Development of a High Temperature Venus Seismometer and Extreme Environment Testing Chamber

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Introduction: Venus exploration has gained considerable interest and relevance in recent years. Venus has significant similarities to Earth in terms of size, initial composition, and solar-radiative influences. However, its present planetary conditions contrast drastically from that of Earth with a significant greenhouse effect [1]. Venus has a very hostile environment with an average surface temperature of 462°C, an atmospheric pressure of 90 atm on the surface, and an atmosphere comprised primarily of CO_2. Missions that have landed on the surface of Venus have typically lasted on the order of hours due to the high temperatures and harsh conditions. Further, the measurement of Venus planetary conditions has generally been limited by the lack of sensor and instrument systems that can operate long term in the harsh Venus environment.

One set of measurements identified as having significant scientific interest in understanding Venus planetary conditions and history is seismometry [1]. Seismometry can determine the activity of the interior of Venus and provide clues related to its history and evolution. A regional or global network of seismometers could answer several important questions related to Venus seismic activity and subsurface structure. Wireless communication may also be an asset, as it would allow the seismometer to be deployed at some distance from the parent lander, partially decoupling the seismometer from oscillations created on the main lander. However, there is a fundamental question as to whether such seismic measurements can be performed given the high temperature, harsh environment of Venus.

Further, the ability to test such a system in relevant temperatures, pressures, and atmospheric constituents is limited. The availability of test systems that can not only handle even moderate size instrumentation, but provide Venus relevant environment for extended testing are limited.

This paper describes efforts to design, fabricate, and demonstrate a proof-of-concept seismometer operating at Venus temperatures, and describes test capabilities being developed to evaluate this and other instruments in Venus relevant conditions. The seismometer development approach is to show operation of a basic seismometer system laying the foundation for more complex instruments. Seismometer design and fabrication are discussed, as well as preliminary results. Further, in order to address shortcomings in the ability to characterize instruments in extreme environmental conditions, development of an Extreme Environment Rig is ongoing. This test capability is a specially designed chamber capable of simulating the pressure, temperature, and chemical composition of the planets in our solar system and elsewhere with particular relevance to Venus in situ planetary investigations. A description of these capabilities will also be provided. An objective of this and other work is to develop and characterize in relevant environments instrumentation that can allow the in-situ characterization of Venus surface properties.

Technical Barriers: A high temperature Venus seismometer does not exist at this time. This is predominantly due to the nature of seismometer measurements, which require operation of the measurement system directly in the harsh Venus environment. In order to produce such a seismometer operating in-situ in the Venus environment, a range of high temperature operable technologies are necessary. These include the seismic measuring instrument itself (mechanical structure), a position transducer, and associated signal processing electronics. Conventional seismometer technologies are not functional in Venus-relevant environments. For example, silicon (Si) based electronics on which standard conventional seismometers are based, do not operate at Venus temperatures [2]. This implies the use of wide bandgap electronics, such as silicon carbide (SiC), or other high temperature electronic systems. Specialized SiC electronic circuits designed for high temperature operation have shown the capability to operate at Venus relevant temperatures for extended periods of time [3-7]. Similarly, although a range of high temperature sensors technology is being developed [8-10] for harsh environments such as aircraft engines, transducer technology and other components of the seismometer mechanical structure are challenged by Venus operational conditions.

Seismometer Design Approach: The development of a proof-of-concept high temperature Venus seismometer operational at temperatures up to 500°C and responsive to seismic vibrations from 1-30 Hz is on-going. The seismometer system has a mechanical structure with a transducer to interface with the planetary environment, as well as signal conditioning and wireless communications electronics [3]. The mechanical structure and transducer are designed for harsh environment operation at 500ºC. The signal conditioning and wireless electronics are based on high-temperature-operable silicon carbide (SiC) electronics.

A high temperature seismometer utilizing a vertical pendulum design has been fabricated and is shown in Figure 1. A leaf-spring seismometer design is used [11]. A seismic mass on a boom supported by crossed hinges is counterbalanced with a leaf spring. A novel thermal expansion compensation mechanism is employed to maintain the boom orientation despite temperature induced changes in the Young's modulus of the spring. Vertical seismic vibrations cause the boom to oscillate, and motion of the boom is sensed using a variable inductance position transducer. A coil is fixed to the seismometer frame and a specialized aluminum probe, mounted on the seismometer boom, is positioned on the inside of the inductor coil, such that a movement of the boom changes the axial position of the probe in the coil and causes the inductance to change.

