# A NEW PARADIGM FOR SEISMIC EXPLORATION OF THE MOON, MARS, AND BEYOND

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**Introduction:** Understanding the origin and evolution of planets remains a major challenge since direct interrogation of planetary interiors other than Earth is either limited or not (yet) available. 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 broadly only on Earth and in a limited capacity on the Moon.

Here we propose a new approach to deployments of planetary seismic instrumentation in the form of Small Aperture Seismic Arrays (SASAs), which builds on well-developed strategies utilized in a broad range of seismic source and structural studies of Earth (e.g., [1]). We submit that the SASA approach should be strongly considered in the design of future missions which include seismic instrumentation. Deployments of SASAs will lead to profound enhancement of seismic signal quality well beyond improvements in seismic instrumentation alone. SASAs can thus produce fundamentally better seismic datasets for use in constraining sources of seismicity and the internal structure of planets. In this abstract, we focus on new strategies for lunar seismic exploration, but note the natural extensions of this approach to Mars and other planetary bodies.

**Lunar Seismic Data:** Data from the Apollo Passive Seismic Experiment (APSE) are well studied (e.g., [2,3]) and have provided 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 a new seismic network on the Moon (e.g., [7,8]).

A profound challenge inherent in APSE data, however, comes in the form of high amplitude ringing of seismic energy that persists following the first arrival (i.e., coda energy). This coda, which can approach 10 minutes in length and even longer for some events, precludes confident analysis of distinct seismic phases that arrive close in time to the first arrival. These later arrivals are therefore extremely difficult to observe, yet they contain the essential information needed to further define and constrain the elastic structure of the interior. The ringing 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 APSE instruments. Deployments of single modern seismometers may help characterize the nature of the coda signal, but the problem of isolating seismic arrivals of interest contained within the coda will remain. Without a significant change in the way future data are collected on the Moon relative to APSE data, new lunar seismic deployments will probably not yield fundamentally better datasets. We are thus compelled to consider new approaches to recording seismic data on the Moon.

**Benefits of SASAs:** On Earth, arrays of closely located seismometers (~1-5 km station spacing) are frequently used to extract coherent seismic signals below single station noise levels. SASAs have been used to study Earth's interior from the uppermost crust to the inner core (e.g., [9]). SASAs are also used frequently for detecting and locating weak seismic sources (magnitudes ≤2.0) over a larger range of distances, such as in the International Monitoring System (IMS) used for Comprehensive Test Ban Treaty (CTBT) monitoring.

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). The primary strength of array seismology is to image impedance contrasts which generate reflections and phase conversions. A SASA can thus enable mapping of important internal horizons, including (but not limited to) the lunar crust/mantle and core/mantle boundaries. Further, a SASA can be used to locate seismicity from lower magnitude events relative to single station detection thresholds.

**New Seismic Array Strategy: Small Aperture Lunar Seismic Arrays (SALSAs):** We propose that one or more deployments of a lunar SASA, hereafter termed a SALSA, is the solution to enable recording of the necessary lunar seismic dataset that will provide a fundamentally improved knowledge of the lunar interior and, in some cases, better constraints on lunar seismic sources. An example SALSA deployment configuration is shown in Figure 1.

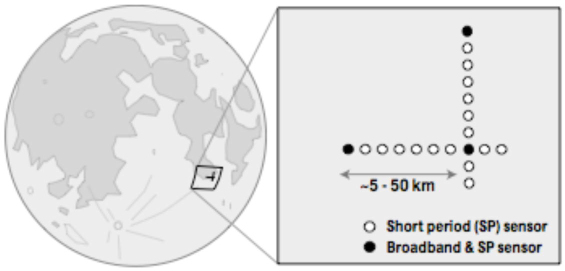

**Figure 1:** Schematic design of a Small Aperture Lunar Seismic Array (SALSA). The L-shaped design enables focusing of the array to any backazimuth without significantly limiting the array aperture. Ideally, broadband seismic sensors are included at the ends and the intersection of the array as noted 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. We note that 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.

**Logistics/Deployment Strategies:** To date, neither global nor dense arrays of seismometers have been deployed for lunar exploration due to challenges of cost and logistics. The ongoing development of planetary seismic sensors (e.g., [10-12]) 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.

**Advantages of SALSAs:** We note that the significantly improved signals recorded from SALSAs would provide distinct advantages compared to deployments of regional or global arrays of individual sensors. Examples of these advantages include:

- *Cost-effectiveness*. A SALSA can be deployed in a single mission using a variety of flexible deployment strategies.
- *More rapid return of scientifically valuable data*. The enhanced signal to noise ratio of SALSA data will 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.
- *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. It is not clear how SALSAs could be deployed via the International Lunar Network (ILN) without redesigning the program architecture.

We note that some disadvantages of an individual SALSA include the inability to record lunar seismicity globally or utilize normal modes to image long wavelength structures in the lunar interior. Most significant, however, is that a robotic lander or human sortie is required to deploy each element of the array. We believe, however, that given the overall expense of collecting seismic data on the Moon, the advantages of SALSA far outweigh the disadvantages.

Finally, we suggest that as plans for a global seismic array on the Moon, Mars, and other bodies are developed that, where feasible, SASA nodes are considered in place of individual sensor installations.

**References:** [1] Rost S. and Thomas C. (2002) *Rev. Geophys., 40*, 2000RG000100, [2] Goins et al. (1981) *JGR, 86*, 378–388. [3] Nakamura Y. et al. (1981) *Tech. rep. #18*, UT Austin. [4] Bulow R. et al. (2007) *JGR, 112*, 2006JE002847. [5] Lognonné P. and Johnson C. (2007) *Treatise on Geophys.*, *10*, Ch. 4. [6] Wieczorek M. et al (2006) *Rev. Min. Geochem., 60*, 221-364. [7] Neal C. R. et al (2004) *LPS XXXV,* Abstract #2093. [8] Johnson C. L. et al. (2008) *LPS XXXIX*, Abstract #2288. [9] Rost S. and Garnero E. J. (2004) *EOS, 85*, 305-306. [10] Lognonné P. et al. (2008) *LPS XXXIX*, Abstract #2099. [11] Yamada R. et al. (2005) *LPS XXXVI*, Abstract #1715. [12] ASU has recently teamed with MET Technology, Inc., to develop terrestrial and planetary microseismometers.