A HIGH-SENSITIVITY BROAD-BAND SEISMIC SENSOR FOR SHALLOW SEISMIC SOUNDING OF THE LUNAR REGOLITH.

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Introduction: The recently undertaken Space Exploration Initiative has prompted a renewed interest in techniques for characterizing the surface and shallow subsurface (0-10s of meters depth) of the Moon. There are several reasons for this: First, there is an intrinsic scientific interest in the subsurface structure. For example the stratigraphy, depth to bedrock, density/porosity, and block size distribution all have implications for the formation of, and geological processes affecting the surface, such as sequential crater ejecta deposition, impact gardening, and seismic settling. In some permanently shadowed craters there may be ice deposits just below the surface. Second, the geotechnical properties of the lunar surface layers are of keen interest to future mission planners. Regolith thickness, strength, density, grain size and compaction will affect construction of exploration infrastructure in terms of foundation strength and stability, ease of excavation, radiation shielding effectiveness, as well as raw material handling and processing techniques for resource extraction.

Drilling or trenching provide the best unambiguous methods for determining properties at depth, but are time-consuming and are limited in their horizontal coverage. Seismic sounding provides a relatively quick way of characterizing the subsurface at reasonably high depth resolution over a wide area. Although the interpretation of the data is sometimes ambiguous, it can provide reliable information when combined with geological observations or, ideally, when combined with limited direct observations at one or more boreholes.

The arrival time of seismic phases along a line of seismic sensors from a controlled source are analyzed to determine wave velocity (and interfaces) as a function of depth, from which the stratigraphy in terms of the elastic moduli, density, and strength (which can be empirically related to the moduli [e.g., 1]) can be inferred. Note that relatively crude active seismic refraction methods were successfully employed to measured the first-order lunar regolith properties during the Apollo missions in the 1970's [2-6].

Requirements: The requirements for a seismic sensor for shallow sounding on the Moon are more challenging than those for terrestrial geophones. Because we are interested in relatively fine structure at shallow depth, we must use higher frequencies than is typical for terrestrial surveys. Given a seismic compressional velocity of order 100 m/s for the unconsolidated surface material [7], it is necessary to resolve frequencies of at least 1 kHz in order to achieve a depth resolution of order ten cm. Terrestrial surveys do not acquire data above 100-200 Hz due to the greater depths and larger structures of interest, and to the higher seismic attenuation (from moisture) and background levels on the Earth. At the same time, the sensor must be linear over a wide frequency band and amplitude range in order to avoid signal distortion by the low-frequency ground roll which is endemic to near-field active sounding. We also require extremely high sensitivity to optimize the quality of the measurement given the likely limitations on the size of the seismic source. This sensitivity can be fully exploited because of the extremely low seismic noise environment of the Moon.

Of course the usual strict constraints on mass, power, and ruggedness for space flight instruments apply here as well, especially as one would like to

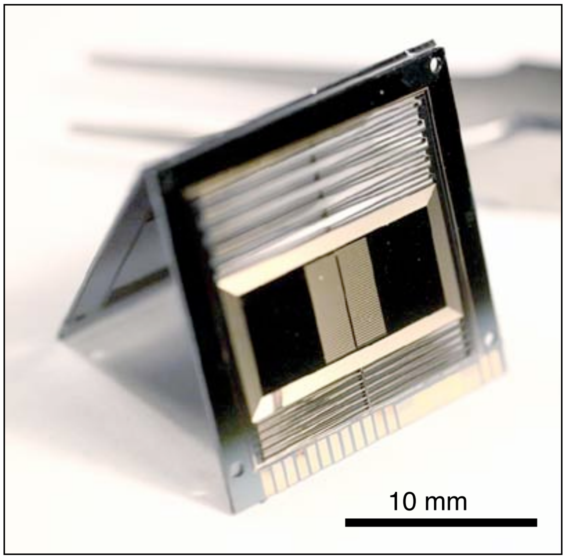

Fig. 1: Seismic sensor suspension showing two sets of springs above and below the proof mass, part of the displacement transducer in the center of the proof mass and the rectangular feedback coils.

