DEVELOPMENT OF A NEXT-GENERATION MICROSEISMOMETER SYSTEM FOR A LUNAR GEOPHYSICAL NETWORK MISSION.
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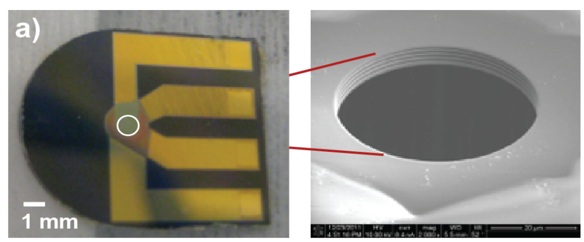
Introduction: Seismic data analysis remains both a fundmental and unique way to constrain lunar interior structure, as well as assess surface hazards. Almost half a century ago, the Apollo program seismic experiments used both active and passive components to examine the lunar interior at a broad range of spatial scales. The natural-source ("passive") experiment was an array to monitor internal seismic activity (deep and shallow focus quakes), as well as external impacts [1-6]. The active component operated at two scales. Crustal and sub-crustal velocities and structure were determined by the impacts of the SIVB and LMAS impacts. Shallow regolith-scale velocities and structure were assessed with astronaut-fired explosives and ground-fired mortars. The seismic data from the Apollo program have been interpreted to indicate a lunar crust thinner on the near-side compared with the farside (more recent studies favor a nearside thickness of ~40 km) [7-10]. P-wave travel times [2] and a more recent reanalysis of deeply reflected P- and S-wave energy [11] suggest that the Moon has a partially molten lowermost mantle and a small core (250-350 km diameter). However, the Apollo data suffer from the limitation that the 4-station array was situated on the central near side and were relatively closes spaced precluding global (and thus farside) coverage.

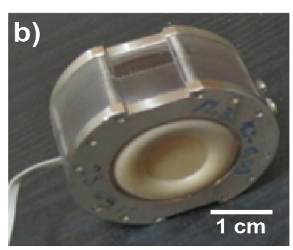
Lunar Geophysical Network: One of the potential NASA New Frontiers missions is the Lunar Geophysical Network (LGN) mission. The goal of such a mission would be to produce unique and new data that provide new constraints on the origin, evolution, and current state of the Moon. The key instrument for LGN is a seismometer to record with high resolution the ground motion induced by quakes and bolide impacts. The mission would comprise a network of stations deployed on the lunar surface to understand current seismic activity, crust-to-core interior structure and the impact rate on the Moon. A significant need exists to develop and mature a next-generation microseismeter suitable for the LGN mission.

Next-Generation Microseismometer System: A major advance in seismic sensor technology has been achieved by our group via the development of the first miniature Molecular Electronic Transducer (MET) sensing cell (Fig. 1), fabricated using MEMS technology [12-14]. We are currently working toward development of an entire seismic sensor system with Technology Readiness Level 5 (TRL 5), providing a low-risk seismic instrument for the LGN mission.

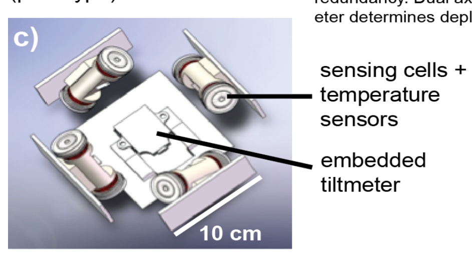
Through sustained funding by NASA, the first prototype sensing element was fabricated and tested successfully in 2012, demonstrating the feasibility of this approach to develop a complete MET-based microseismometer. This new instrument is based on microfabrication using an liquid electrolyte as the sensing element, providing high sensitivity, high environment tolerances, and flexibility for installation. Ongoing efforts include improving and streamlining the fabrication process and assembling sensing packages, details of which are described here. The sensor packages are scheduled to be tested at the IRIS PASSCAL Instrument Center (PIC) in Fall 2015, with additional tests at both the PIC and the USGS Albuquerque Seismological Laboratory (ASL) in late 2015 / early 2016.



