THE RATIONALE FOR DEPLOYMENT OF A LONG-LIVED GEOPHYSICAL NETWORK ON THE MOON

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The Inner Planets Panel, NRC Decadal Survey for the Planetary Sciences Division,
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INTRODUCTION

This white paper focuses on the scientific rationale for deploying a global, long-lived network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core. The information will allow the examination of planetary differentiation that was essentially frozen in time at ~3-3.5 Gyr. Such data are critical to understanding the early differentiation processes that occur in the planets of the inner Solar System and for understanding the collision process, which generated our unique Earth-Moon system. These geophysical observations of the Moon will yield a wealth of knowledge from regions heretofore inaccessible using the Apollo database. Data collected over a minimum period of 6 years (covering one lunar tidal cycle and hopefully more) will yield information on the nature and evolution of the lunar interior using a combination of seismic, heat flow, laser ranging, and magnetic field/ electromagnetic sounding data, and will help to better understand the Moon environment, including the meteoritic hazards. These data are required in addition to the observations made by the Apollo Lunar Surface Experiments Packages or ALSEPs (at Apollo 12, 14, 15, 16, and 17) and where extended by the Lunakhod 2 retroreflector (Fig. 1; Lunakhod 1 retroreflector is no longer functioning). The ALSEPs contained a variety of different experiments that produced significant information regarding the nature of the lunar surface environment as well as the lunar interior. The impact of these data has been hamstrung by the fact that the ALSEP stations were clustered in the equatorial regions of the Moon on the near side within the proximity of the Procellarum KREEP Terrane [1]. This is particularly significant for understanding the nature of the deep lunar interior (via seismicity and laser ranging) and for interpreting heat flow.

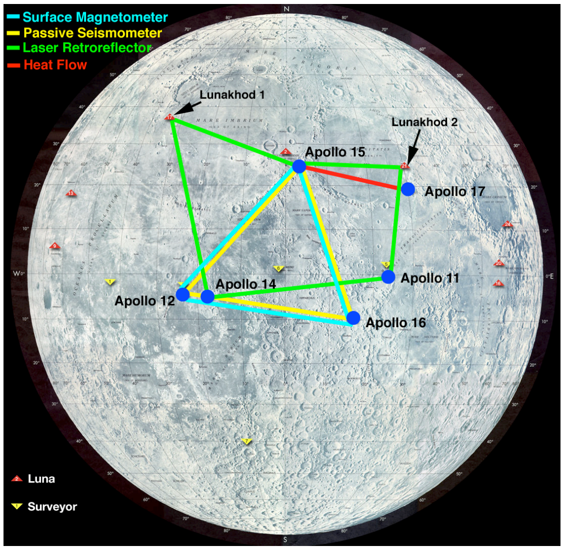

Figure 1: Location of lunar landing sites and the ALSEP stations. Instruments deployed at multiple sites are linked.

BACKGROUND – SURFACE AND ORBITAL DATA

Apollo Passive Seismic Experiment (PSE – [2,3]): These seismometers were deployed at every Apollo site, except Apollo 17. However, the instrument at Apollo 11 provided data for only 21 days. A network of four seismometers was completed in April 1972 (Fig. 1), and operated until they were all switched off on 30 September 1977. During the time the network was operational, it clearly demonstrated that the Moon exhibits seismic activity on a similar scale to that of an intraplate setting on Earth [4-7]. Four types of lunar seismic events have been defined from the Apollo PSE seismic database:

Thermal moonquakes – related to diurnal temperature changes; the smallest of all seismic events [8].

Deep moonquakes – originating between 700-1,200 km within the Moon and the most abundant (>7,000 events recognized; e.g., [9-14]), with Richter scale magnitude <3. Their origin is unclear, but their temporal occurrence suggests they are related to tidal influences.

Meteoroid impacts - these surface seismic events exhibit characteristic amplitude variations with distance and >1,700 events representing meteoroid masses between 0.1 and 10,000 kg were recorded between 1969 and 1977 [15-20].

Shallow moonquakes – with inferred focal depths between 50 and 200 km, these are the strongest type of moonquake, with seven of the 28 recorded events being greater than magnitude 5 [4,6,7,21].

Heat Flow Experiment (see Langseth et al., 1970; Fig. 1). Three heat flow experiments were attempted – at Apollo 15, Apollo 16, and Apollo 17 [22,23]. The attempt to deploy the Heat

Flow Experiment at Apollo 16 failed due to a broken cable linking the heat flow electronics to the ALSEP Central Station. The depths of penetration were ~160 cm at Apollo 15 and ~250 cm at Apollo 17. Tens of thousands of terrestrial heat flow measurements have been made on the land and at ocean bottom [24]. In contrast there are only four measurements from the Moon [23]. To determine the interior heat flux to an accuracy better than Apollo, multiple heat flow measurements in a given geologic environment are required to average out local variations due to topography and subsurface variations. A single measurement would be very useful, but would also have very large error bars. On the Moon, two heat flow measurements were made (at each site) about 10 meters apart and differed by ~30% [23], which could be due to variances in thermal conductivity (dependent upon texture, density, and temperature; [25]). Ideally three or more measurements should be made in holes spaced 10s to 100s of meters apart, at depths that extend from the surface to at least 1 m below the penetration depth of the annual thermal wave (2-3 m target depth) and use this to estimate the thermal diffusivity.

