgecrest, CA on July 4 and 6, 2019 generated a lengthy sequence of low-intensity aftershocks, resulting in over 10,000 earthquakes of magnitude 1.5 and above over the next six weeks. These aftershocks presented a unique opportunity for the observation of infrasound produced by natural earthquakes from a freely-floating balloon platform. We manufactured and launched four "heliotrope" solar-heated hot air balloons [11] on July 22 and August 9, 2019, to lift infrasound sensor packages into the stratosphere and overfly the seismogenic zone near Ridgecrest, CA.

A total of 82 earthquakes of magnitudes 1.5-4.2 occurred during the flight of the four balloons, with a large fraction of them concentrated near Ridgecrest (Figure 1). All four sensor packages were recovered and their data were analyzed in conjunction with seismometer data obtained from the dense United States Geological Survey (USGS) network in the area. In addition, we deployed seismoacoustic simulation tools to understand infrasound wave generation and

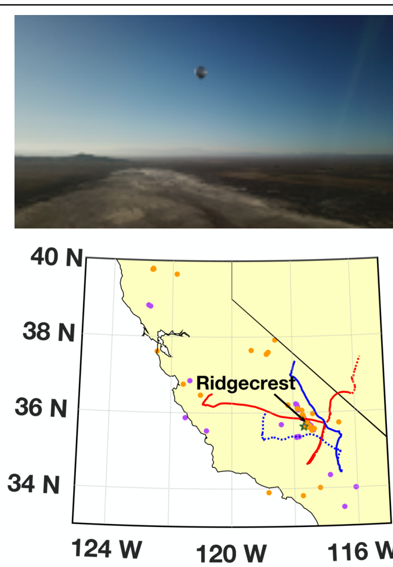

Figure 1: (Top) A heliotrope balloon shortly after launch on August 9, 2019 (Bottom) A map showing the trajectories of balloons on July 22 (blue) and August 9 (red). Earthquakes on July 22 are marked as magenta dots and those on August 9 are marked as orange dots.

propagation from the shallow and predominantly strike-slip earthquakes in this sequence and narrow the list of quake candidates for further analysis.

Lessons learned from the Ridgecrest campaign will now be incorporated into a 3-year-long Earth-analog infrasound campaign funded by the NASA Planetary Science and Technology from Analog Research (PSTAR) program. This campaign will include twice daily heliotrope flights in July/August 2021 and 2022 in Oklahoma, which has high levels of seismicity due to activities associated with natural gas fracking. Our initial estimates suggest that a quake may be detectable every two days if barometer noise levels can be driven down to 0.005 Pa in the 1-10 Hz band, which was achieved in the Ridgecrest campaign.

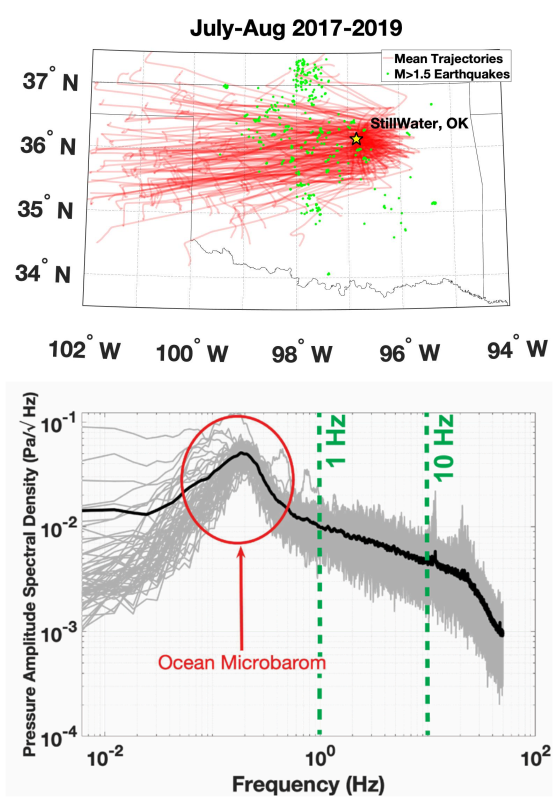

Figure 2: (Top) Simulated daily trajectories for heliotrope balloons launched from Stillwater, OK for July/August 2017-2019. Green dots show earthquakes with magnitude greater than 1.5 in the same period. (Bottom) Recorded background noise during Ridgecrest campaign shows ~0.005 Pa noise level between 1-10 Hz.

Presentation Content: In this presentation, we will first discuss our Ridgecrest campaign and subsequent analysis in 2019 and 2020. Our presentation will share further details of our analysis of balloon and ground-based data, and simulation tools used to aid the analysis. In addition, we will present our analysis of Oklahoma earthquakes from 2017-2020 and expected detection statistics for our upcoming campaign. We will also share our progress as we prepare for the first campaign in July/August 2021. Finally, we will share our vision for the future of these techniques and their path to infusion into a Venus mission.

References:

[1] P. K. Byrne *et al.*, "The Lithosphere of Venus has been Broken and, in Place, Mobile," in *49th Lunar and Planetary Science Conference*, 2018, no. 2083, p. 1935.

[2] M. A. Ivanov and J. W. Head, "The history of volcanism on {Venus}," *Planet. Space Sci.*, vol. 84, pp. 66–92, 2013.

[3] A. J. P. Gülcher, T. V. Gerya, L. G. J. Montési, and J. Munch, "Corona structures driven by plume–lithosphere interactions and evidence for ongoing plume activity on Venus," *Nat. Geosci.*, vol. 13, no. 8, pp. 547–554, Aug. 2020.

[4] A. T. Wood, R. B. Wattson, and J. B. Pollack, "Venus: Estimates of the surface temperature and pressure from radio and radar measurements," *Science (80-.).*, vol. 162, no. 3849, pp. 114–116, Oct. 1968.

[5] S. J. Arrowsmith *et al.*, "A seismoacoustic study of the 2011 January 3 Circleville earthquake," *Geophys. J. Int.*, vol. 189, no. 2, pp. 1148–1158, 2012.

[6] J. B. Johnson, "Generation and propagation of infrasonic airwaves from volcanic explosions," *J. Volcanol. Geotherm. Res.*, vol. 121, no. 1–2, pp. 1–14, Feb. 2003.

[7] S. Krishnamoorthy *et al.*, "Detection of Artificially Generated Seismic Signals Using Balloon-Borne Infrasound Sensors," *Geophys. Res. Lett.*, vol. 45, no. 8, pp. 3393–3403, Apr. 2018.

[8] S. Krishnamoorthy *et al.*, "Aerial seismology using balloon-based barometers," *IEEE Trans. Geosci. Remote Sens.*, vol. 57, no. 12, pp. 10191–10201, Dec. 2019.

[9] R. F. Garcia *et al.*, "An active source seismo-acoustic experiment using tethered balloons to validate instrument concepts and modelling tools for atmospheric seismology," *Geophys. J. Int.*, Dec. 2020.

[10] R. Garcia, P. Lognonné, and X. Bonnin, "Detecting atmospheric perturbations produced by Venus quakes," *Geophys. Res. Lett.*, vol. 32, no. 16, pp. 1–4, 2005.

[11] D. C. Bowman *et al.*, "Multihour stratospheric flights with the heliotrope solar hot-air balloon," *J. Atmos. Ocean. Technol.*, vol. 37, no. 6, pp. 1051–1066, Jun. 2020.