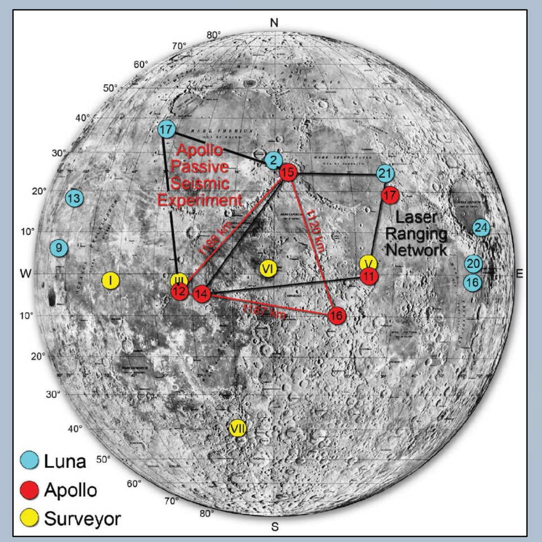
LUNAR SEISMOMETER AND BURIAL SYSTEM

S. H Bailey[1], R. Weber[2], B. Avenson[3], D. N. DellaGiustina[1], K. Zacny[4], N. C. Schmerr[5], M.A. Siegler[6], V. J. Bray[1], N. Murdoch[7], C. Neal[8]
[1]Lunar and Planetary Laboratory, University of Arizona (hbailey@lpl.arizona.edu). [2]Marshall Space Flight Center, Huntsville, AL, [3]Silicon Audio, Inc. Austin, TX, [4]Honeybee Robotics, New York, NY, [5]University of Maryland, College Park, MD, [6]Planetary Science Institute, Tucson, AZ, , [7]ISAE, Toulouse, France, [8]Notre Dame University, South Bend, IN.

Introduction



Beginning in 1969, Apollo successfully deployed a long-lived network of seismometers on the Moon. Seismic studies provide definitive knowledge of internal planetary structure, and analysis of the Apollo seismic data has contributed to the magma ocean hypothesis for initial terrestrial planetary differentiation [Wieczorek et al., 2006]. While the general model is widely accepted, details such as mantle composition, stratification and possible overturn, lateral structure, and thermal inhomogeneities remain unresolved.

The Moon experiences moonquakes at varying depths [Nakamura, 1983]. Shallow quakes are relatively large but rare, similar to terrestrial intra-plate earthquakes. Deeper quakes are comparatively smaller but more frequent, occurring periodically according to the tidal cycle. On the Moon, the lack of an atmosphere enables seismic experiments to potentially constrain meteorite impact flux, which informs cratering rates assumed throughout the solar system. The large diurnal temperature variation between day and night also induces thermal moonquakes, which may contribute to regolith production [Duennebier & Sutton, 1974; Weber et al., 2017].

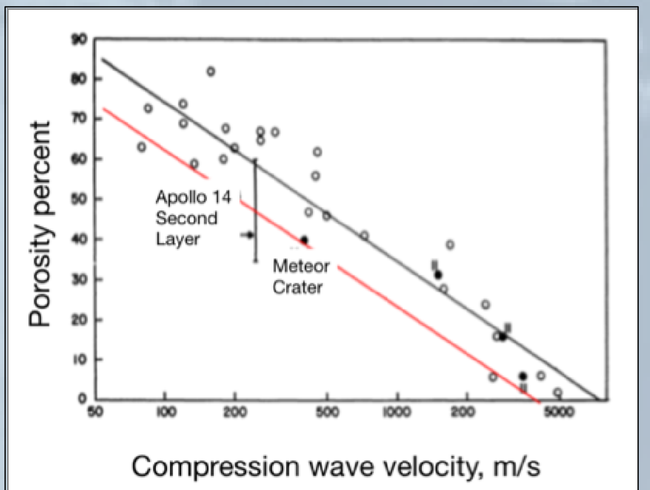
Still, many questions remain regarding the frequency and distribution of natural moonquakes. This translates into an incomplete understanding of the Moon's hemispherical dichotomies in crustal thickness, mare volcanism, seismicity, and the distribution of heat-producing elements. **The Planetary Decadal Survey (National Research Council, 2013) identifies a New Frontiers Lunar Geophysical Network (LGN) mission to answer such questions.**

