ENABLING TECHNOLOGIES FOR A FUTURE LUNAR & PLANETARY GEOPHYSICS NETWORK.
C. Neal,1 D. Currie2, R. Grimm3, S. Kedar4, S. Nagihara5, M. Siegler6, R. Weber7, and K. Zacny8. 1University of Notre Dame (neal.1@nd.edu), 2University of Maryland, 3Southwest Research Institute, 4NASA-JPL, 5Texas Tech Univ., 6Planetary Science Institute, 7NASA-MSFC, 8Honeybee Robotics.

Introduction: While recent re-analysis of geophysical data from the Apollo missions have advanced our understanding of the Moon’s internal structure [1], seismic activity [2], heat flow budget [3,4], and electrical conductivity [5], significant unresolved questions remain. General models of the processes that contributed to the formation of the present-day lunar interior are currently being challenged (e.g., [6,7]) and many questions remain as to lunar origin and evolution. While reinterpretation of the Apollo seismic data has led to identification of a lunar core [1], it has also produced a thinning of the nearside lunar crust from 60-65 km in 1974 [8], to 45 km in 2002 [9], 30 km in 2003 [10], and 31-38 km in 2006 [11]. With regard to the deep interior, Apollo seismic data have been used to infer the presence of garnet below ~500 km [12,13], but the same data have also been used to identify Mg-rich olivine instead [14]. Clearly, a global lunar geophysical network is required to define the nature of the lunar interior. Such a network would also add tremendous value to the GRAIL and SELENE gravity data.

The small size of the Moon means that it has preserved its primary differentiation. It represents an end member in terrestrial planet differentiation so identifying the global interior structure and composition of the Moon is critical for Solar System science. Identification of lateral and vertical heterogeneities, if present, will yield important information about, for example, the presence of a global lunar magma ocean (LMO) as well as investigating the stratification in the mantle from LMO cumulate overturn [15]. Advancing our understanding of the Moon’s interior is critical for addressing these and many other important lunar and Solar System science and exploration questions.

In 2007, the National Academies [16] designated understanding the structure and composition of the lunar interior (to provide fundamental information on the evolution of a differentiated planetary body) as the second highest priority lunar science concept that needed to be addressed. Fueled by this endorsement, two major efforts at establishing a new Lunar Geophysical Network (LGN) followed. 2008: NASA-SMD Planetary Science Division formulated the International Lunar Network (ILN) mission concept [17], which attempted to enlist international partners to enable the establishment of a global geophysical network on the lunar surface, but the effort never materialized with a change in Space Policy in 2010. 2010: the LUNETTE single-node geophysics lunar mission was proposed to NASA as a Discovery-class mission [18], but lost out to the single-node InSight Mars geophysical observatory [19]. It was found that a true network consisting of a minimum of four long-lived geophysical stations would not fit within the cost cap of a Discovery-class mission, and in 2013 the Planetary Decadal Survey recommended that NASA include the Lunar Geophysical Network (LGN) for a New Frontiers (NF)-class mission in the decade 2013-2022, as part of the NF-5 call. This is described in detail on pages 130-132 of [20] and summarized on page 15: “This mission consists of several identical landers distributed across the lunar surface, each carrying instrumentation for geophysical studies. The primary science objectives are to characterize the Moon’s internal structure, seismic activity, global heat flow budget, bulk composition, and magnetic field.” With the NF-4 call poised for release at the time of writing this abstract, the time is now to take stock of the current status of enabling technologies for a new LGN.

Better than Apollo: The Moon represents the only planetary body, other than Earth, for which we have geophysical data (so far). A future LGN should be better than and learn from the Apollo experience. Each station should contain a seismometer, heat flow probe, electromagnetic sounding instrumentation, and a laser retroreflector for nearside stations.

Seismometer: the Apollo passive seismometer [21] consisted of three long period sensors (X, Y, Z, all with detection limits of 0.3nm at 0.004-2 Hz) and one short period sensor (Z with a detection limit of 0.3nm at 1 Hz). The seismometer for the LGN needs to have ≥4 sensors that have at least an order of magnitude better sensitivity than that used during Apollo and over a much broader frequency range (0.1 to >10 Hz).

