A PLANETARY BROADBAND SEISMOMETER (PBBS) FOR THE LUNAR GEOPHYSICAL NETWORK AND OCEAN WORLDS: EXPERIMENT AND THEORY ON THE THERMAL DRIFT DUE TO EFR

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Introduction: The NRC Decadal Survey for Planetary Science identified the Lunar Geophysical Network (LGN) as a high-yield New-Frontiers-class mission concept that will 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 will enable examining the initial stages of planetary differentiation frozen in time some 3-3.5 billion years ago. LGN's objectives are designed to discover the interior structure and composition of the Moon, which was not possible with the Apollo network [1-3].

Although a large set of seismic data has already been collected during the Apollo missions, key questions remains about the sizes and states of the lunar crust, mantle, and core. It was found during Apollo that the Moon is seismically rather quiet compared to the Earth, and that the seismometers deployed were not sensitive enough to resolve the background noise of the Moon. As a result, valuable scientific information was not recorded, even though, the Apollo seismometers are very sensitive, even by today's standards [1-2, 4]. The LGN will require a very sensitive broadband (0.01-1Hz) seismometer ~10 times more sensitive than the state of the art.

The development of a sensitive seismometer that can operate in a cryogenic environment is also **in line with NASA's broader mission goal, to** understand the evolutionary history and make-up of ocean worlds. Precise seismic measurements on the crustal thickness of icy moons [5] and the depth of their oceans will help in the evaluation of their ability to harbor and sustain life. [5]. Sensitive seismometers are critical for detecting faint motions deep within a planet which can be used to reconstruct its interior and shed light on processes such as plate tectonics and ocean waves [6].

We are currently pursuing a 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 (PBBS). The aim of the PBBS is to not only meet, but exceed the requirements necessary for the LGN. To accomplish this task, the PBBS makes use of a new technology to reduce its natural frequency through electrical means, as opposed to the traditional mechanical frequency reduction.

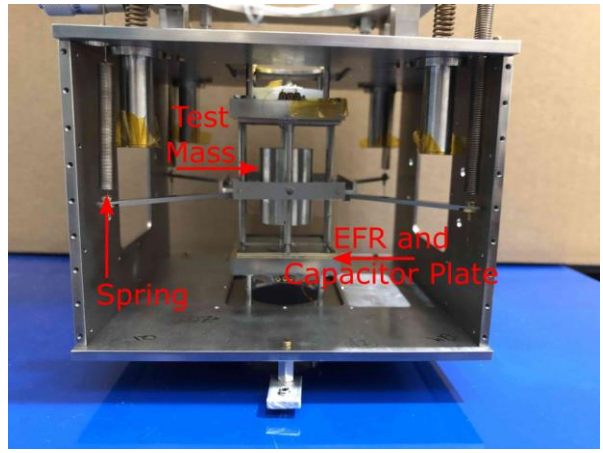

Figure 1: An image of a partially assembled PBBS prototype for illustrating the main components related to this work.

PBBS Description: The principle of operation of the PBBS is based on the electrostatic frequency reduction (EFR) technique, which was first discussed by Griggs *et. al* [7]. An applied voltage applies an electrostatic force on the test mass which opposes the spring force, effectively reducing the spring rate. The displacement of the test mass relative to the ground is recorded by capacitive sensing plates (see Figure 1).

Ground Motion Testing: We operated the PBBS without force feedback to evaluate its acceleration noise. We discovered that despite using low coefficient of thermal expansion (CTE) materials for construction, the PBBS is highly sensitive to temperature (see Figures 2 and 3), and that this sensitivity increases with the frequency reduction.

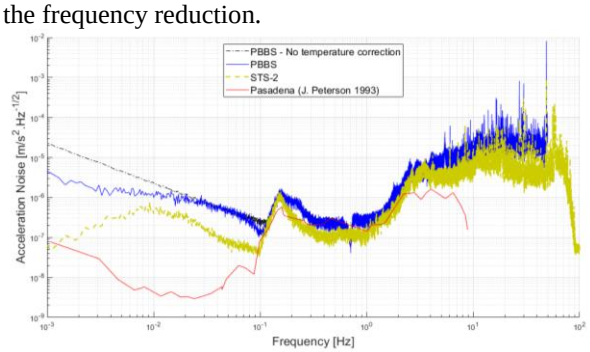

Figure 2: Ground acceleration noise of the PBBS without temperature correction (black dash-dot line), with temperature correction (solid blue line), of a commercial seismometer (dashed gold line), and a previous estimate of the Pasadena, CA noise (solid red line) [8].