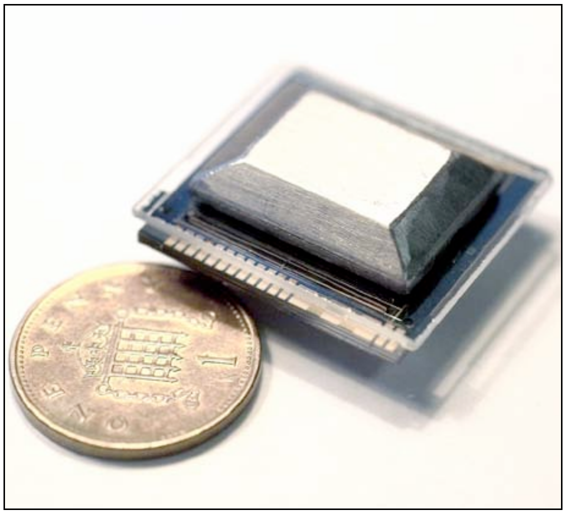

Fig. 2: A packaged seismic sensor showing the magnetic assemblies. The total mass is 32 g.

deploy as many sensors as possible (~10-100) for a given seismic profile.

Instrument description: A micromachined silicon seismometer is currently under development to reach these requirements. The suspension is formed by through-wafer etching of the silicon [8] to produce a motion in the plane of the wafer (Fig. 1). A capacitive position transducer measures the displacement of the suspended proof mass in response to the seismic vibrations. Feedback to stabilize the mass position is accomplished through electromagnetic feedback, with coils on the proof mass and two sets of magnetic assemblies on each side on the suspension (Fig. 2).

A lunar deployment offers both advantages and challenges compared to terrestrial applications. The absence of an atmosphere ensures that there is no gas damping of the motion of the proof mass. As this damping contributes to the background noise of the sensor, a lunar seismic sensor will enjoy improved noise performance compared to the Earth – by at least a factor of ten (Fig. 3). The calculated sensor noise is below 1 ng/√(Hz) which is of benefit in the very quiet environment of the Moon. Secondly, the reduced gravity on the Moon reduces the amount of sag the suspension needs to accommodate. This in turn reduces the size of the sensor.

The increased bandwidth required for shallow lunar sounding requires that the suspension is free from spurious resonances over at least 1 kHz. This can be achieved in an all-silicon suspension due to the large cross-section aspect ratio of the spring made possible by deep reactive ion etching, which minimizes the mass of the springs themselves while maintaining good cross-axis stiffness. The current design pushes these unwanted resonances to above 2 kHz.

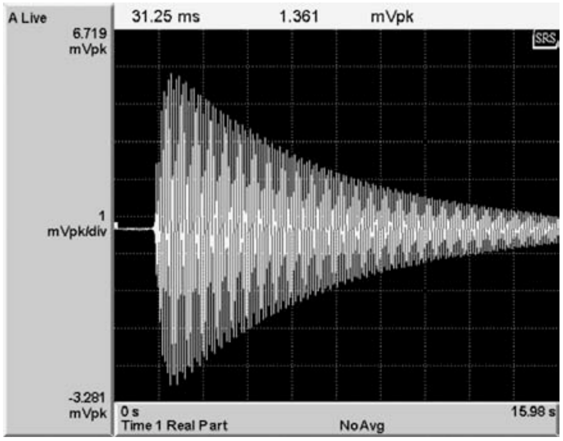

Fig. 3: Damping of the proof-mass motion of the seismic sensor measured in open-loop operation at atmospheric pressure. In a lunar deployment the damping will be dominated by the silicon of the suspension itself, giving a tenfold reduction in the sensor noise.

Because of the requirement for vacuum in the suspension to minimize damping, the effects of landing shock on the sensor cannot be mitigated by gas damping. Therefore additional dissipative material (which is engaged only when the suspension is overdriven) has been incorporated into the suspension design.

Conclusions: We have developed a high-sensitivity broad-band seismic sensor which is well-suited for characterizing the upper few meters of the lunar regolith. This device could be of great value to both scientific investigations and geotechnical characterization for exploration.

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