MoonShake: a future Lunar Seismic Network Delivered by Penetrators

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Seismometer based on SEIS-SP

Deep Space 2 Penetrator designed for Mars
Polar Lander

“Mote” penetrator design from Space Initiatives Inc
(SII)

The proposed mission would bury seismometers on the Moon using penetrators deployed directly from a small spacecraft or from a descending lander. This paper identifies the most compelling questions in lunar science:

- 1) To constrain the thickness of the lunar core to within 50 km and determine whether it is liquid;
- 2) Determine crustal thickness (at the target sites) to within 5 km, and constrain the average thickness in conjunction with data from the GRAIL gravity mission;
- 3) Determine the depth of deep moonquakes to within 50 km, and determine whether they occur at a range of depths;
- 4) Determine the number of meteoroids that hit the Moon every year;
- 5) Analyze lunar asymmetry in crust, mantle and core;
- 6) Determine regional variations (for example, differences between high and low heat-flow regions);
- 7) Determine properties of the lunar regolith from the deceleration of the penetrator (at each site).

Introduction

Seismic experiments were deployed on the Moon by the astronauts during the Apollo missions. These experiments were part of the Apollo Lunar Surface Experiments Package (ALSEP). The experiments began in 1969 with Apollo 11 and continued with Apollo 12, 14, 15, 16 and 17. Seismic stations from Apollo 12, 14, 15 and 16 remained operational until the final transmissions in 1977. Seismologists have observed and categorized several types of moonquakes, and over 13,000 seismic arrivals were recorded by the seismometers¹. These include deep moonquakes, meteoroid impacts, shallow moonquakes, thermal quakes and also artificial impacts.

Penetrators are bullet-shaped vehicles designed to penetrate a surface, and embed instruments beneath the ground. Penetrators have been considered as a delivery mechanism for scientific instruments since at least the 1970s². Two Deep Space 2 penetrators with instrumentation flew on-board Mars Polar Lander in January 1999³, but the lander failed to communicate after the descent phase. The penetrators, which may not have left the spacecraft, also failed to communicate. The Japan Aerospace Exploration Agency (JAXA) designed a penetrator for LUNAR-A, with seismometers that survived 8000 *g* impact tests⁴. The agency cancelled LUNAR-A in 2007, but the penetrator and its seismometer narrowly missed selection for a new mission in 2018. Penetrators dropped from lunar orbit or ejected from a soft-lander during landing could provide a low-cost, low-risk, delivery mechanism for seismometers engineered to survive a hard landing.

Lunar Science

Dating of zircon fragments⁵ indicates that the lunar crust differentiated within the first ~60 million years after the birth of the solar system. This suggests that the Moon formed, and largely solidified, early on in the formation of the solar system. The Moon is generally thought to have originated after a collision between the young Earth and a Mars-sized planet, known as Theia. Lack of significant surface processes, such as plate tectonics or erosion, means that even the Moon's surface retains a record of the history of the solar system. The Moon's small size means that it differentiated early, and makes it an end-member among the terrestrial planets.

Understanding the Moon's interior provides a window into the earliest stages of evolution of the terrestrial planets.

There are many remaining questions about the formation and structure of the Moon. One of these questions concerns the Moon's asymmetry. The farside is mountainous. Its nearside is low and flat, and is dominated by the dark volcanic maria. The nearside is also richer in heat-producing elements, and contains a region known as the Procellarum KREEP (potassium/rare-earth element/phosphorus) Terrane. Jutzi and Asphaug⁶ suggested that, after its formation, the Moon may have been involved in another collision with a companion Moon ('The Big Splat'). The theory remains controversial, but may explain the asymmetry of the lunar highlands and the regions of heat producing elements. The later volcanism of the nearside is probably related to the KREEP terrane. Elardo et al.⁷ suggest that a KREEP component in rocks both lowers their melting temperature and enhances the heating of these rocks.

Lunar Seismology

Seismology can answer questions about the current structure of the Moon, and therefore help us understand more about its formation and evolution. Since the Moon is our closest neighbor, it is also the easiest to explore. Garcia et al.⁸ contains a recent review of models of the interior structure of the Moon.

The surface of the Moon retains a record of bombardment, from soon after to the formation of the solar system up to the present. The present flux of meteoroid bombardment is not well determined. A closely-spaced network of seismometers will allow characterization of the current meteoroid flux distribution. This measurement would constrain the evolutionary history of the Earth-Moon system.