Lunar Surface Magnetometer (LSM – [26]). The LSM was deployed as part of the ALSEP by the Apollo 12, 15 and 16 missions (Fig. 1) and the network was switched off on 14 June 1974. The LSMs, along with Apollo subsatellites and Explorer 35, were used to study:

a. *Structure and composition of the lunar interior*. The interaction between the moon and the solar wind produces an induced electromagnetic (EM) field that depends on internal structure. The magnetic transfer function between the Apollo 12 LSM and the distantly orbiting Explorer 35 satellite was used to constrain core size, mantle free-iron and alumina abundance, and interior temperature and thermal evolution (e.g., [27-29]).

b. *Surface remnant magnetic fields*. Portions of the lunar crust are highly magnetized (e.g., [30-32]), which, when considered together with sample paleointensities, indicates the existence of an early high-field epoch. Other strong magnetic anomalies are correlated with basin ejecta materials [27] and with unusual albedo markings of the Reiner Gamma class (e.g., [33]).

c. *Lunar EM environment*. The lunar atmosphere and ionosphere on the geomagnetic tail, velocity and thickness of the magnetospheric boundaries were investigated [34,35].

Paleointensity estimates for returned samples suggested the existence of a "high-magnetic-field epoch" during the 3.6 to 3.9 Gyr period interpreted as reflecting magnetization of the samples in a lunar dynamo field [36]. However, new paleomagnetic studies re-open the discussion of a possible early lunar dynamo. First, paleomagnetic measurements using modern laboratory methods, together with a re-evaluation of existing measurements, indicate that the although some samples with ages of 3.6 to 3.9 Ga are strongly magnetized, the magnetizations are not consistent with a primary thermal remanence, acquired in a lunar dynamo field [37]. Second, other new paleointensity experiments have been used to suggest a lunar dynamo at ~4.2 Gyr [38]. Thus, current paleointensity measurements do not support the existence of a 3.9–3.6 Ga lunar dynamo with 100 mT surface fields, but still leave open the possibility of an earlier dynamo, results that are in better agreement with satellite measurements of crustal magnetism and that presents fewer challenges for thermal evolution and dynamo models. Surface magnetometer measurements showed that the strongest surface fields (> 300 nT) were measured near the Apollo 16 landing site, a region dominated by impact basin ejecta materials [27]. Low-altitude orbital measurements with instruments on the Apollo subsatellites and the Lunar Prospector spacecraft showed that anomalies on the lunar near side correlated often with impact basin ejecta materials including the Fra Mauro Formation, the Cayley Formation, and the Descartes mountains [39-43]. The global distribution of orbital anomalies was characterized by large concentrations of strong anomalies in regions antipodal to the four youngest large impact basins [43-45]. Correlative studies have also shown that the strongest individual anomalies often occur coincident with unusual albedo markings of the Reiner Gamma class [33,46-48].

Lunar Laser Ranging (LLR) (see [49,50]): Retroreflectors were deployed by Apollo 11, 14, and 15, and were also fitted to the Soviet rovers Lunokhod 1 and 2 (Luna 17 and 21, respectively; Fig. 1) to allow laser ranging. Although Lunokhod 1 is not an operational site, there have now been ~40 years of increasingly accurate laser ranges that indicate that the lunar core is at least partly fluid (e.g., [49-55]). LLR allows an evaluation of the deep lunar interior that extends below the reach of the current geophysical data sets, as it provides information on interactions at the core-mantle boundary, as well as the Moon's tidal response and tidal dissipation. Dissipation at the core-mantle boundary suggests that the core is fluid and has a radius that is about 20% of the whole Moon (e.g., [54-56]). In addition, laser retroreflectors deployed on lunar orbiters surveying the Moon would be very useful to establish an accurate and absolute positioning reference between near side lunar measurements (altimetry, gravity field, surface temperature maps, etc) and the International Terrestrial Reference Frame (ITRF) adopted on Earth. Past and current generations of lunar orbiters have not been equipped with retroreflectors, except for NASA's Lunar Reconnaissance Orbiter, which has been recently tracked successfully by the Space Geodesy Facility at Herstmonceux, UK. The fundamental physics questions are addressed in a separate white paper to the Inner Planets panel by Stephen Merkowitz et al. entitled "The Moon as a Test Body for General Relativity" and lunar laser ranging is addressed in the white paper "Lunar Science and Lunar Laser Ranging"

FUNDAMENTAL QUESTIONS STILL REMAIN

Lunar Seismicity:

a. The narrow area covered by the PSE (Fig. 1) meant that comparisons could not be made between seismic waves (from the same event) that passed through the deep interior of the Moon with those that did not. The mineralogy and temperature of the upper mantle, nature of the lower mantle, the size, state, and composition of a lunar core, and the existence of an inner core remain to be unequivocally addressed (see [20,57-62]).

