High-Temperature MEMS Based Venus Seismometer

Hot Operating Temperature Technology - NNH21ZDA001N-HOTTCH

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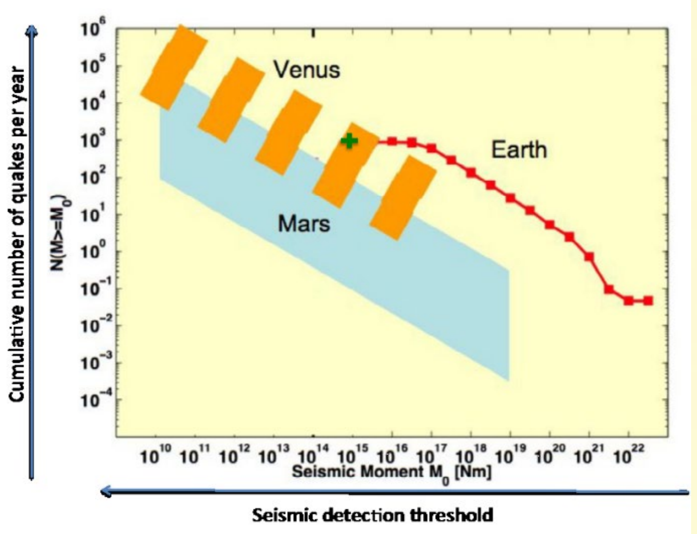


Figure 1: Estimate of Venus seismic activity

Objectives and Expected Significance

Seismology is the method of choice for studying a planet's interior and assessing current tectonic activity. With a single strategically placed seismometer, or preferably a network of seismometers, a variety of key aspects of a planet can be evaluated. The level and nature of seismicity observed provides a gauge of current geologic, especially tectonic, activity. Where tectonic activity is and is not occurring illuminates what regions and geologic features on the planet are currently active, thus, constraining global geodynamics. Larger distal earthquakes can be used to determine major compositional and structural boundaries within a planet's interior, providing major constraints on planet formation and interior evolution. Seismometers have been deployed successfully on the Moon and Mars. Only small subsets of the scientific knowledge that can be gained from seismology can be obtained from alternative scientific approaches, such as global gravity solutions or repeat-pass interferometry.
By virtue of its similar size to Earth, Venus is likely to be highly seismically active (Fig. 1, [1]). Even at Earth-like levels of seismology, returning meaningful data would require observation over a period that is at least 2–3 orders of magnitude longer than the 1–2 h lifetime of previous Soviet landers. Clever insulation could extend the lifetime of standard electronics in a modern lander to perhaps 24 h [2]. While active cooling of electronics for a Venusian lander is plausible, this approach would require considerable technological advancement and will likely come at a high monetary and mass cost [2]. The high density of the Venusian atmosphere at the surface should mean that there is good coupling of seismic energy into the atmosphere, such that seismology using infrasound from a balloon platform is currently being explored, and observations of the upper levels of the atmosphere from orbit has also been proposed [3]. Besides losing all shear wave information with these two methods, calibrating and interpreting seismic information that has been distorted by, and convolved with, atmospheric phenomena will be challenging without existing seismology data collected through surface seismometers (optimally, simultaneous surface seismological observations would be made).

In short, the most expedient and cost-effective path forward for obtaining critical information about the Venusian interior and level of current tectonic activity is development of a seismometer that can operate for a few months at ambient Venus surface conditions. We seek to develop a battery-powered seismometer that can operate on the Venusian surface (temperature T ≈ 460 °C) for at least 60 days.

Relevance and Perceived Impact

Table 1 traces how a Venus seismometer addresses several investigations in the Venus Exploration Analysis Group (VEXAG) Goals, Objectives, and Investigations (GOI) [4]. The GOI document in turn ties these investigations to the Decadal Survey [5]. We are proposing to develop an instrument to conduct planetary science for more than 60 days in an operating environment that exceeds 500 °C on the surface of Venus, making this proposal relevant to the Hot Operating Temperature Technology (HOTTech) program. It is clear from Table 1 that inclusion of the proposed seismometer in a future mission would have high impact on our understanding of Venus.

