Small Aperture Lunar Seismic Arrays (SALSAs). M.J. Fouch[1], E.J. Garnero[1], M.S. Thorne[2], P. Lin[1], N. Schmerr[3], R. Weber[4], M.S. Robinson[1], and H. Yu[1]; [1]Arizona State University, School of Earth and Space Exploration, Tempe, AZ 85287 (fouch@asu.edu); [2]University of Utah, Dept. of Geology & Geophysics, Salt Lake City, UT 84112, [3]Carnegie Institution of Washington, Dept. of Terrestrial Magnetism, Washington DC 20015, [4]U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ 86001.

Introduction: Understanding the origin and evolution of the Moon remains a major challenge, since direct interrogation of its interior is still significantly limited. Seismic analyses provide the most detailed picture of present-day internal elastic structure and sources of seismic energy, but collecting seismic data represents a unique logistical challenge which has been successful only in a limited capacity on the Moon.

Here we describe the potential enabled by deployments of Small Aperture Lunar Seismic Arrays (SALSAs), which builds on well-developed strategies of seismic data collection and analysis utilized in a broad range of seismic source and structural studies of Earth (e.g., [1]). We have recently suggested that SALSAs should be considered in the design of future lunar missions with seismic components [2]. Deployments of SALSAs will lead to significant enhancements of seismic signal quality well beyond improvements in seismic instrumentation alone. We are currently developing methods to evaluate SALSA configurations which will produce fundamentally better seismic datasets for use in constraining sources of seismicity and the internal structure of the Moon.

Apollo Passive Seismic Experiment Data: Data from the Apollo Passive Seismic Experiment (Apollo PSE) have been well studied (e.g., [3-5]), providing first-order information regarding the distribution and style of lunar seismic sources, the radial distribution of seismic wavespeeds, and estimates of crustal thickness variations (e.g., [4-6]). Based on these results and the obvious need for more information about the lunar interior, a compelling case has been made for deploying seismic networks on the Moon (e.g., [7-9]).

A profound challenge inherent in Apollo PSE data comes in the form of high amplitude ringing of seismic energy that persists following the first arrival (i.e., coda energy). This coda, which ranges in length from just a few to tens of minutes, has precluded clear analysis of distinct seismic phases that arrive after primary arrivals such as P and S waves. Later arrivals, such as those that may reflect off of or be transmitted through a lunar core, are therefore extremely difficult to observe. These later phases contain the essential information needed to further define and constrain the elastic structure of the interior. We note that new analyses are currently underway to examine Apollo PSE data for the presence of lunar core phases [10].

The lunar seismic coda is likely due to inherent structural characteristics of the Moon, including weak attenuation in the lunar interior and substantial scattering in highly fragmented regolith, dessicated crust, and lithospheric structure beneath the Apollo PSE instruments. New approaches to modeling seismic scattering in the lunar interior will help determine the nature of the coda signal [e.g., 11-13]. However, the problem of isolating seismic arrivals of interest contained within the coda will remain an inherent problem in single station deployments. Thus, significant changes in the way future seismic data are collected on the Moon, such as through SALSAs, are necessary to acquire fundamentally better seismic datasets relative to Apollo PSE data.

Array Seismology: The basic approach in multiple station analyses (known as “array seismology”) is to time shift and sum individual array element waveforms to form a composite stacked signal that corresponds to “aiming” the array’s focus to a specific incoming angle (direction from the body’s interior). Using array seismology, coherent signals are greatly enhanced relative to background noise, thus enabling detection of sources and structures that cannot be pursued with single station approaches from even the highest quality seismic data (i.e., low internal instrument noise, broadband instrument response, and low site noise). A SALSA thus can enable mapping of important internal horizons, including (but not limited to) the lunar crust/mantle and core/mantle boundaries. Further, a SALSA can be used to locate seismicity from lower magnitude events relative to single station detection thresholds.

Configuration of SALSAs: On Earth, small aperture arrays (~1-5 km station spacing) have been used to study Earth’s interior from the uppermost crust to the inner core (e.g., [14]), and are also used frequently for detecting and locating weak seismic sources (magnitudes ≤2.0) over a larger range of distances.

An example SALSA deployment configuration is shown in Figure 1. We note that the design of such an array must be fully evaluated via synthetic seismogram modeling to determine appropriate node spacing. To this end, we are currently evaluating SALSA designs (station spacing and numbers of stations) using a new synthetic waveform code which has been developed specifically for lunar applications [11,13].