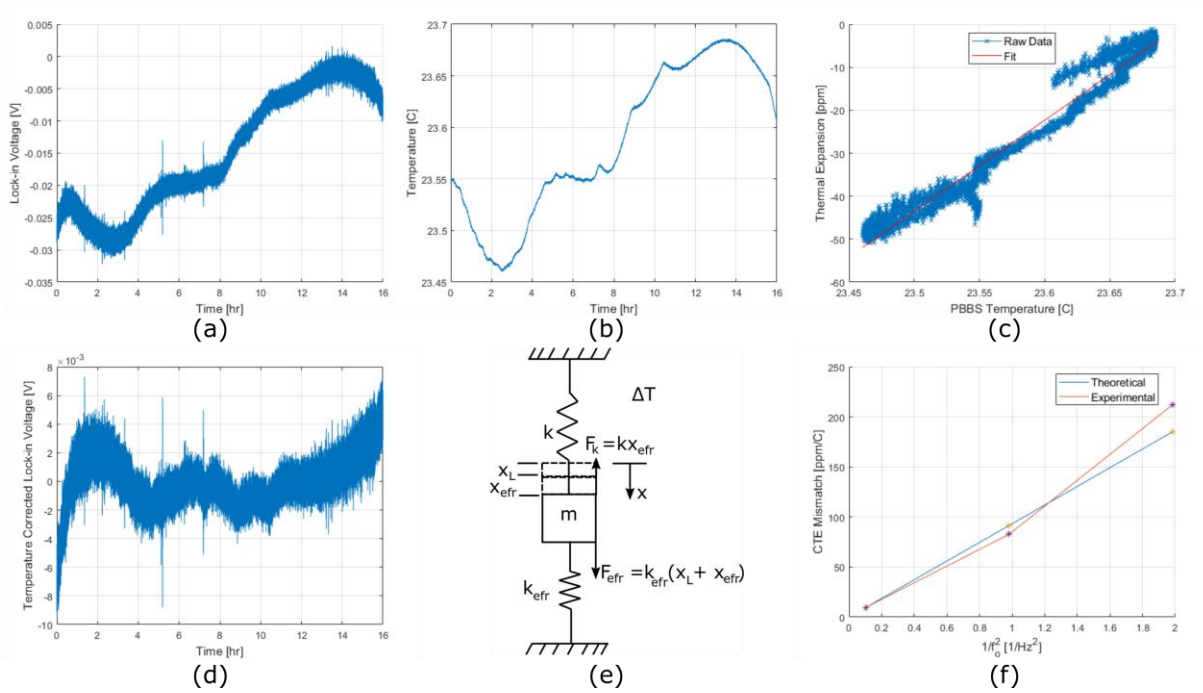

Figure 3: (a-d) Data from an overnight recording of seismic data with the PBBS. (a) The lock-in voltage measurement of the PBBS displacement capacitor sensor, and (b) the corresponding temperature. (c) The experimental displacement and temperature are well-correlated. (d) The lock-in voltage after removing the linear temperature dependence. (e) A sketch identifying the displacement x_{efr} which explains the observed drift. (f) Comparison of the theoretical effective coefficient of thermal expansion (CTE) versus the experimentally observed CTE mismatch as a function of $1/f_o^2$.

Thermal Drift due to EFR:

Experiment. Seismic data was recorded from the PBBS with the EFR voltage set to 206 V, reducing the resonant frequency, f_o, from 3.1 to 0.71 Hz. The displacement was measured through the capacitive displacement sensing bridge, while temperature was also recorded inside the seismometer. Reference seismic data was recorded with a commercial seismometer.

From this experiment we observed a large $1/f$ noise below 0.1 Hz. Figure 3 (a-c) shows the drift of the test mass, the corresponding temperature, and the correlation of the two (R^2=0.969). Removing this temperature dependence (Figure 3, d) alleviates some of the observed $1/f$ noise (see Figure 2, blue line). We hypothesize that the remaining discrepancy between the STS-2 and the PBBS is likely due to temperature gradient.

Theory. As a result of CTE mismatch, the test mass moves away by x_L from the center of the capacitor plates. Now EFR applies an electrostatic force F_{EFR}, resulting in the test mass coming to rest at the final position of x_L+x_{EFR} away from the center (Figure 3, e). The physics reveals that this larger total displacement arises from a larger effective CTE which is given by

$$CTE(V) = \left[\frac{f_o(0)}{f_o(V)}\right]^2 CTE(0),$$

where the dependence of the CTE and f_o on the applied EFR voltage, V, is expressed explicitly.

Conclusion: Using the principle of EFR has many merits for a lunar seismometer; however, the squared increase in effective CTE mismatch with natural frequency reduction causes some issue. We will resolve this issue through the use of a force feedback loop to fix the test mass position at the center of the sensing capacitor plates so that CTE mismatch is not enhanced.

References: [1] ILN (2009) Final Report: Science Definition Team for the ILN Anchor Nodes. [2] Shearer C. (2011) Lunar Geophysical Network, NASA Planetary Science Decadal Survey. [3] Khan A. et al. (2014) *J. Geophys. Res.*, 119, 2197-2221. [4] Weber R. C. et al. (2011) *Science*, 309-312. [5] NASA (2014), Strategic Plan, online. [6] Pappalardo R. T. (2013), *Astrobiology*, 13, 740-773. [7] Griggs C. E., et al. (2007) *Nucl. Phys. B* (*Proc. Suppl.*), 166, 209-213. [8] Peterson J. (1993) *USGS*.

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