MET sensing cell



MET single axis sensing cell (prototype)



Complete MET microseismometer package

Figure 1: Images of the MET microseismometer. MET sensors measure hydrodynamic fluid flow of an electrolyte through a membrane. The design increases sensor performance to enable deployment in more environments than current technology.

a) MET sensing element.
b) Prototype MET single axis sensing cell in housing from from original MET sensor.
c) Sketch of complete sensor package. 4th element included at a separate angle for system redundancy. Dual axis inclinometer determines deployment angle.

Current Development and Next Steps: Our current effort has centered on the design and production of all necessary components and subsystems to complete the prototype instrument. The primary tasks in the fabrication of the complete system include: (1) development of a high-performance electrolyte capable of maintaining integrity over a broad temperature range; (2) production of an integrated sensing cell package containing the electrolyte and feedback system; (3) optimization of signal read out circuitry and design of interface for the data acquisition system; (4) fabrication and testing of the sensing element; and (5) design and fabrication of the entire seismic system assembly, that consists of the sensor cells, circuit board, and temperature and inclination sensors.

Development of high performance electrolyte. We have successfully developed a novel electrolyte solution that remains liquid over a large temperature range (-97°C to 189°C) [15]. We continue to develop this material to extend to greater temperature ranges while maintaining limited variance in viscosity.

Production of integrated package with electrolyte and feedback system. The complete sensing cell includes (1) a sensing element with low hydraulic impedance, (2) electrolyte, (3) a tube containing electrolyte, (4) flexible diaphragms to cover the tube ends, (5) a feedback loop, consisting of magnets and coils, and (6) temperature sensors that directly measure sensor cell temperature.

For prototyping purposes, we currently utilize 3D printing to manufacture the entire cell package as a single element. We then attach the flexible cap, magnets, coils and sensing element. We continue to mature this package through testing of polymers for the diaphragm that possess an appropriate Young's modulus and operational temperature range. We are in the process of optimizing the feedback system to enable higher sensitivity while maintaining flat velocity response. Finally, we are integrating temperature sensors that enable monitoring of potential viscosity changes in the electrolyte to further enhance the response of the sensor.

Optimization of circuits. The electronics for the MET seismometer system includes: the signal read-out (analog) and data conversion (ADC). The signal read-out circuit has been optimized with an integrated feedback circuit and to reduce the noise. A feedback circuit converts the output voltage signal to current, which powers the coil to generate the magnetic field. We are currently developing the interface between signal read-out circuit with sigma-delta ADC data conversion.

Fabrication and testing of the sensing element: We have fabricated a MET sensing element using micro-fabrication technology. The self-noise floor of the sensor is compatible with a traditional CMG-6T seismometer, the sensitivity reached ~5000 $V/m/s^2$, settling time was<1 msec, and the dynamic range was 120 dB. We have conducted harsh environment operation of the sensing element to verify TRL 5 for that component. Our tests demonstrate that the sensing elements can operate across a temperature range of -196°C to 200°C under the vacuum (up to 10^{-8} Torr) and a 200 krad dose of 1.2 MeV gamma rays from ^{60}Co. We have also performed preliminary shock tolerance testing via drop tests and demonstrated that the sensing element continues to perform after impacts of 23.3 kG, where G is 9.8 m/s^2. We will perform further optimization on the seismometers to achieve the LGN required sensitivity of 0.001 Hz to 50 Hz with a dynamic range of 145 dB.

Fabrication of complete seismic package. The seismic system assembly design is a cubic box with 4 cells mounted on the walls at 45^o that is printed using a 3D printer. The 4 sensor cells provide redundancy of operation; if one fails, the other three are sufficient still to provide 3-axes measurements. We also include 2 inclinometers installed back to back to provide 360^o tilting angle measurements, that provide the proper reference point to calculate the seismic signal related to vertical.

Conclusions: We are developing a next-generation seismic system to be ready for deployment and operation in the lunar environment. Ongoing lab, bench, and field testing will bring the entire system to Technology Readiness Level 5 (TRL 5), providing a low-risk seismic system for the LGN mission.

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