A PLANETARY BROADBAND SEISMOMETER (PBBS) FOR THE LUNAR GEOPHYSICAL NETWORK AND OCEAN WORLDS

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Introduction: In the coming years and decades, NASA may launch a series of missions to explore our Moon and the ocean worlds of the Solar System (e.g., Europa and Enceladus). An important objective of these missions is to gain knowledge of the structure and composition of the interiors of these bodies. For the Moon, such knowledge would allow the examination of the initial stages of planetary differentiation frozen in time some 3-3.5 billion years ago. For the ocean worlds, this knowledge would hold clues for understanding their planetary evolution, their thermal and chemical make-up and thus their habitability [1].

The NRC decadal survey [1] identified the Lunar Geophysical Network (LGN) as a high-yield New-Frontiers-class mission concept that would place a long-lived and globally distributed network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core. This would allow the examination of the initial stages of planetary differentiation frozen in time some ~3-3.5 billion years ago. The objectives of LGN hinge on the capabilities of an ultra-sensitive, very broad-band seismometer. LGN's objectives are designed to discover the interior structure and composition of the Moon that was not possible with the Apollo network due to narrow optimized frequency of the seismometer and narrow distribution on the lunar surface. To meet these objectives, a seismometer ~10 times more sensitive than the current state-of-the-art planetary instruments (Fig. 1) is required that would maintain its sensitivity over a wide temperature range.

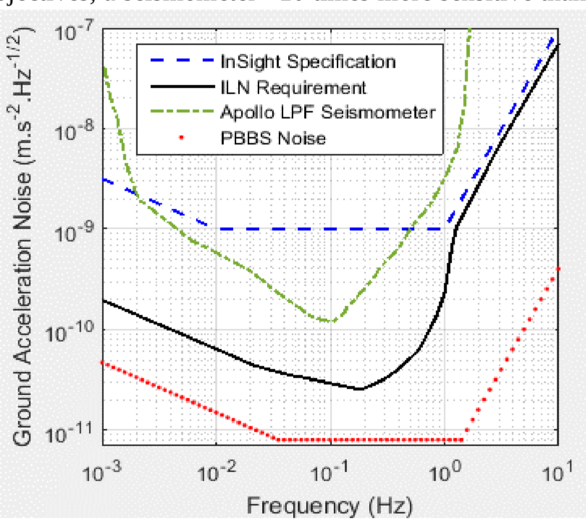

Figure 1: The Planetary Broadband Seismometer (PBBS) is designed to meet a sensitivity requirement necessary to achieve LGN science, as defined by International Lunar Network Science Definition Team [2].

In September 2017 we launched a 4-year technology advancement task under the umbrella of the NASA Maturation of Instruments for Solar System Exploration (MatISSE) program to develop a LGN mission enabling prototype Planetary Broad Band Seismometer. The project objective is to achieve Technology Readiness Level (TRL 5) by the end of 4 years.

PBBS Challenges and Design Approach: The LGN requires seismometers with sensitivities far exceeding any previously built. Ocean World seismometers at Titan, Ganymede, or Callisto may levy similarly demanding requirements [1]. Furthermore, both the LGN and Ocean World seismometers would have to function in a harsh high-radiation environment and extreme temperatures. Moreover, the LGN mission concept also requires a network of several landers (including the lunar far side) and operating for many years. To meet the above challenges, the PBBS applies two key design innovations:

- Using Electrostatic Frequency Reduction (EFR) to dramatically lower the seismometer's natural frequency and subsequently reduce its frequency-dependent noise floor.
- Employ a single-mass triaxial architecture that will substantially reduce the seismometer's mass and size.

PBBS Operating Principle – Electrostatic Frequency Reduction (EFR) Technology: A figure of merit of a seismometer is the resonance frequency f_o of its suspended mass. A lower f_o represents a higher sensitivity to low frequency seismic signals, or the ability to detect small signals from far away. Below f_o the suspended mass tends to move with the ground, hence the sensitivity to ground motion is greatly reduced. Typically, f_o is reduced by mechanically changing the configuration of the suspension system. The key PBBS technology is the EFR technique invented by H. J. Paik [4], in which f_o is reduced to near zero by applying an electrostatic force.

