

**FIBER OPTIC GEOPHONES FOR USE IN PLANETARY SUBSURFACE EXPLORATION.** C.C. Amos<sup>1</sup>, N.E. Putzig<sup>2</sup>, M.R. Perry<sup>2</sup>, B.N.P. Paulsson<sup>3</sup>, J. Thornburg<sup>3</sup>, M. Wylie<sup>3</sup>, H. Hardiman<sup>3</sup>, R. He<sup>3</sup>, P. Sava<sup>4</sup>, S.W. Courville<sup>4</sup>, K. Zacny<sup>5</sup>, G. Paulsen<sup>5</sup>, T.D. Mikesell<sup>6</sup>, <sup>1</sup>Hess Corporation ([camos@hess.com](mailto:camos@hess.com)), <sup>2</sup>Planetary Science Institute ([than@psi.edu](mailto:than@psi.edu)), <sup>3</sup>Paulsson Inc., <sup>4</sup>Colorado School of Mines, <sup>5</sup>Honeybee Robotics, Ltd., <sup>6</sup>Boise State University.

**Introduction:** Relative to highly sensitive seismometers such as the Seismic Experiment for Interior Structure (SEIS) on the InSight mission [1], geophones are less complex but limited in their sensitivity and bandwidth. Traditional wired geophones built around a mass-and-coil system are extremely rugged, however they are susceptible to electromagnetic (EM) interference and have a limited tolerance to temperature extremes. Sensors using microelectromechanical systems (MEMS) are widely used in terrestrial seismic surveys and have been developed for planetary use, however these sensors are also susceptible to EM interference. This susceptibility is a major hurdle to the use of geophones at locations such as Europa, where interference due to Jupiter's magnetic field is extreme.

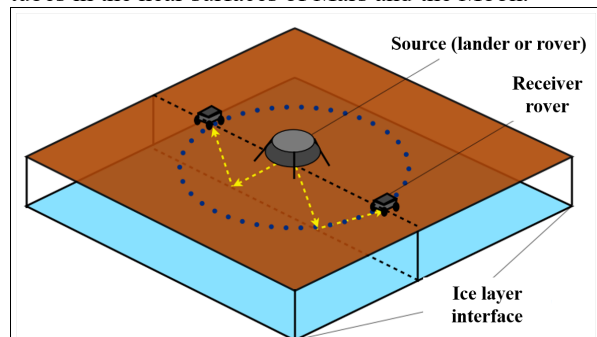
A promising technology that can be adapted for planetary use is the Fiber Optic Seismic Vector Sensor (FOSVS<sup>TM</sup>) developed by Paulsson, Inc. [2], which retains durability while greatly reducing vulnerability to EM interference. As opposed to traditional or MEMS geophones, the principle behind FOSVS<sup>TM</sup> is sensing based on optical interferometry rather than electrical measurements. Thus the base measurement made by the fiber optic sensor will have greater fidelity in a noisy EM environment. Additionally, wide operational temperatures (-269°C to +700°C) have been reported for gold-coated fiber, potentially making this material an ideal geophone component for the temperature extremes of planetary applications.

**Relevance:** Obtaining knowledge of subsurface materials and geologic structures (e.g., caves, buried ice, shallow brine pockets) is key to achieving NASA's Planetary Decadal Survey goals concerning characterization of planetary interiors, the distribution of volatiles, connections to habitability, and *in situ* resources. The identification of *in situ* resources for human missions, the examination of habitable environments, and (for Mars) understanding past climate are three important aspects of NASA's plans for future missions to Earth's Moon, Mars, and icy moons of the outer planets. Such environments and resources are likely to be largely located in the subsurfaces of these bodies. To identify the location and extent of these zones of interest, remote sensing techniques such as radar and active source seismic methods will be critical.

**Active source seismic studies and ARES:** For the last century, active source seismic surveys have been used to image the shallow structural interior of the

Earth. Apollo missions to the lunar surface carried out the first and only non-terrestrial active source seismic experiments. Similar to terrestrial surveys, the Apollo experiments required extensive human interaction to couple geophones to the surface, deploy cables connecting these geophones to the recording system, and initiate the seismic sources (weight drops and explosives). Many advances in active-source methods have occurred since the Apollo era, including the development of wireless geophones and robotic platforms that might be used to carry and deploy equipment such as seismic sources and geophones. For scientific studies and advance site characterization in prelude to landed human missions, the development of a means to autonomously carry out such seismic experiments using multiple mobile platforms is highly desirable.

The Autonomous Roving Exploration System (ARES) is an instrument concept to conduct active source seismic imaging robotically. Figure 1 illustrates the ARES concept. A collection of autonomous source and receiver rovers provide configurability and redundancy to collect enough reflection seismic data to create highly detailed images of the subsurface. The goal of this concept is to image water-ice layers and lava tubes in the near surfaces of Mars and the Moon.



**Figure 1.** Illustration of the robotic ARES concept for active source seismic exploration. Mobile source and receiver deployment allows for high experiment configurability and data collection redundancy.

Imaging these targets is important for site characterization to enable human exploration and *in-situ* resource utilization (ISRU) in the future. Courville et. al. [3] have begun modeling seismic acquisition scenarios over relevant lunar and Martian subsurface targets. Future work on the concept includes conducting experiments with a prototype over analog sites on Earth. As part of the larger ARES concept, we propose the de-

velopment of a wireless fiber optic geophone able to be robotically deployed in non-terrestrial active source seismic surveys.