Challenges of Lunar Seismology

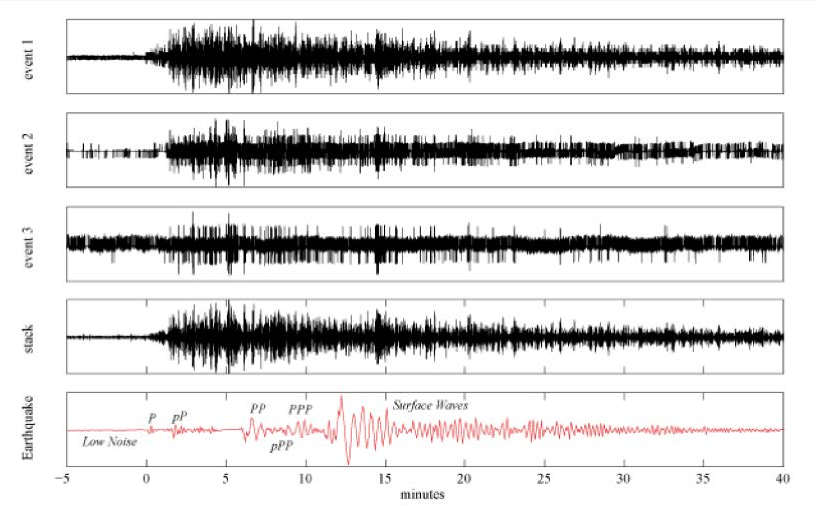
The Moon is covered with a remarkably low-density regolith layer. Surface material density can be as low as 1200-1300 kg/m-3 with ~60% porosity. However, due to the evolution of the regolith with impact gardening, density increases roughly exponentially within the top ~50 cm to roughly 1900 kg/m-3 and ~40% porosity (Fig. 2) [Carrier et al., 1991; Vasavada et al., 2012]. This near-surface regolith structure has profound effects on seismic science for the proposed LGN mission [Cohen, 2010; Neal et al., 2019].

The low-density surface layer increases seismic signal scattering. The powdered surface regolith layer has very low P-wave seismic velocities - less than 100 m/s [Watkins & Kovach, 1973]. This decrease is most dramatic within the top 1 m, where seismic velocities drop to nearly 50 m/s. Low density causes increased near-surface trapping and scattering of seismic noise, generating multiple reverberations, which effectively spreads over important secondary signals. Distant and low magnitude quakes are lost in this noise-train.

The effects of noise from the surface can be mitigated by deploying instruments below the scattering layer, as is routinely done on Earth. A lander, which cannot be entirely shielded from the sun, will continuously expand and contract with the diurnal cycle. This thermal stressing creates noise at many frequencies that will contaminate seismic signals of interest for a robotically deployed surface seismometer. Robotically deployed seismometers will be < 1 m away from their noisy spacecraft; however, burial 1 m below the low-density surface layer will eliminate much of this noise and decrease the scattered noise from these signals.