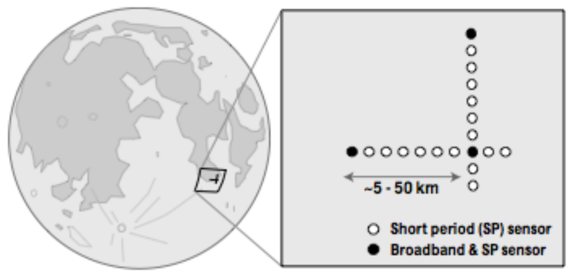

Figure 1: Schematic design of a Small Aperture Lunar Seismic Array (SALSA). The L-shaped design enables focusing of the array to any backazimuth without significantly limiting the array aperture. Ideally, broadband seismic sensors are included at the ends and the intersection of the array as noted in this figure, but this configuration is not a requirement for successful array seismology processing. The aperture and number of instruments in the array will be limited by the available payload and time in the field for SALSA deployment. Other array configurations are also feasible and can be developed to accommodate specific landing site requirements.

Primary scientific targets for SALSA analyses:

- The nature of the crust/mantle boundary and fundamental improvements to estimates of crustal thickness and composition.
- The location of other yet undiscovered layers and anomalous zones in the crust and mantle, including potential regions of partial melt.
- The location and state of the core.
- The geographical and depth distribution of lunar seismic sources (moonquakes and impacts).
- Specific regions of geologic interest such as the central far-side highlands, the Procellarum-KREEP region, and mare basalt regions such as Imbrium.

Logistical Advantages of SALSAs: We note that the significantly improved signals recorded from SALSAs would provide distinct advantages compared to single station deployments, and could be implemented in the design of regional or global lunar seismic networks. Examples of these advantages include:

- *Components of seismic networks*. SALSAs can be deployed as nodes of a regional or global network, providing significantly enhanced data at a site relative to single station deployments.
- *Rapid return of scientifically valuable data*. The enhanced signal to noise ratio of SALSA data can result in a higher quality dataset, since more seismic events will be recorded over a broader distance range from the array over a shorter period of time.
- *Improved moonquake detection*. Because SALSAs enable analysis of significantly enhanced seismic signals, smaller moonquakes can be detected and source locations can be determined with improved accuracy and precision.
- *Better boundary detection accuracy*. The location and relative differences between layers can be more accurately determined. Layers of weaker contrast can also be detected, which is not possible with single station deployments.
- *Reduced chance of failure*. If an element of a SALSA malfunctions, the array will continue to provide high-quality data. Single station deployments do not provide station redundancy.
- *Flexible deployment strategies*. SALSAs can be deployed by humans at outposts or in sortie missions, as well as by rovers over short time periods.

We note that a disadvantage of an individual SALSA is the inability to record lunar seismicity globally, which is also a problem for a single broadband instrument deployment. Most significant, however, is that a robotic lander or human sortie is required to deploy each element of the array. We therefore suggest that SALSAs should be considered as an important augmentation to some nodes of regional or global seismic array plans.

Deployment Strategies: The ongoing development of planetary seismic sensors (e.g., [15,16]) will enable deployment of robust, relatively low-cost, low-power, lightweight, small form factor instrumentation. These instruments could be deployed easily and quickly via a variety of means, thus enabling SALSA deployment. We envision that an individual SALSA could be deployed by rover, robot, or humans with an array aperture of ~5-10 km and perhaps more. For example, a single lander mission with a rover could install an entire SALSA in just a few weeks, and a human tended outpost in a matter of days.

References: [1] Rost S. and Thomas C. (2002) *Rev. Geophys., 40*, 2000RG000100. [2] Fouch M.J. et al. (2009) *LPS XL*, Abstract #2233. [3] Goins et al. (1981) *JGR, 86*, 378–388. [4] Bulow R. et al. (2007) *JGR, 112*, 2006JE002847. [5] Lognonné P. and Johnson C. (2007) *Treatise on Geophys*., *10*, Ch. 4. [6] Nakamura Y. (2005) *JGR 110*, 2004JE002332. [7] Wieczorek M. et al (2006) *Rev. Min. Geochem., 60*, 221-364. [8] Neal C.R. et al (2004) *LPS XXXV,* Abstract #2093. [9] Johnson C.L. et al. (2008) *LPS XXXIX*, Abstract #2288. [10] Weber R. et al. (2010) this meeting. [11] Thorne, M.S. et al. (2009) *NLSC II*. [12] Lawrence J. and C. Johnson (2009) *NLSC II*. [13] Thorne M.S. et al. (2010) this meeting. [14] Rost S. and Garnero E.J. (2004) *EOS, 85*, 305-306. [15] Lognonné P. et al. (2008) *LPS XXXIX*, Abstract #2099. [16] Yamada R. et al. (2005) *LPS XXXVI*, Abstract #1715.