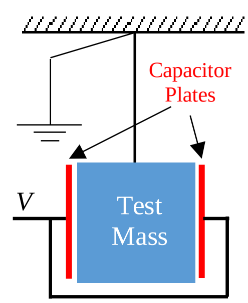

Figure 2: EFR counteracts the pendulum restoring force with electrostatic force.

Consider a pendulum (Fig. 2). When the mass is moved away from its center position, gravity exerts a force to return it to the center. This gives rise to a positive spring constant. However, when a voltage is applied to the red capacitor plates around the mass, they exert an electrostatic force that pulls the mass further away from the center. This results in a negative spring constant, and f_o can be dramatically reduced to near zero by fine voltage adjustment.

This technique also allows remote adjustment of f_o to a level of precision heretofore unachievable. The ability to remotely or autonomously tune f_o is particularly important to operations in the harsh thermal environment of planetary bodies. The springs in traditional seismometers become stiffer when cooled to cryogenic temperatures resulting in an increase in f_o and a degradation in the low-frequency sensitivity.

PBBS Architecture: Single-Mass 3-Axis Seismometer: With lessons learned from a prototype, we have designed a 3-axis PBBS in which the test mass is suspended by 4 springs (Fig. 3).

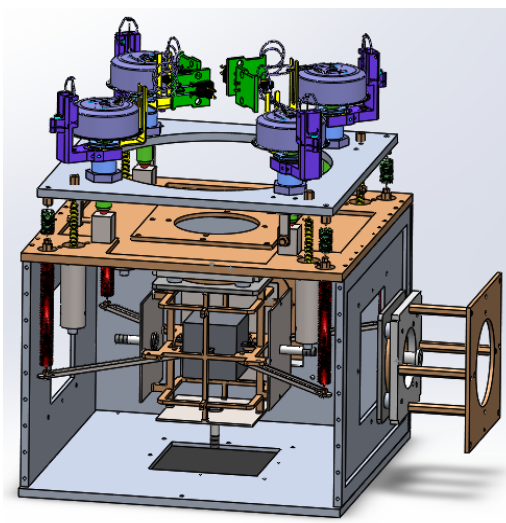

Figure 3: The PBBS triaxial design.

The test mass and readout-EFR assemblies are highly symmetrical about the center of mass of the test mass. The suspension points are also in the center-of-mass plane. This high degree of symmetry reduces unwanted effects due to misalignments that tend to couple force applied in one axis into unwanted rotational motions. To reduce coupling into the rotational modes, the moment of inertia of the test mass is reduced by using a high-density material, tungsten, while the ground plane for capacitive readout and for EFR are made as light as possible. To further reduce rotational coupling, the suspension points of the test mass are spread as far apart as practical, which increases the restoring torque for any rotation. Four small cryogenic motors [5] are used to level the test mass. A material with low thermal elastic coefficient (Ni-SPAN-C [6]) will be used to construct the springs. Any residual change of the spring constant with temperature will be compensated by adjusting the EFR voltage. With the current design, the mass of the sensor head will be < 5 kg, the capacitor gaps will be kept at 1/8 mm, and a voltage of < 200 V will be used for EFR. Anticipated total power for operation is <2.6 W.

PBBS Prototype and Testing: The EFR technology was verified under a task supported by the Planetary Instrument Definition and Development Program (PIDDP) from 2008 to 2013. A prototype was built with a cylindrical test mass suspended by three strings at the University of Maryland. The f_o of this prototype was successfully reduced from 1.15 to 0.1 Hz. A prototype of the new triaxial design (Fig. 4) is being assembled. Tests of key PBBS elements (EFR and feedback) will begin in early 2018.

Figure 4: PBBS Prototype Assembly

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