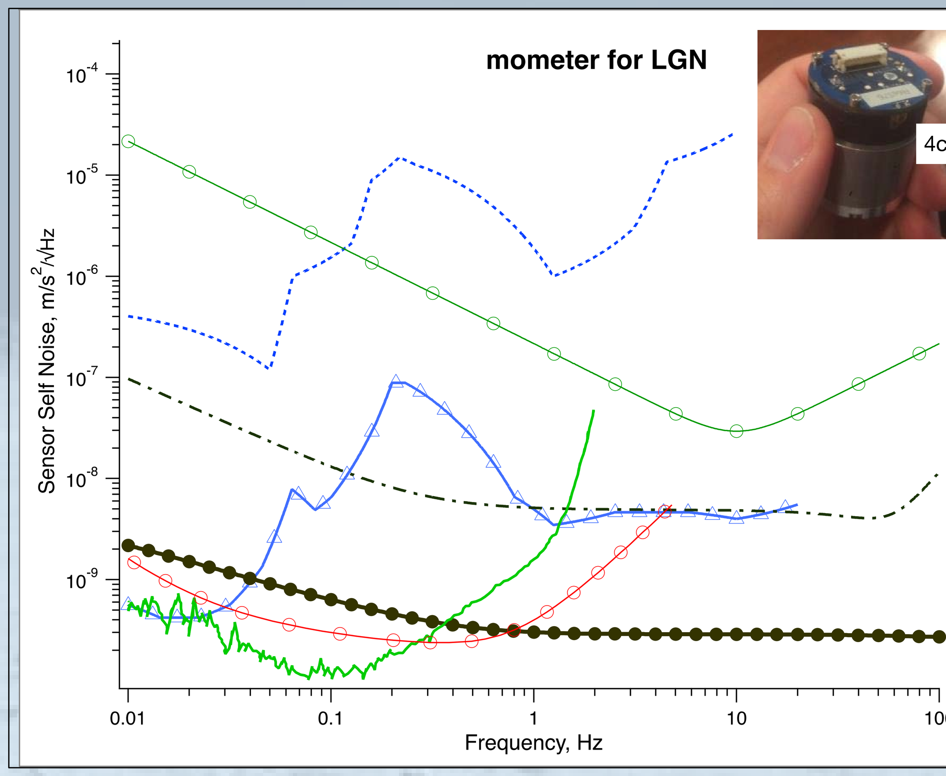
Lunar wave velocity vs. porosity from Watkins and Kovach [1973, LPSC]. Lunar seismic waves and those near terrestrial craters were found to have low seismic velocity as a function of porosity (the red line).



Silicon Audio Seismometer for the Lunar Geophysical Network

Silicon Audio manufactures sensors that represent a paradigm shift in seismometer technology. The technology was originally developed as a seismic monitoring tool to support the Comprehensive Test Ban Treaty Organization's world-wide ban on nuclear testing. The COTS Silicon Audio device has been tested for eventual lunar deployment by a NASA-funded Phase I SBIR. Our team was also selected by NASA for a Planetary Science and Technology Through Analog Research (PSTAR) program to deploy the COTS sensor in lander-like small arrays in terrestrial analogs thereby providing real world experience with the device.

Silicon Audio's optical seismometers have lower self-noise and a substantially higher signal saturation level than other scientific grade seismic sensors. This allows a single sensor to capture high and low-noise signals simultaneously across a wide bandwidth of frequencies (0.005 Hz to 400 Hz) free of spurious resonances. Prior planetary seismic experiments, including SEIS on InSight [Lognonne et al., 2019] and the Apollo seismic surveys [Goins et al., 1981], have required multiple sensors to record signals across the desired range of frequency bands. Due to its high clip level, the Silicon Audio sensor enjoys the largest dynamic range in the industry at 183 dB. The SiAu sensor also has ultra-low distortion.

