DEVELOPMENT OF A SEISMOMETER FOR THE MOON: OVERCOMING BROWNIAN MOTION

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Introduction: The Lunar Geophysical Network (LGN) is 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 [1]. Through the LGN, a better understanding of the nature and evolution of the lunar interior from the crust to the core might be obtained. In particular, the LGN could enable examining the initial stages of planetary differentiation frozen in time over 3 billion years ago [2-4]. A key instrument in answering questions about the lunar interior is a very broadband (0.001-20 Hz) seismometer [2]. To this day, the primary source for our scientific understanding of the lunar interior comes from data collected on the Moon with seismometers from the Apollo Missions [5].

It was found during the Apollo missions that the Moon is seismically quiet compared to the Earth, and that the seismometers themselves could not resolve the lowest background noise [6]. As a result, while data from the Apollo seismometers has increased our understanding of the lunar interior, it also created many new questions and left some key ones unanswered [2-5]. In particular, the free oscillations of the Moon were not measured, which would have informed on the core [7]. As a result of the lower noise floor on the Moon, the LGN concept [1] will require a very sensitive broadband seismometer, approximately 10 times more sensitive than the Apollo seismometers, to help further our understanding of the lunar interior (see Fig. 1).

We are developing a Planetary Broad Band Seismometer (PBBS) which could meet the requirements of the LGN. To meet the sensitivity requirements, the PBBS makes use of a new technique, electrostatic frequency reduction (see Fig. 2), to reduce its natural frequency through electrical means [8], as opposed to the traditional mechanical frequency reduction. We have developed and tested a prototype for the vertical component of the seismometer which verified the use of the electrostatic frequency reduction technique [9]. Through these tests, we discovered that the dominant loss mechanism in our seismometer was due to internal friction in the suspension element. As a result, the field of seismometer's traditionally accepted Brownian motion due to air damping and/or eddy current damping in vacuum is not complete. Instead, performance at long periods will be limited by Brownian motion due to internal friction as described by instrumentation literature in the field of gravitational wave detection [10].

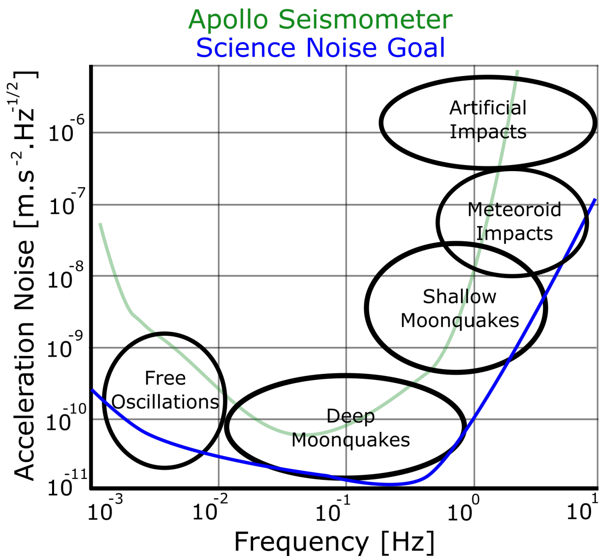

Figure 1: Notional estimates from forward modeling and Apollo data observations for the lunar geophysical signals to be measured by an LGN enabling seismometer [1-2, 11-13].

Electrostatic Frequency Reduction: Our seismometer uses capacitive sensing to measure the difference between ground motion and that of the test mass. By applying a DC voltage to the same capacitor plates, an electrostatic force is created. For sufficiently small regions, there exists a linear relationship between this electrostatic force and displacement of the test mass relative to ground, creating a linear negative stiffness mechanism for frequency reduction (see Fig. 2), which increases sensitivity to long period ground motion.

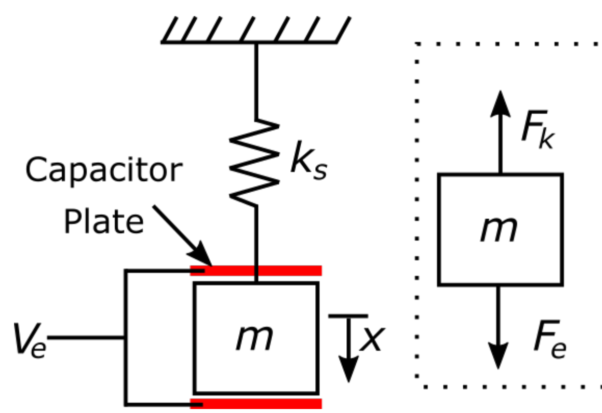

Figure 2: Simplified illustration of a seismometer including the suspension element (k_s), test mass (m), and displacement (x). We apply a DC voltage (V_e) to create an electrostatic force (F_e) that counteracts the spring's restoring force (F_k).