Heat Flow: Apollo heat flow was measured at the Apollo 15 and 17 sites and consisted of two probes ~11 m apart, with each probe consisting of two sections reaching 1.5-m and 2.4-m depths, respectively [22]. Measurements of absolute temperature were to ±0.05K. Thermal conductivity (0.009-0.014 W/mK) was determined for two depth intervals with ~15% accuracy from modeling the downward propagation of annual thermal waves [22]. The instrument used by LGN should be able to measure temperature every 20 cm to a depth of 3 meters and a relative accuracy of 0.01K. Measurements should be taken every hour. Thermal conductivity should be determined at several intervals (at least every 50 cm).

Electromagnetic Sounding (EMS): Wideband magnetic fields were measured at the surface by Apollo 12,
15, and 16, and from orbit on Apollo 15 and 16. Electrical conductivity of the mantle was determined from the transfer function between Explorer 35 and Apollo 12, but suitable spatial and temporal overlaps for the transfer functions for the other stations, as well as data degradation, have limited the robustness of EMS [23]. A dense magnetometer network would enable EMS by gradiometry (geomagnetic depth sounding). Better yet, measurement of electric and magnetic fields (magnetotellurics) provides an independent conductivity profile at each site. Natural-field variations can be supplemented by artificial fields (transmitters) for better resolution of the upper mantle/lower crust.

Lunar Laser Ranging: LLR is the only Apollo experiment that is ongoing. Laser retroreflectors were placed by the Apollo 11, 14 and 15 missions and the two Soviet Lunokhod rovers (Luna 17 and 21 missions) also carried retroreflectors. The restricted range of the LLR network means tidal librations are poorly constrained. The variations of pole direction, physical librations, and solid-body tidal distortions provide information about the Moon. Expansion of the network with the next generation of retroreflectors will constrain tidal librations. The new retroreflectors must be at least a factor of two better return signal.

Science: Integrating datasets obtained by the geophysical network allows a comprehensive examination of the structure and composition of the lunar interior. For example, the heat flow probes yield crustal estimates. Combined with EMS, the temperature profile of the deep interior can be modeled along with mineralogy. The seismic and LLR data also yield structure and compositional information of the lunar interior and the high fidelity data would enhance the usefulness of the GRAIL and Selene gravity data. The network must be globally distributed and last at least 10 years.

Technology Development: There are ongoing efforts within the United States to improve planetary seismometers, heat flow probes [24,25], and corner cube laser retroreflectors [26]. In terms of magnetometers and electrodes, the instruments are developed, but the deployment mechanism will need some refinement.

During the ILN effort some lander development was pursued at MSFC, but geophysical lander technology and instrument deployment still requires fine tuning. However, given that there are several commercial transportation companies that may be available to deliver packages to the lunar surface, this capability is currently being developed by the commercial sector.

Maybe the biggest issue is power supply. Ideally these LGN stations should have a minimum life of 10 years. The longer the time these stations are active, the greater the likelihood that more stations could be added by subsequent launches, either by international cooperation (i.e., as in ILN), the United States, and/or commercial entities. Power becomes critical in enabling network longevity, thus also enabling the addition of stations to the network over time. Development of highly efficient nuclear power sources (e.g., $^{238}$Pu Radioisotope Thermal Generators) with multi-decadal capabilities are enabling for creation of multi-station geophysical and other long-lived monitoring networks (e.g., space weathering, exosphere variations, etc.).

Vision. The need for the LGN has been recognized by the last decadal survey [20]. Commercial landers could carry additional stations to enhance the network and/or create local networks in areas of specific interest. However, by 2050 human presence should be in the lunar vicinity if not on the lunar surface. It is critical that the LGN be established prior to renewed human lunar activity because we currently do not know the exact locations or causes of the shallow moonquakes – the largest magnitude seismic events recorded by Apollo (at least 1 event/year of magnitude ≥5; [27,28]). Establishing infrastructure near shallow moonquake epicenters needs to be avoided.

Establishment of the LGN prior to renewed human activity can allow the effect exploration has on the lunar environment to be studied. Enhancing LGN stations with advanced dust detectors and mass spectrometers (e.g.) will show how the environment responds to multiple landings in a month, mining activities, and sustained activity in one or several regions. This would address Objective Sci-A-1 of the LEAG LER [29].