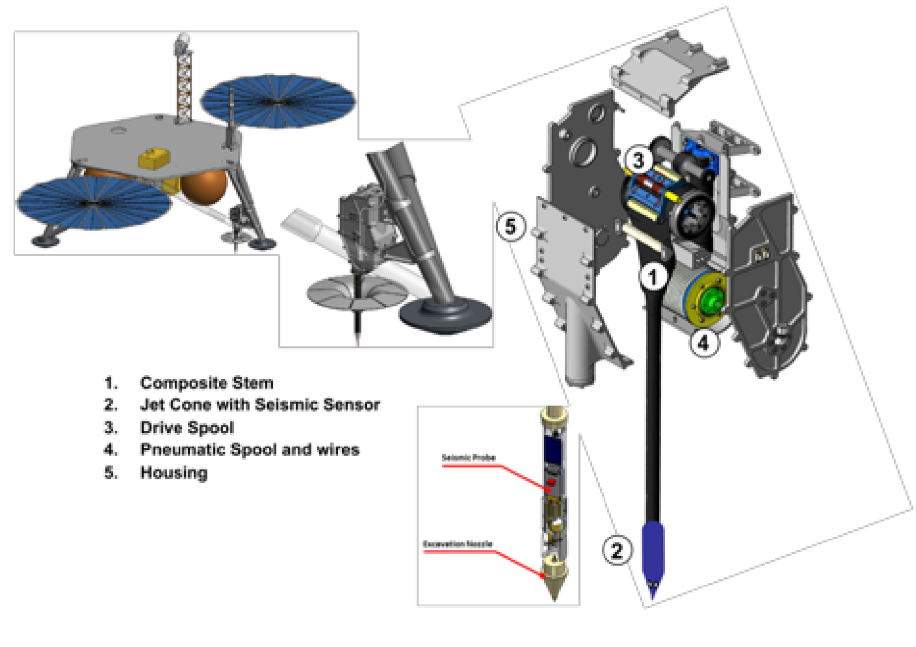


Unlike most seismic instruments that only allow for a few degrees of tilt misalignment, the Silicon Audio sensor is 180-degree tilt-insensitive in the lower gravity field of the Moon and self-calibrates to compensate for tilt. This is a major benefit, as the remote robotic deployment of a seismic experiment on irregular terrain does not guarantee a preferred sensor orientation.

The Silicon Audio sensor is now currently funded for development under both the DALI (Development of Advanced Lunar Instrumentation) and ICEE2 (Instrument Concepts for Europa Exploration) NASA opportunities.

Pneumatic Drilling with the Honeybee Robotics Burial System

To realize the benefits of sensor burial, SLN adapts a low-mass, low-power burial system developed by Honeybee Robotics for the NASA-funded lunar Heat Flow Probe. This system was developed under a previous NASA SBIR and NASA PIDDP grant and is currently at TRL4. The system uses pressurized gas to create a vertical hole in the regolith [Zacny et al., 2009], into which the instruments can be said to "drop." In the current design, a flattened glass fiber stem is spooled out to form a rigid tube. The tube has a cone with strategically placed holes for gas jets. Compressed gas is fed through a hose within the tube that is firmly attached to the cone. The regolith is lofted by the compressed gas through the tight annular space between the tube and the borehole wall. Unlike drilling on Earth, no downward weight is applied to this "bit;" all of the excavation is provided by the action of the gas jet. Once the gas flow stops, the non-cohesive lunar soil flows back in to cover the sensors. The TRL 4 breadboard system developed for the Heat Flow Probe project deployed to a depth of ~2 m in 1.9 g/cc NU-LHT-2M lunar soil simulant within two minutes.



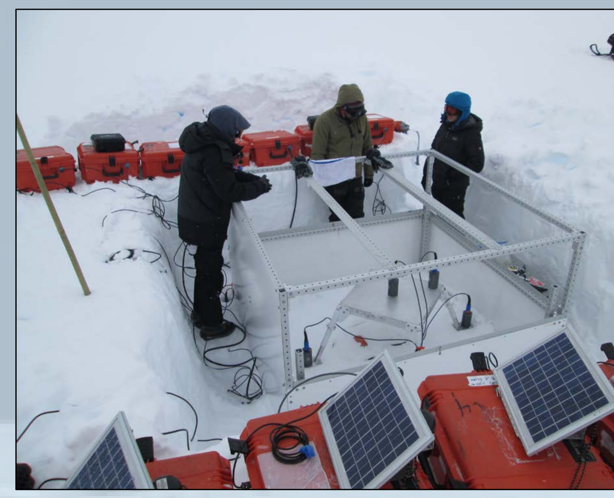
Honeybee LGN Burial System. Schematics showing SiAu seismic sensor head attached to a leg of a lunar lander (left), and the major components (right). The seismic deployment probe will be based on this principle.

