SEISMOLOGY ON ARTEMIS III: EXPLORATION AND SCIENCE GOALS

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A seismometer[1], integrated in the Early Apollo Scientific Experiment Package (EASEP), was deployed by the Apollo 11 astronauts during the first crewed landing on the Moon. EASEP was a simplified, solar-panel-powered version of the Apollo Lunar Surface Experiments Packages (ALSEPs) deployed later by Apollo 12[2] and 14-17 astronauts. The EASEP and four ALSEP stations were equipped with three-axis long-period and vertical-axis short-period seismometers in addition to other instruments. Apollo 17 astronauts deployed a gravimeter, and Apollo 14, 16, and 17 also carried geophones, enabling active-source seismology on the surface of the Moon in addition to passive listening. See [3] for sensor details.

Analyses of the Apollo seismic data have continued for the last 50 years and have revolutionized our understanding of lunar seismicity, the present impact rate on the Earth-Moon system, lunar internal structure[4–10], and dynamic evolution of the Moon. Discoveries made by Apollo seismology have fostered a suite of new science questions about the Moon, several of which are crucial for the safety of future permanent assets and astronauts near the South Pole, our understanding of the lunar interior, and the importance of the Moon-forming impact for conditions on early Earth, including habitability. A few of these key questions addressable by seismology are listed below.

• ***What is the seismicity near the South Pole?***

Although lunar seismicity is much less than that of Earth (Fig 1), shallow moonquakes are similar to intraplate earthquakes and might involve near-surface fault slip[11] sufficiently strong to trigger landslides[12]. One of the largest shallow moonquakes (SMQs), with moment magnitude ~4, occurred 6° from the lunar South Pole[13]. The event depth remains unknown, as well as the precise location of the fault system associated with this quake, leaving order of magnitude uncertainties for assessing the risks to surface habitats.

• ***What is the impact rate near the South Pole?***

Impacts were one of the major sources of Apollo seismic signals (Fig 2), and their flux can be measured by seismometers[14]. Large uncertainties remain on the flux of small meteoroids on the Moon, especially for those carrying energies sufficiently large to damage structures or EVA suits[15]. The expected flux varies from 10 to 300 impacts per decade per km^2 for impacts carrying as much kinetic energy as a bullet (2-3 kJ) and increases by eight for energies ten times smaller[14-15,17–19]. Impacts could also serve as sources for measuring shallow physical properties.

• ***What is the ground stability near the South Pole?***

Apollo seismometers were not able to resolve the lunar seismic noise, due to limitations on the acquisition systems available at the time (Fig 3b). The performances of future gravitational[16] and astronomical observatories deployed near the South Pole will depend on the seismic noise floor, which will be constrained to better than nrad and Ångström levels in tilt and displacement, respectively, and might be detectable at levels a factor of 10 smaller than Apollo[14] through careful human installation of seismic sensors.

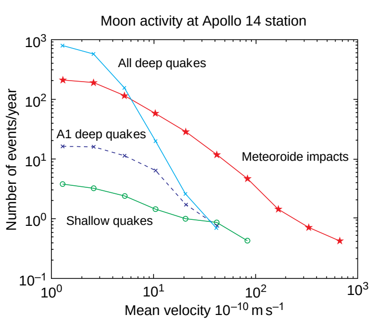

Figure 1. Seismic event rate (in events/year) on the Moon, as a function of ground velocity measured at the Apollo 14 site, ranging from 0.1 to 10 nm/s[17]. A factor of 10 better performance will resolve >1000 impacts and >5,000 deep moonquakes (DMQs) per year, and likely about 10 SMQs globally if an active fault system is present near the lunar South Pole.

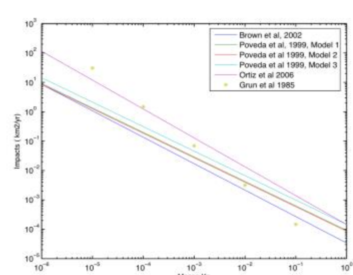

Figure 2. Estimates of the flux of small meteoroids,[18-20], demonstrating an uncertainty as high as an order of magnitude. Average lunar impact velocities are 20 km/s.