Just as the surface of the Moon retains a record of bombardment by meteoroids, so does its subsurface. One of the surprises of Apollo-era seismology was the strength of the scattering of the seismic energy. Fig. 1 shows seismograms from a deep moonquake, a meteoroid impact, a shallow moonquake and an artificial impact. In each case, the energy has a slow rise time, and an even longer decay time. Shaking lasts for around thirty minutes for the deep moonquake, and over an hour for the other examples. This pattern, which is characteristic of lunar seismology, is explained as a strongly scattering layer, with very low attenuation of the signal. The energy reverberates for a long time.

Fig. 1: Examples of a Deep Moonquake, a Meteoroid Impact, a Shallow Moonquake and an Artificial Impact Event⁹.

Mission Concept

We envision a mission concept where clusters of up to eight seismometers would be delivered to several sites around the Moon by penetrators. Penetrators have many potential advantages for planetary targets, including low mass, good ground-coupling, and ease of deployment. Penetrators launched from lunar orbit or ejected before landing would provide a low-cost, low-risk, delivery mechanism for seismometers engineered to survive a hard landing. Many seismometers could be deployed as a distributed network, forming local arrays of seismometers covering different regions of the Moon.

Deployment of a large number of penetrators would allow us to tolerate the loss of some penetrators due to the rocky and varied nature of the lunar surface. Survival of two or more penetrators within a cluster would enable us to stack signals, reducing random noise, and increasing the signal-to-noise ratio. There is also an opportunity to reduce non-random noise using the same method. Billions of years of bombardment by meteoroids have left the lunar surface highly fractured. Seismic energy which travels through the fractured layer, is scattered, and the resulting seismograms often last for over an hour and have long seismic coda (Fig. 1). Stacking the signals could potentially reduce some of the scatter introduced by the near-surface layer, and result in cleaner signals from the core-mantle boundary and other features of interest.

One major improvement from Apollo seismology will be provided from terrestrial (nearside) monitoring of meteoroid impact flashes¹⁰. This monitoring will provide known seismic sources and locations (reducing the unknowns in the parameterization), allowing for better-calibrated models of the lunar interior.

The Lunar Geophysical Network (LGN) is one of the possible candidates for NASA New Frontiers 5 missions. The LGN would have three to four geophysical stations operating simultaneously^{11,12}. In addition to the seismometers, the LGN would carry one or more heat flow probes, electromagnetic (EM) instrumentation, and laser retroreflectors. MoonShake could either act as a stand-alone mission or provide additional seismic nodes to the LGN. The LGN seismometers would likely have better sensitivity at frequencies below 1 Hz than MoonShake, allowing for improved monitoring of lower frequency lunar signals.

Lunar Science Goals

Using a technique called polarization filtering, Weber et al.¹³ determined that the Moon has a solid inner core, a liquid outer core and a partial melt layer above the core. Using a similar technique, Garcia et al.¹⁴ found a liquid outer core and did not detect either a partial melt layer or an inner core. The use of signal stacking will create cleaner signals from the core, which will significantly enhance this technique, enabling constraints on the state and thickness (to within 50 km) of the core.

Observations using the seismic data from the Apollo missions constrained the thickness of the lunar crust. Similarly, observations using data from the GRAIL gravity mission to the Moon constrained the thickness of the Moon's crust¹⁵. However, there are trade-offs between thickness and other parameters such as porosity. We can re-estimate the thickness at each site. Using

observations from GRAIL and a single site would constrain the global thickness of the Moon's crust. Additional sites would reduce the uncertainty further.

Deep moonquakes are an important (and somewhat surprising) class of moonquakes. They occur at depths of around 900 km. Stacking of signals at each site would provide a cleaner signal. Seismic data from a network of seismometers would provide better constraints on the depths. We would aim to constrain the depths to within 50 km, and this will provide clearer information about whether these quakes are caused by fluids or by phase changes within the lunar mantle.

A global seismic network could determine the number of meteoroids that hit the Moon every year. Although adjustments will need to be made to adjust for the smallest size of meteoroid detected, versus distance from the station, a global network is ideal to constrain the global flux of meteoroids. In turn, this gives better constraints on the number of meteoroids in the solar system.

Using seismometers which are arranged around the Moon, we could investigate the asymmetry of the thickness of the crust, variations in the seismic velocity of the mantle, and possibly the thickness of the lunar core. The question is whether the asymmetry is only skin deep. Similarly, regional variations, such as differences between high and low heat-flow regions, could be assessed.

As each penetrator is decelerated by the lunar regolith, it will encounter differences between the thickness of the dusty and rocky layers. Data from a small on-board accelerometer could answer many questions about the subsurface.

Instrumentation

For this mission, we propose a microseismometer for the Moon:¹⁶ the Silicon Seismic Package (SSP). The SSP's sensors are etched in silicon. We predict that the noise floor will be below $2 \times 10^{-10} (\text{m/s}^2)/\sqrt{\text{Hz}}$ between 0.3 and 3~Hz (similar to the Apollo instruments, Fig. 2). The first-generation version of this sensor, the SEIS-SP, was deployed on Mars in 2018 as part of the InSight mission's seismic package^{17,18}.