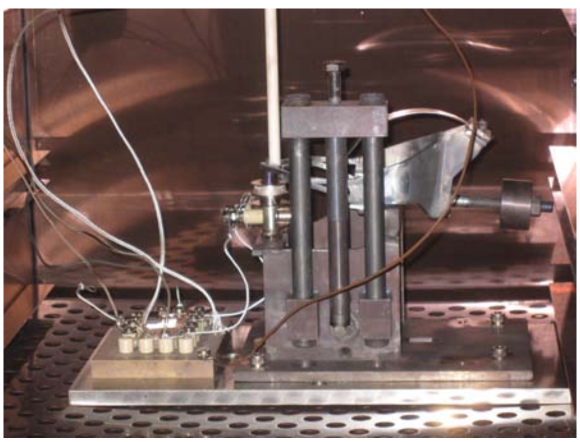

Fig. 1. Photograph of the wireless seismometer mechanism and circuit in an oven.

Silicon carbide electronics are used to enable this seismometer design. A simple signal conditioning circuit is employed in which the variable inductance transducer is used in an oscillator circuit to convert the sensed boom position to an electrical frequency which is transmitted wirelessly by an antenna. The oscillator is based on a Clapp-type design and presently uses a commercial SiC MESFET (metal semiconductor field effect transistor) [5-9]. Although the MESFET is not designed for operation at extremely high temperatures we have found that it provides sufficient reliability at temperatures up to 475°C to demonstrate the viability of this approach. Thin film capacitors and inductors capable of 500ºC operation are included in the oscillator circuit. The oscillator as presently designed operates at 100 kHz, which, as necessary, is less than the 600 kHz self-resonant frequency of the transducer coil.

Preliminary Data: Preliminary testing of the seismeter has been performed over the temperature range from 425ºC to 475ºC. For this measurement, the seismic mass is adjusted to lift the probe to its maximum height, and a ceramic rod attached to a micromanipulator is used to lower the aluminum probe in a controlled, stepwise manner. Figure 2 shows the measured spectra of the signals wirelessly transmitted as a function of probe position. The seismometer with electronics is at 426°C and there is a 1 m distance between transmitting and receiving antennas. The oscillator frequency is wirelessly transmitted as the position of the probe is varied from 1-11 mm. As can be seen in Figure 2, the signal strength is 40 dB above the noise floor at 426°C, and changes in oscillator frequency are measured with changing probe position.

Subsequent data in Figure 3 show the seismometer/oscillator system operated stably for 73 hours at 475°C, although subsequent degradation of the oscillator circuit occurs. The seismometer mechanism is still operational after this testing. Future generations of this system will use more durable SiC JFETs (junction gate field-effect transistor) [5-7], rather than commercial MESFETs. In addition, specialized high-temperature on-chip metallization and packaging will be employed.

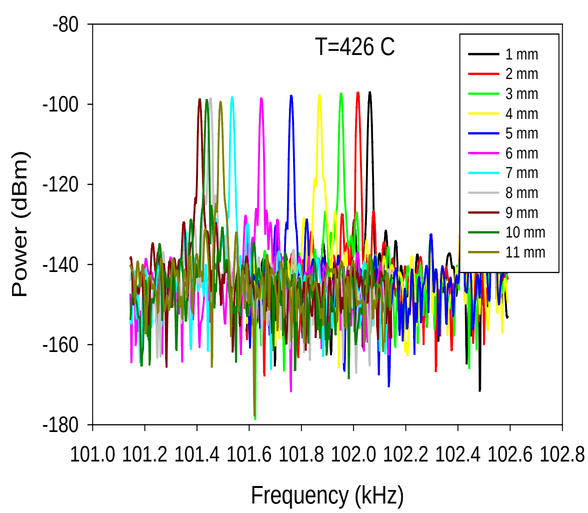

Fig. 2. Measured spectra of the received signal from the wireless seismometer for probe positions from 1 to 11 mm, at 426°C.

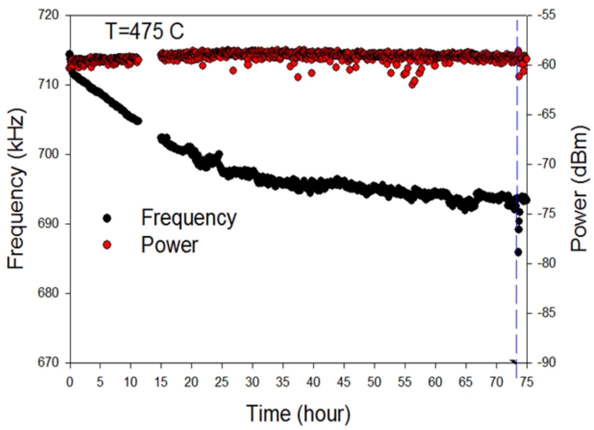

Fig. 3. Measurement of received oscillator frequency and power of the seismometer system at 475℃ over time.