VEXAG investigation	How Venus seismometer(s) addresses it
I.A.RE. Search for structural, geomorphic, and chemical evidence of crustal recycling on Venus.	Identify subduction-associated earthquakes.
I.B.LI. Determine lithospheric parameters on Venus that are critical to rheology and potential geodynamic transitions, including: stress state, water content, physical structure, and elastic and mechanical thicknesses.	Use earthquake locations and returned signal to constrain lithospheric stress state, constrain composition and water content, and identify major structural boundaries.
I.B.CO. Measure the size of the core of Venus and determine whether it remains partially liquid.	Use timing and nature of seismic wave reflections and refractions from large, distal earthquakes to determine deep interior structure.
III.A.GA. Characterize current volcanic, tectonic, and sedimentary activity that modifies geologic units and impact craters and ejecta on Venus.	Use earthquake locations, frequency of occurrence to characterize current volcanic and tectonic activity.
III.A.CR. Determine the structure of the crust of Venus in three dimensions and thickness across the surface.	Use local/regional quakes to constrain crustal properties in the region containing the seismometer.

Table 1. Venus surface seismometer addresses several desired science investigations.

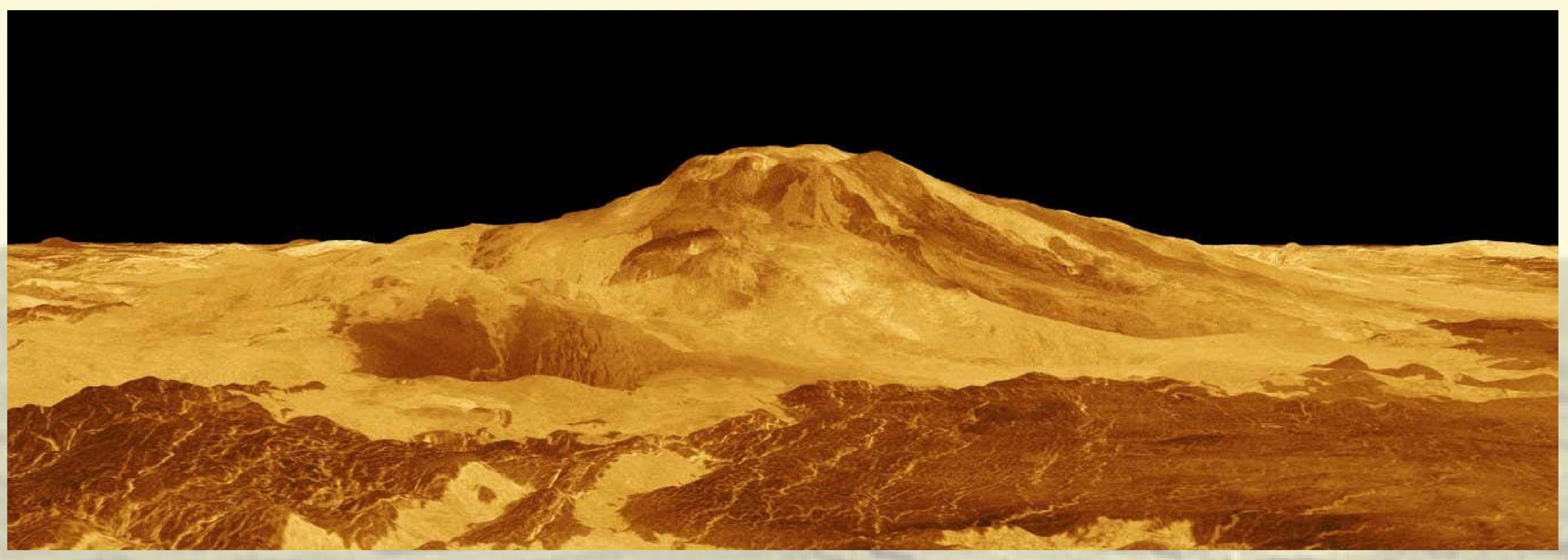


Figure 2: Venus may have regular quakes linked to the activity of volcanoes like the giant Maat Mons, which towers nearly 5 kilometers above the surrounding plains

Requirements Development

This project establishes science-derived Venus seismometer requirements that are compatible with a small energy-limited lander including:

- Defining the expected environmental conditions and mission life
- Defining the expected seismic activity of Venus and the measurement range of the seismic sensor
- Defining and limiting expected noise from sources such as wind and thermal gradients
- Defining requirements for high-temperature electronic circuits that will interface to the microelectromechanical system (MEMS) seismic sensors.
- Defining lander system requirements to power and communicate with the seismometer
- Define orbiter requirements for collecting data sent from the lander