Gas-drill architecture is an ideal low mass, low power approach for excavating holes in the lunar regolith. Under lunar vacuum, very little gas is needed to excavate large amounts of regolith. During vacuum+lunar-g tests inside a Zero-g Corp airplane, we found that 1 gram of gas can loft up to 6000 grams of JSC-1a lunar soil simulant [Zacny et al., 2013]. The gas required is modest (a few grams) and can come from a part of the lander's residual propulsion gas. A small, dedicated tank is also an option.

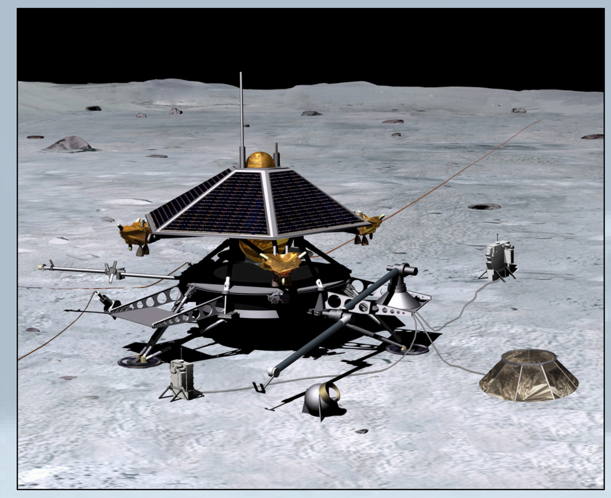
Under NASA SBIR Phase 1 project, Honeybee Robotics tested pneumatic penetration with a dummy Silicon Audio lunar seismometer canister. The tests were done with a 50 mm diameter probe, sufficient to accommodate one axis of the sensor. The other two axes will be stacked inside the probe to make a three-axis seismometer.

Future Work

Build and test a prototype LGN Silicon Audio sensor
Under NASA's DALI program, we design, build and test a Silicon Audio seismometer prototype LGN sensor. For the LGN sensor the prototype will be redesigned to achieve a noise floor of 1x10-9 m/s2/√Hz with a modest reduction in bandwidth compared to the COTS device. The redesign takes into account the electro-mechanical characteristics of the system and subtle variations in materials and mechanical design details while preserving sensor size and mass to achieve lower noise. In traditional sensor designs, increasing the displacement sensitivity excessively limits the tilt tolerance and dynamic range of the instrument. [Wielandt, E. (1982), Matichard, 2016; Habbak, 2016]. By contrast, the interferometric readout of the Silicon Audio sensor increases the displacement resolution by orders of magnitude over capacitive measurements while maintaining tilt tolerance. The design changes required for LGN preserves the low required power of the sensor since the interferometric system consumes the same power and the power required for electromagnetic force feedback increases only slightly. The resulting LGN prototype will be tested in relevant environments to demonstrate TRL6.



PSTAR field testing the SiAu instrument in an analog environment, using a lander simulator



LGN concept lander

Honeybee Robotics designs, fabricates, integrates, and tests the LGN burial system
The LGN burial system will reach 50 cm depth into compacted lunar regolith simulant (90+% relative density, consistent with lunar environments) in a vacuum chamber. Honeybee uses the experience and lessons-learned from the earlier SBIR project to design a purpose-built prototype. Material selection will enable a system mass of 1KG. Stem materials will be selected for lunar vacuum, temperature and radiation compatibility; gas-jet holes will be optimized to provide efficient excavation. A 'dummy' seismic subsystem will be incorporated. The system will be tested in air to debug the software, controls, and mechanical system. Once the system operates satisfactorily in air, several tests will be performed in a vacuum chamber and in compacted NU-LHT-2M.

Field demonstration of burial
Under our currently-funded NASA PSTAR program we have established seismic stations in Alaska and Greenland to compare the Silicon Audio COTS sensor performance to terrestrial standards, short and long-baseline arrays of Silicon Audio sensors and lander-mounted and shallow burial sensors. During our next field campaign we will bury Silicon Audio sensors at varying depths to simulate burial in lunar regolith and compare those results to shallow burial.

References

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