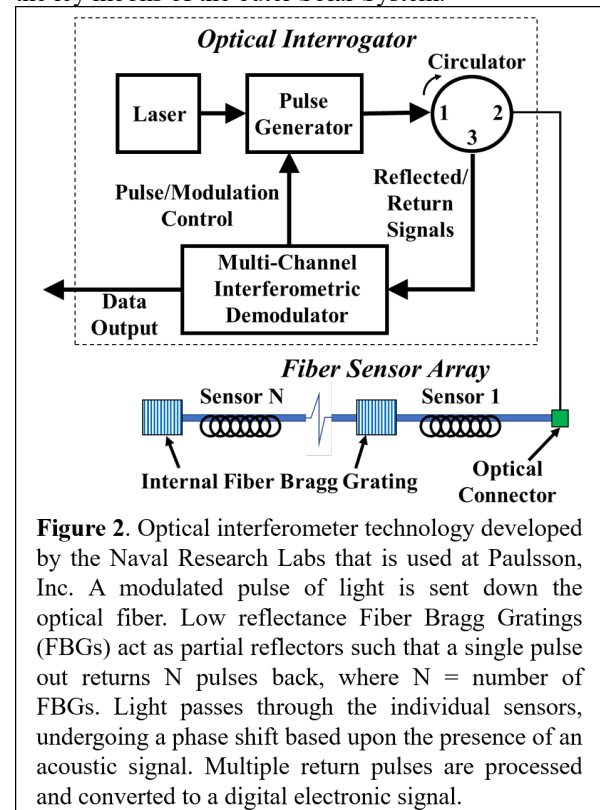
**Fiber optic geophones:** While both mass-and-coil and MEMS geophones are proven technologies, they possess disadvantages for some applications within planetary science. Both systems are intrinsically susceptible to EM interference, and MEMS sensors can be mechanically delicate by design. A promising new technology that specifically addresses these disadvantages is the fiber-optic seismic vector sensor. Over the last three and a half decades, much progress has been made towards implementing fiber-optic technology in single-point motion sensing [2,4,5]. Note that this is distinct from Distributed Acoustic Sensing (DAS), a method that measures vibratory strain along the length of a fiber-optic cable deployed either horizontally along the ground or vertically in a borehole. The basic principle behind an interferometric fiber-optic accelerometer is sensing seismic-induced phase shifts along a small coil of fiber-optic cable using periodic reflectors, a process which is immune to EM interference and affords a robust mechanical design. The EM immunity of fiber-optic measurements presents two important advantages over mass-and-coil and MEMS sensors: 1) increased reliability of the measured data by eliminating a source of measurement interference and 2) reduced instrument mass by removing traditional EM shielding. These advantages should enable higher quality seismic measurements for future Mars missions and help address the significant hurdle of high measurement interference from EM radiation at important targets like Europa.

**Sensor details.** A time- and wavelength-division multiplexing system can be used to interrogate an interferometric fiber-optic accelerometer. This technology, developed by the Naval Research Laboratory, is in use aboard Virginia-class submarines for hydrophone-based sensing [6]. FOSVS™ is an engineered interferometric fiber optic spring-mass accelerometer that translates vibration into optical phase changes. Paulsson, Inc. has spent the last decade refining the system for deployment in hostile environments reaching temperatures of 300°C and pressures of 200 MPa. By substituting gold-coated fibers in the design, the high temperature limit can be extended to 700°C. Regarding the low temperature limit, other optical sensors have been used for monitoring temperatures as low as -270°C [7].

Figure 2 presents an implementation of a sensor and interrogator that uses periodic fiber Bragg gratings as reflectors that separate the sensing locations. A laser is pulsed using a device such as a Semiconductor Optical Amplifier (SOA) and routed into a sensing array via an optical circulator. The periodic reflections from the

array create sensing regions (Sensors 1 through N in Fig. 2). Each sensing region is a section of fiber wrapped around a mandrel. By combining three orthogonal FOSVS™, a three component pod is created that can accurately measure any incoming seismic signal in a 3D space. The FOSVS™ has been proven to detect signals up to 10 kHz and readily measures signals up to 2 kHz in field trials.

**Future work:** Adaptation of FOSVS™ for planetary use will first focus on selection of component materials suited to expected environmental conditions, followed by implementing standalone wireless capability. Beyond the proposed geophones, we envision separate efforts to develop impulsive and vibratory seismic sources to use in conjunction with the planetary FOSVS™, while working toward automation of the overall seismic acquisition system. In total, these efforts will establish viable mission scenarios for subsurface sounding investigations on the Moon, Mars, and the icy moons of the outer Solar System.



**Figure 2.** Optical interferometer technology developed by the Naval Research Labs that is used at Paulsson, Inc. A modulated pulse of light is sent down the optical fiber. Low reflectance Fiber Bragg Gratings (FBGs) act as partial reflectors such that a single pulse out returns N pulses back, where N = number of FBGs. Light passes through the individual sensors, undergoing a phase shift based upon the presence of an acoustic signal. Multiple return pulses are processed and converted to a digital electronic signal.

**References:** [1] Mimoun et al. (2017) *Space Sci. Rev.*, 211, 383-428. [2] Paulsson et al. (2015) *Proc. World Geothermal Conf.* [3] Courville et al. (2018) *AGU Fall Meeting*, Abstract# P54D-02. [4] Kersey et al. (1982) *Electron. Lett.*, 18, 559. [5] Zhang et al. (2007) *Proc. SPIE*, 6770. [6] Cole et al. (2004) *Wash. Acad. Sci.*, 90, 40-57. [7] Thévenaz et al. (2002) *Proc. SPIE*, 4694, 22-27.