Sensor Development

ICL is providing a series of sensors that will provide an evolutionary development from the proven InSight design towards a Venus-compatible approach. The four major challenges are
1. Developing a capacitive transduction scheme that can operate without feedback over the required tilt range to obviate the need for magnetic feedback;
2. Moving to compressive bonding that can both bond-up the sensors and provide the electrical interconnections to replace the solder bonding used for InSight;
3. Replacing the solder shock protection with a high-temperature compatible interposer that performs the same function; and
4. Optimizing the performance so that the sensor and electronics together provide sufficient performance to reach the science goals of seismic detection on Venus.

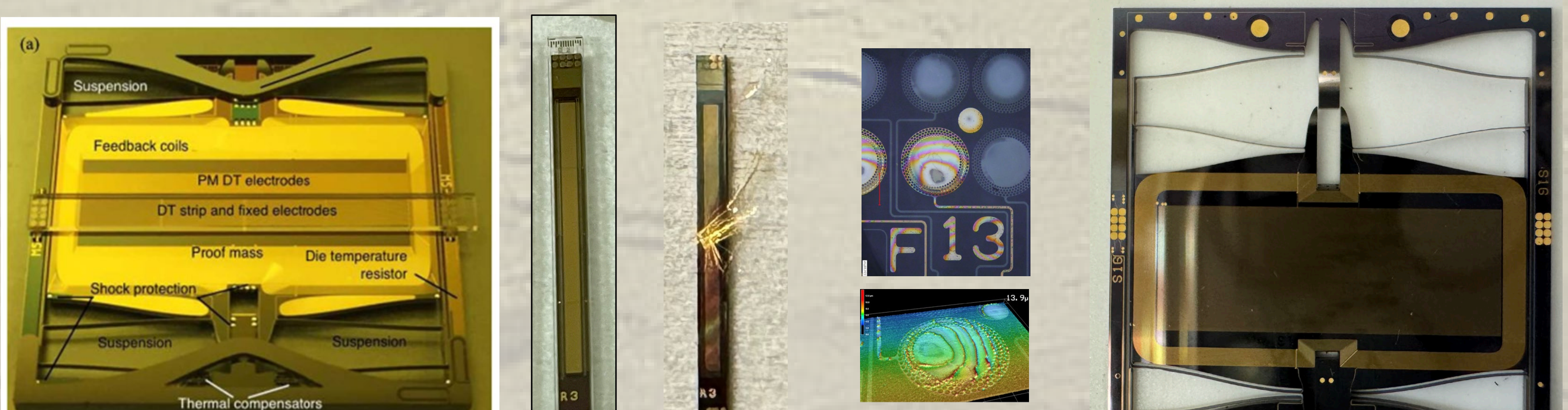


Figure 4: Progression of Venus Seismometer; from left to right (1) InSight Seismometer (2) First InSight sensor strip modified for Venus conditions (3) First GEER test of sensor strip (4) 3-D analysis showing pads lifting (5) Current seismometer sensor post GEER testing showing no visual signs of degradation after 10 days of exposure

Electronics Development

A core of this work is to produce a seismometer with electronics operable at Venus surface temperatures and conditions. The electronics produced in this project are based on the only technology shown to operate for 60 days in simulated Venus surface conditions. However, specific electronics will need to be designed and fabricated to operate a long-lived Venus seismometer. There are two major functions of the proposed design. The first major function is to provide a measurable signal from the seismometer sensor. The ICL seismometer structure is a capacitive sensor, and so, supporting high-temperature electronics for this seismometer needs to be able to interrogate a capacitor For a power-constrained Venus application a second required function is to determine if a change in seismic signal actually represents a quake or is a function of background noise. In other words, a trigger to activate the seismometer into an active mode of measurement and transmission.