High Fidelity Testing: Extreme environmental conditions including high temperatures and radiation fields have limited the range and duration of solar system exploration. This is due to the many practical limits encountered with electronics, instrumentation, materials, organics and other space vehicle components. While much progress has been made in the development of radiation hardened components, high temperature and harsh chemical environments are still a limiting factor. For example, the surface of Venus exceeds 400°C and many technologies either do not operate or are too inefficient to operate in that environment. For these and other reasons, our knowledge of Venus and other extreme temperature locations is limited and the need for in-situ testing capability is great.

Recently, NASA GRC began the development of an extreme environment test chamber that is intended to simulate any atmosphere in the solar system, including the extreme conditions on the Venus surface. This test chamber can be used to validate in-situ technologies such as the seismometer detailed in this work. Moreover, it can be used to better understand extra-solar planets for which no direct in-situ measurements can be made at this time.

GEER: The Glenn Extreme Environment Rig (GEER) shown in Figure 4 is intended to provide capability to, for example, confirm the performance of the seismometer and related instrumentation in a high fidelity Venus environment. The GEER is a specially designed chamber capable of simulating the pressure, temperature, and chemical composition of the planets in our solar system and potentially recently discovered exoplanets. The Venus environment is perhaps the most challenging to simulate in our solar system because of the high pressure, temperature, and harsh chemical environment, particularly on the surface of the planet.

Specifications: The GEER can be operated between -196°C and 500°C, at pressures from a vacuum to 100 bars. It is approximately 1 m in diameter and slightly longer in the axial direction. It can accommodate any mixture of corrosive or acidic gases down to ± 1 parts per billion (ppb), and provide a range of gases such as carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen fluoride (HF) hydrogen chloride (HCl) and carbonyl sulfide (COS) in the part per million (ppm) to percentage range. The chamber has a removable liner to enable any atmospheric composition to be safely tested. The parts per billion gas mixer can accurately recreate any atmosphere in the solar system. The GEER gas mixer (see Figure 5) has nine gas streams and a corrosion/acid resistant construction, two streams are Inconel 625, seven streams are 316 Stainless 4Ra finish, independent gas adjustments, temperature, pressure, and mass flow monitors. An H_2O bubbler adds water vapor, if necessary. It is capable of essentially any atmospheric composition.

Fig. 4. Glenn Extreme Environment Rig (GEER).

For the Venus experiments, we will initially use a purely carbon dioxide (CO_2) and N_2 atmosphere. Once the functionality of a given instrument is verified, a full Venus atmosphere simulant consisting of CO_2 (~96.5%), sulfur dioxide (130 ppm), HF (5 ppb), HCl (0.5 ppm), CO (15 ppm), COS (27 ppm), N_2 (~3.4%), and H_2O (30 ppm) will be used to determine durability and responsiveness of the instrument, component, or system. This will be done not only at temperature but also within the range of chemical species that are present in the Venus atmosphere.

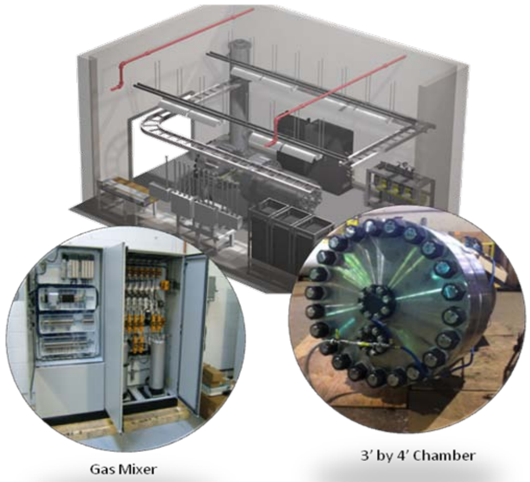

Fig. 5: Extreme Environment Chamber and Gas Mixer.

Future Development: Continued development of the seismometer is targeted to demonstrate a complete proof-of-concept seismometer to show the potential viability of an operating seismometer at Venus relevant temperatures for a number of days. This includes longer term testing and characterization of a range of parameters associated with the instrument operation. This proof-of-concept seismometer is designed to demonstrate operation in an important seismic frequency subrange providing the core for a wider frequency range seismometer system operating at 500ºC. This seismometer is a first generation prototype to demonstrate seismic sensing at extremely high temperatures. Further refinements of the seismometer, e.g. miniaturization and insertion in a vacuum chamber, will be required to produce a seismometer suitable for use on Venus.

As GEER becomes available, it will allow the capability to characterize the Venus seismometer in relevant Venus conditions for extended periods of time. However, the Venus seismometer is not the only instrument that might be considered for characterization in this facility. A range of technologies are being developed that may have relevance to Venus surface exploration. These include sensor systems operable at 500°C and able to measure properties such as pressure, temperature, wind flow, and chemical species. Such a combination of technologies can enable measurement of both seismic and meteorological properties on the surface of Venus to provide new information on its present atmospheric conditions in conjunction with geological information.

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