The seismometer will be tested to ensure that it can survive the hard shock of an impact landing. Hopf et al¹⁹ added sublimants, such as paradichlorobenzene (PDB), to add shock protection to the SSP. The seismometer will be designed to a tilt-tolerance of 15°, and the orientation of the seismometer axes will be calculated after landing.

We envisage a penetrator with a forebody, containing the seismometer, which is buried upon impact, and an aft-body which remains above the surface. Communications and power would be placed in the aft-body. The Deep Space 2 penetrator³ meets these requirements, and is being considered as a prototype.

Alternative technology, which also meets the requirements, is being developed within commercial companies. A "Mote" penetrator is being developed commercially under a U.S. Air Force contract. The 338 mm penetrator is intended to be deployed with landing velocities up to 300 m/s and could be deployed from NASA Commercial Lunar Payload Services (CLPS) landers during its descent and, by descending before the main lander touch down, could observe the seismic signature of

the soft-landing sequence. The nominal deployment sequence would provide an array of 16 penetrators spread over a km-sized strewn field, capable (even with penetrator losses) of providing a local seismic array with each CLPS landing.

Fig. 2: Predicted noise floor for the Silicon Seismic Package (SSP) microseismometer for the Moon (dashed pink line). The plot shows spectra for a selection of events (recorded on Apollo 16's mid-period seismometer), ranging from small (dark-green line), medium (medium-green line), and large (light-green line). The S16 short-period instrument recorded the same events (light-, medium- and dark-green dotted lines respectively). The largest signal was recorded by Apollo 12's mid-period seismometer (orange line) when the short-period seismometer was not functioning. The plot shows spectra for a selection of traces containing only noise on the mid-period instrument (mid-blue lines) and the short-period instrument (light-blue lines). The spectra are most reliable between 0.3 and 0.9 Hz for the mid-period instrument and between 1 and 5 Hz for the short-period instrument (indicated by thicker lines). We calculated spectra for ten minutes after the first arrival. The solid gray line shows the low Seismic Background Noise level for Earth²⁰. Figure from Nunn et. al.¹⁶.

Enabling Future Missions to the Moon and other targets

Penetrators have a huge potential for other solar system targets, including asteroids, dwarf planets, icy moons and volcanically active moons such as Io. Since the Moon is relatively near, and there are likely to be many missions to the Moon over the coming decade, this mission has great potential to test the penetrators and reduce risk for future missions. The missions could

characterize potential landing sites for human exploration and future mining expeditions. We envision that each penetrator would carry a single main science instrument. However, additional penetrators containing different instrumentation could be added to each delivery vehicle.

Mission Designations

The Science Value Matrix shows the trade-offs between mission cost and complexity versus the science return.

Technical Demonstrations

1a A technical demonstration, carried on-board a CLPS mission, with only 2 penetrators.

1b A technical demonstration, carried on-board a CLPS mission, with 8 penetrators. We anticipate the loss of some penetrators (for example, due to a penetrator hitting a rock and being unable to penetrate or be significantly deflected from its target angle), and therefore, 1b has significant advantages over 1a. Both 1a and 1b test the penetrators and the instruments in-situ, and therefore significantly reduce risk for future missions.

Dedicated Missions, without a preliminary technical demonstration

2a A dedicated mission which covers four nearside sites.

2b A global, dedicated, mission, which covers two nearside and two farside sites.

Dedicated missions, following a preliminary technical demonstration

Follow-on missions which follow a successful technical demonstration. Follow-on missions could use their own dedicated orbiter, or be ejected from different CLPS landers.

3a Follow-on mission with two farside and one nearside location (in addition to the original site).

3b Follow-on mission which also uses the Lunar Geophysical Network (LGN). Sites would be selected to be far away from LGN sites, to increase coverage.

Class 3 missions (3a or 3b) have reduced risk (since they follow on from a technical demonstration) and have maximum scientific return. We envision that a follow-on mission could fit within a Discovery cost-cap.

Conclusion

Seismology can directly address questions about the structure of Moons and planets, and whether the planet's core is solid or liquid. By answering these questions about the Moon, which is small, and solidified very early in the formation of the solar system, we can look at one end-member among the terrestrial planets. A future lunar seismic network, delivered by penetrators, would answer a number of scientific questions about the evolution of the solar system. It would also be an excellent test of the instruments in-situ, to provide a test for penetrators to hit other targets, such as asteroids, dwarf planets and icy moons. The concept is suitable for either a stand-alone mission or as a cost-effective way to add coverage to a future Lunar Geophysical Network.

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