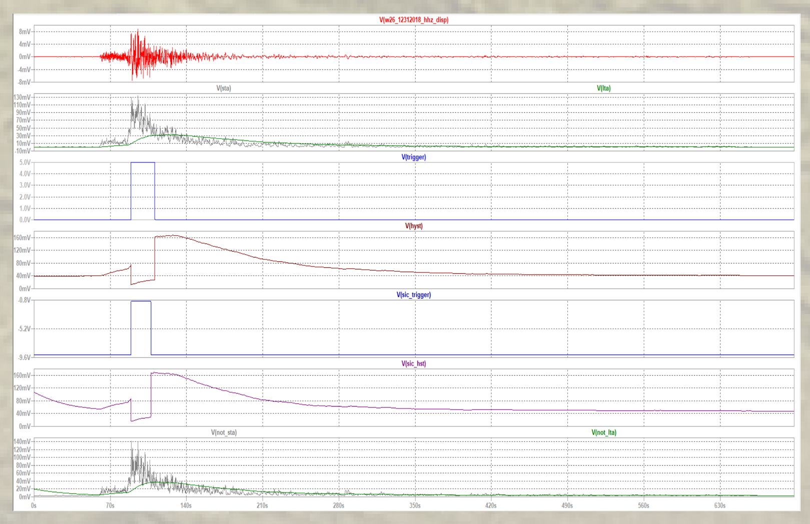


Figure 3: Actual quake data (top), sensor output, trigger signal, trigger hysteresis, and modeled trigger in SiC

Field Testing

The Alaskan Earthquake Center, (AEC), operates a network of ~250 seismic stations across Alaska in geologic settings that include proximity to active volcanoes and convergent plate boundaries, as well as stations in relatively quiet intraplate settings. The Venus seismometer, whose output signal will be reconstructed using Si electronics, will be mounted with the traditional seismometers and monitoring the same events. In the frequency ranges applicable, the objective is to show that the Venus seismometer operates and triggers from quake events in a manner that is comparable and predictable to traditional seismometer systems, thus confirming the sensor suitability as the baseline around which the seismometer instrument will be designed and fabricated.

Figure 6: Alaskan field test site (photos provided by UAF)

Demonstration in the Glenn Extreme Environments Rig (GEER)

This group is the only one to have successfully operated high-temperature electronics in GEER for 60 days in simulated Venus conditions [27]. In year 3 of this project, the Venus durable high-temperature seismometer, consisting of both high-temperature electronics and a seismic sensor on a circuit board, will be tested in the GEER to demonstrate operation in simulated Venus surface conditions for 60 days. The approach will be to mount the Venus seismometer in the chamber. The output of the seismometer when triggered will be a data stream to conventional electronics outside of the chamber. The conventional electronics serve the role of "lander" that would, on an actual mission, transmit the data to an orbiter/back to Earth.