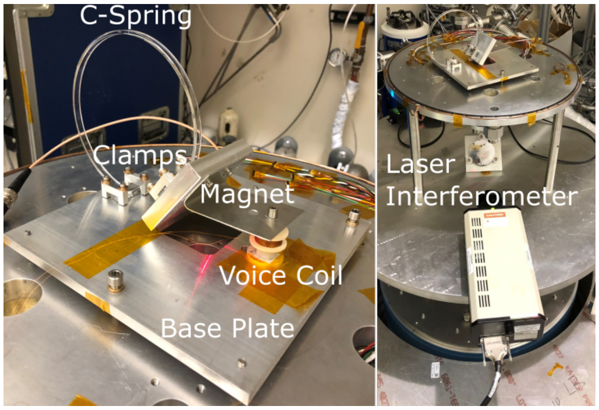

Figure 3: Setup for measuring the quality factor of a fused silica spring that could be incorporated into a seismometer.

Seismometer Suspension Element: After verification of the electrostatic frequency reduction technique for our vertical seismometer [9], we discovered that dissipation in vacuum was due to internal friction in the spring. This leads to a formulation for Brownian motion that is proportional to the suspension element's loss angle, which is the inverse of the quality factor. As a result, using low loss materials, such as fused silica or beryllium copper, as the suspension element could lead to a seismometer with lower Brownian motion [10].

Our group has developed a fused silica spring that has a stiffness and form factor compatible with that of a compact very broadband seismometer (see Fig. 3). To verify its quality factor, we placed a simple mass-spring setup in a vacuum chamber. A voice coil was used to excite the mass-spring system, and a laser interferometer measured the resulting velocity. We estimate the quality factor of this spring to be 50,800 (Fig. 4). With a 1 kg test mass, a seismometer with this suspension element could have Brownian motion lower than the ILN requirement by a factor of two (Fig. 5).

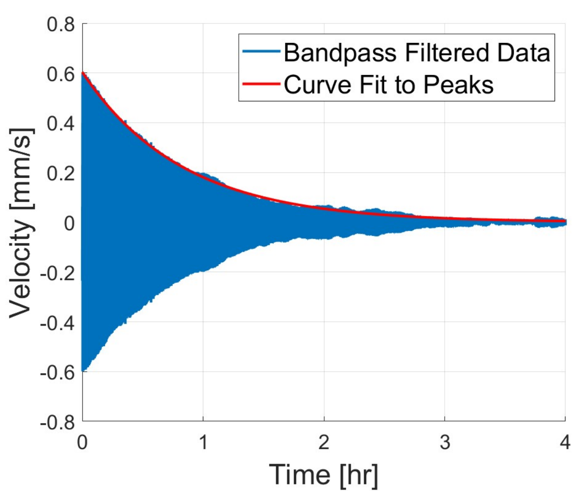

Figure 4: Ring-down experiment for the fused silica spring.

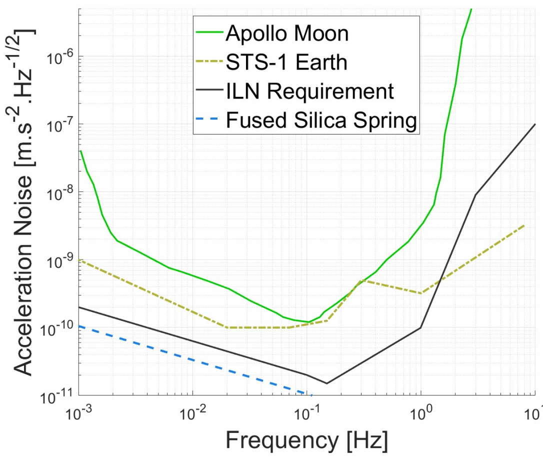

Figure 5: Comparison of the ILN noise requirement [2] with the Apollo long period flat seismometer [14], STS-1 instrument-noise [15], and predicted Brownian motion for our fused silica spring with a 1 kg test mass.

Conclusion: We have found that the theory of Brownian motion due to internal loss is applicable to the design of a seismometer with low $1/f$ noise. Such instrument noise will be particularly important for a lunar seismometer. In our design, this will be addressed through the use of low loss materials in the suspension.

References: [1] Shearer C. (2011) Lunar Geophysical Network, NASA Planetary Science Decadal Survey. [2] ILN (2009) Science Definition Team for the ILN Anchor Nodes. [3] Khan A. et al. (2014) *J. Geophys. Res.*, 119, 2197-2221. [4] Weber R. C. et al. (2011) *Sci.*, 309-312. [5] Watters T. R. et al. (2019) *Nat. Geosci.*, 12, 411-417. [6] Lognonné P. et al. (2009) *J. Geophys. Res.*, 114, E12003. [7] Nakamura Y. et al. (1982) *J. Geophys. Res.*, 87, A117-A123. [8] Griggs C. E., et al. (2007) *Nucl. Phys. B (Proc. Suppl.)*, 166, 209-213. [9] Erwin A. et al. (2019) *LPSC L*, Abstract #1052. [10] Saulson P. R. (1990) *Phys. Rev. D.*, 42, 2437-2445. [11] Khan A. and Mosegaard K. (2001) *Geophys. Res. Lett.*, 28(9), 1791-1794. [12] Lognonné P. (2005) *Annu. Rev. Earth Planet. Sci.*, 33, 571-604. [13] Chenet H. et al. (2006) *Earth Planet. Sci. Lett.*, (1-2), 1-14. [14] Lognonné P. and Pike T. (2015) *Planet. Seismom.*, 36-48. [15] Ringler A. T. and Hutt C. R. (2010) *Seismol. Res. Lett.*, 81, 972-983.

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