• ***What is the deep interior structure, from the crust to the core, as seen from South Pole?***

As argued by several advisory groups[21-22], understanding the deep interior structure of the Moon is an important priority but requires further information, including the characterization of any compositional mantle stratification; the size, composition, and shape of the core; the size of any solid inner core; and seismic anchoring of lunar crustal thickness models derived from lunar gravity and topography[23].The last two objectives will benefit from the South Pole location and the controlled seismic sources generated by the impact of the first stage or tanks of the Artemis Ascent Vehicle (Fig 3a-b). This artificial impact might be complemented by Earth-based impact flash detection of natural impacts, providing a strategy for determining the South Pole crustal structure even with only a single seismic station[24]. For deeper structure, a factor of 10 better sensitivity than Apollo and more than 3 months of monitoring will allow the detection of core-reflected phases from records of DMQs[25] at one station[26], given that stacks of energy are used over long operation times (Fig 3c).

These exploration and science goals will be achieved with modern, space-qualified seismic sensors and acquisition systems, with performances about a factor of 10 better than those achieved by Apollo. Ideally, the best configuration will be made with a central node equipped with high-sensitivity long- and short-period seismometers, surrounded, like Apollo 17, by three short-period seismometers or geophones at walking distance. This configuration will enable subsurface imaging, micrometeoroid flux determination, seismic noise monitoring including its wavefield gradient[27] and location of high-frequency seismic signals. This seismic station will have to operate for more than one year and would be not only the first long-term seismic observatory on the Moon since Apollo, but also the reference South Pole station of a future Lunar Geophysical Network[28–29]. The station would benefit from such other geophysical measurements as lunar laser ranging, electromagnetic sounding, and heat flow[30-31]. Mass and volume will be comparable to those of Apollo, despite the better performances. Flight readiness is demonstrated by the seismometers for several NASA missions in operation[32], in fabrication[33], and in development[34–36].

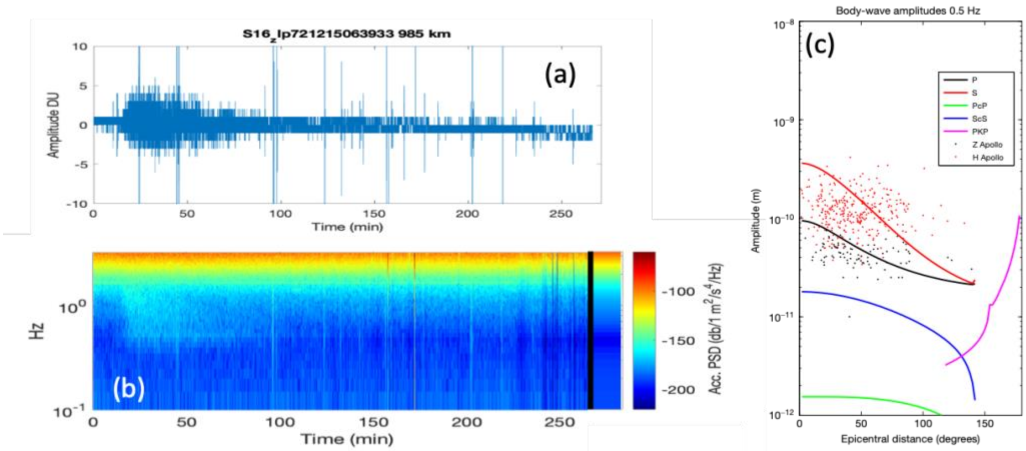

Figure 3. A factor of 10 better sensitivity than Apollo would capture the seismic signal generated by the Artemis ascent vehicle. (a) The detected but weakly resolved record of the impact of the Apollo 16 ascent vehicle at the Apollo 16 long-period seismometer. (b) A spectrogram, in acceleration power, shows the limitation of the 9-bit acquisition noise, indicated after the black line. (c) Amplitude sensitivity a factor of 10 better than Apollo will resolve core phases (e.g., ScS, PKP, PcP) on single records, in contrast to Apollo, which detected only direct P and S phases[17]. Red and black points are Apollo records of P and S phases, while the expected core phases were all below the instrument resolution and required stacking to detect.

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