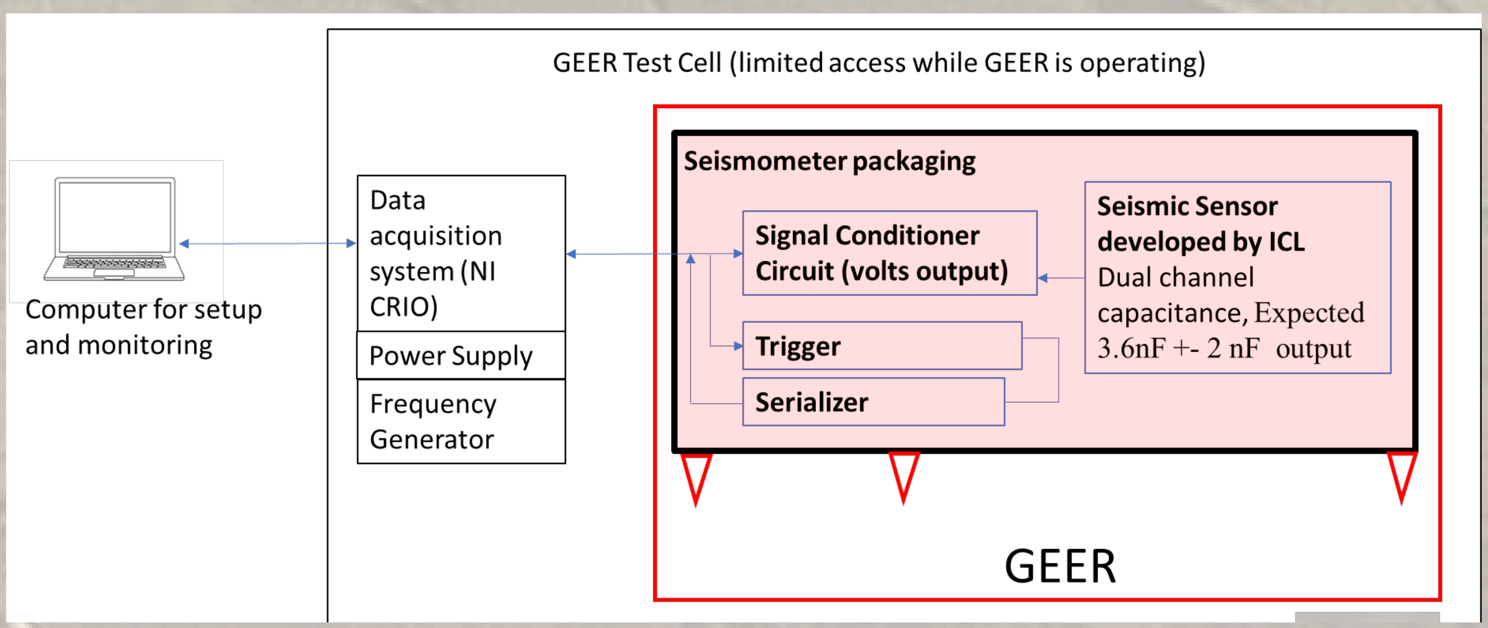
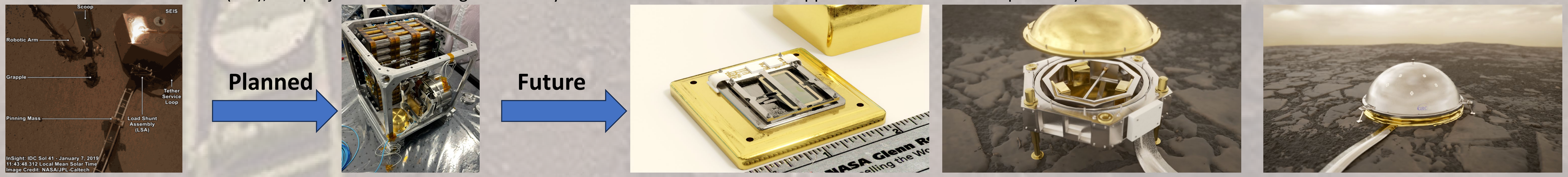


Figure 5: GEER test setup to demonstrate seismic sensor operation under Venus surface conditions

Preparing for Future Missions

The project has been focused on compatibility with a small, low power long lived lander emphasizing: 1) high-temperature electronics and systems that operate without cooling at Venus surface conditions, 2) use of instrumentation with emphasis on low data volume, and 3) minimizing energy utilization through a novel operations approach. Furthermore, by basing this work off the existing InSight sensors; which will also be used for the Lunar Far Side Seismometer (FSS); the project is maintaining consistency of measurements that can be applied to Venus and other planetary bodies.



Mars InSight (Completed mission) | **Lunar Far Side Seismometer (2026)** | **Conceptual Extreme Environments Seismometer with front end electronics** | **Conceptual Venus compatible tri-axial, self leveling seismometer suite** | **Venus Compatible tri-axial seismometer with wind and thermal shield installed**

Figure 6: Progression of MEMS seismometer in outer worlds

References and Acknowledgements

(1) Keck Institute for Space Studies (KISS), 2015. Probing the Interior structure of Venus, https://kiss.caltech.edu/final_reports/Venus_final_report.pdf
(2) Venus Exploration Analysis Group (VEXAG), 2019. Venus Technology Plan.
(3) Krishnamoorthy, S., Komjathy, A., Cutts, J.A., Lognonne, P., Garcia, R.F., Panning, M.P., Byrne, P.K., Matoza, R.S., Jolly, A.D., Snively, J.B., 2020. Seismology on Venus with infrasound observations from balloon and orbit. Sandia National Lab. (SNL-NM), Albuquerque, NM (United States).
(4) Venus Exploration Analysis Group (VEXAG), 2019. Goals, Objectives, and Investigations, https://www.lpi.usra.edu/vexag/documents/reports/VEXAG_Venus_GOI_2019.pdf
(5) Committee on the Planetary Science Decadal Survey: Vision and Voyages for Planetary Science in the Decade 2013–2022,. ISBN: 13: 978-0-309-22464-2

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