Fiber Optic Geophones for use in Planetary Subsurface Exploration

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Abstract

We proposed the adaptation of the Fiber Optic Seismic Vector Sensor (FOSVS™), developed by Paulsson, Inc. [**1**], for planetary active source seismic surveys. This technology retains the durability of a traditional terrestrial geophone, is tolerant of temperature extremes, and unlike mass-and-coil or microelectromechanical system (MEMS) geophones provides a ground-motion measurement that is immune to electromagnetic (EM) interference. The planetary FOSVS™ could then be incorporated into the larger ARES instrument concept (far right).

Background and Relevance

Active source seismic methods could provide critical information for NASA's Planetary Decadal Survey goals concerning characterization of planetary interiors, the distribution of volatiles, connections to habitability, and location of *in situ* resources by allowing remote sensing of planetary subsurfaces. For the last century, active source seismic surveys have been used to image the shallow structural interior of the Earth allowing insights regarding tectonic and climatic evolution as well as identifying locations of natural resources. Apollo missions in the 1970's conducted the first and only non-terrestrial active source seismic experiments to characterize material properties and layering in the upper 1.4 km of the Moon [**2**].

Environments at the Moon, Mars, and icy satellites of the outer solar system would provide temperature and radiation challenges to the electrical-based ground-motion measurement of mass-and-coil or MEMS geophones. FOSVS™ are based on 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. Additionally, various specialized fiber coatings have been used to enable other sensor measurements over a wide temperature range (-270°C to +700°C [**3, 4**]). These attributes should allow for the development of a planetary FOSVS™ yielding high quality seismic measurements for future Mars and Moon missions, and help address the significant hurdle of high measurement interference from EM radiation at important targets like Europa.

Apollo 14 Active Seismic Experiment
(Image Credit: NASA)



FOSVS™ Development

Building on technology developed by the Naval Research Laboratory [**5**], Paulsson, Inc. has spent the last decade refining an interferometric fiber optic spring-mass accelerometer (FOSVS™) for borehole acoustic monitoring applications [**6**]. Figure 1 shows FOSVS™ sensors encased in a deployment housing prior to a borehole monitoring project. FOSVS™ have been proven to operate in high-temperature / high-pressure borehole environments, while also retaining high sensitivity (Figure 2).

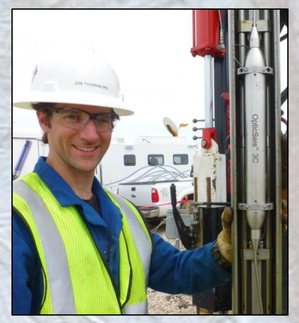

Figure 1. Co-author Jon Thornburg with three FOSVS encased in deployment housing.

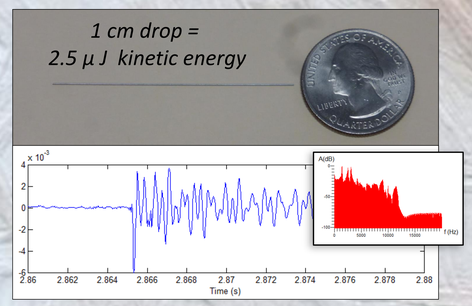

Figure 2. Pin-drop test illustrating high sensitivity of FOSVS. Top: Pin, dimensions OD 0.011", length 2", weight 24. mg. Bottom: sensor response of pin drop at 1 cm height. Inset: Frequency response of sensor with high-fidelity data upwards of 10 kHz.

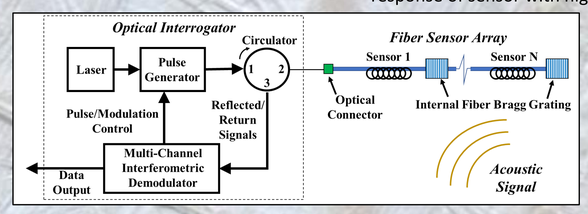

Figure 3. Optical interferometer technology developed by the Naval Research Labs that is used at Paulsson, Inc. A modulated pulse of light is sent down the optical fiber. Low reflectance Fiber Bragg Gratings (FBGs) act as partial reflectors such that a single pulse out returns N pulses back, where N = 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.

Figure 3 shows a schematic of the Paulsson, Inc. fiber optic seismic monitoring system to be adapted for planetary use. 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 (Fiber Bragg Gratings), a process which is immune to EM interference and affords a robust mechanical design.

Future Work

Adaptation of FOSVS™ for planetary use will first focus on selection of component materials suited to expected environmental conditions and testing optical fiber and sensor-block materials at relevant temperatures. This will be followed by developing a compact optical interrogator and implementing standalone wireless capability. The developed sensor will be tested against standard MEMS and geophone devices and compared to documented performances of the InSight SP seismometer.

Beyond the proposed geophones (accelerometers), 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 (see ARES section). 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.

ARES Concept

Martian underground caves (e.g., lava tubes) and mid-latitude water ices, as either buried ground ice or debris-covered glaciers, are important targets for exploration. Beyond their geological and climatological interest, caves and ground ice represent potential habitats for existing or extinct life. Additionally, caves may serve as ready-made shelters from cosmic radiation, whereas buried ices may provide in situ resources for future human missions. Locating caves and buried ice from the surface is likely to be a critical task for future robotic missions to Mars, enabling science investigations and site reconnaissance in preparation for human exploration. Active source seismic methods are ideally suited to play an important role in these missions, and our goal is to develop the means to autonomously carry out such seismic experiments using mobile platforms.

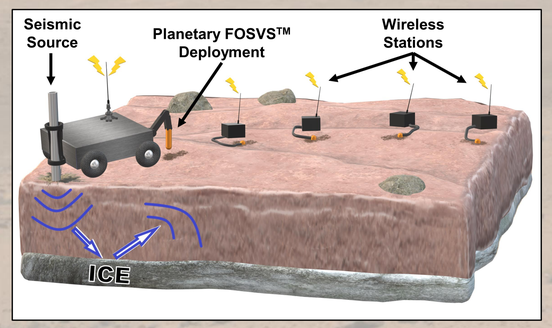

Figure 4. One potential deployment scenario for ARES illustrating a mobile seismic source and fixed wireless receivers surveying for subsurface ice. Mobility of system allows for high configurability of seismic experiments.

The Autonomous Roving Exploration System (ARES) is an instrument concept to robotically conduct active source seismic surveys. Figure 4 illustrates how such a survey may be deployed. Courville et. al. [**7**] have begun modeling seismic acquisition scenarios over relevant lunar and Martian subsurface targets, and future work on the concept includes conducting experiments with a prototype over analog sites on Earth. The proposed planetary FOSVS™ would integrate into the larger ARES concept.

References

[1] Paulsson et al. (2015) *Proc. World Geothermal Conf.* **[2]** Stanford Univ. Dept. of Geophys. (1976) NASA Report 147760. **[3]** www.fiberguide.com **[4]** Thévenaz et al. (2002) *Proc. SPIE*, 4694, 22-27. **[5]** Cole et al. (2004) *Wash. Acad. Sci.*, 90, 40-57. **[6]** Paulsson et al. (2015) *Proc. World Geothermal Conf.* **[7]** Courville et al. (2018) *AGU Fall Meeting*, Abstract# P54D-02.

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