b. Estimating epicenter locations for seismic events requires knowledge of the lunar interior seismic velocity structure in terms of both radial and lateral variations; the small areal extent of the APSE means that the average radial structure is not constrained below ~1000km, and that lateral variations cannot be resolved. This directly affects compositional inferences. For example, seismic data have been interpreted to indicate the presence of garnet in the lower lunar mantle (e.g., [63-65]). However, the same seismic data were also interpreted to represent an increased proportion of Mg-rich olivine (Nakamura et al., 1974; Nakamura, 1983).

c. Variations in the lunar crust (mineralogical and thickness) have been difficult to estimate away from the PSE network sites. Although recent work by [66] employed a Markov chain Monte Carlo algorithm along with seismic wave arrival times from 7 artificial impacts and 19 meteoroid impacts to estimate crustal thickness variations, studies of this type are still limited because the seismic arrivals from such impacts are highly uncertain. Questions such as what is the nature of the crust between different terranes remain unanswered.

d. While >7,000 deep moonquakes were recorded, clustered in 318 source regions called nests, only three nests are undisputedly on the far side These far side nests exhibit no clear shear wave arrivals at distant stations suggesting there is a plastic zone located somewhere in the deep lunar interior. Three major questions remain: (i) Are there other nests on the lunar far side that were not detected by the Apollo PSE? In other words, are they distributed globally? (ii) What is the nature and extent of the purported plastic zone and what implications does this have for lower mantle structure? (iii) What is the triggering mechanism for deep moonquakes?

e. The exact locations and origin(s) of shallow moonquakes are unknown. While they appear to be associated with boundaries between dissimilar surface features (e.g., impact basin rims – [21]), the exact origin of these events is still unclear. A recent development suggests shallow Moonquakes may originate from interaction of the Moon with nuggets of high-energy particles ("strange quark matter") originating from a fixed source outside the solar system [67]. As these are the largest of the lunar seismic events and may have implications for any permanent lunar habitat, these are not only important scientific questions, but also important for exploration initiatives. Secondary questions include: (i) Do they pose any risk to a lunar habitat? (ii) How does the lunar regolith affect transmission of seismic energy? (iii) What is the effect of seismic shaking in a low gravity environment? (iv) Can we detect passing of postulated "strange quark matter" through the Moon [67]?

f. The seismic discontinuity at 500-600 km depth might be a signature of the base of the lunar magma ocean (LMO), but is this a global feature? Answering this question has implications for our current understanding of lunar evolution via the LMO. If this discontinuity is not global, the LMO model may need to be revised. If it is global, it suggests that the Moon did not completely melt, which has implications for the thermal evolution of the Moon.

Lunar Heat Flow: Scientific questions that are unresolved with regard to lunar heat flow center around better defining the global heat flow budget for the Moon in order to better constrain the thermal evolution of our only natural satellite, as well as the bulk composition of the Moon in terms of radioactive heat-producing elements:

a. Are the two data points of lunar heat flow representative? Indeed, [23] emphasized the need for extended areal (global) coverage to define potential variations in heat flow. The next heat flow measurements should be well inside terrane boundaries.
b. What is the heat flow from highlands regions? While Apollo 17 landed in the Feldspathic Highlands Terrane, the heat flow was measured in a mare.
c. Is the Apollo 15 heat flow result representative of the Procellarum KREEP Terrane?
d. Do different lunar terranes have unique heat flow budgets?
e. Can a measurement within the South Pole-Aitken basin yield a mantle heat flow measurement as opposed to a crust + mantle signature elsewhere?

Lunar Surface Magnetic Measurements: The Apollo surface magnetometer measurements were obtained at locations that were not ideal for testing hypotheses about the origin of the lunar crustal magnetic field. Unresolved scientific questions include:

a. What is the electrical conductivity structure of the outermost 500 km of the moon and its lateral variations? This zone is important as it contains a possible transition from upper-mantle melt residuum to the pristine lower mantle, as well as differences in crustal composition and lithospheric thickness and heat flow associated with the primary geological provinces of the moon.
b. What it is the deep structure of the moon and its heterogeneity? A tighter average mantle conductivity profile will better constrain temperature and composition. Lateral variations in internal temperature could be evidence of mantle convection. Very long-period measurements could distinguish a molten silicate from an iron core.
c. Are basin ejecta the dominant sources of lunar magnetic anomalies? Although correlative studies suggest this is the case, ground truth evidence is so far limited to the Apollo 16 landing site, which did not exactly coincide with a strong orbital anomaly.
d. What are the origins of the unusual albedo markings associated with strong lunar magnetic anomalies? Unlike most high-albedo markings on the Moon, the Reiner Gamma-type markings do not appear to be associated with a fresh young crater. Solar wind ion bombardment may play a role in the darkening with time of freshly exposed lunar surface materials, so that the strongest lunar magnetic anomalies are able to stand off the solar wind producing regions on the surface that are shielded from the solar wind ion bombardment. Deployment of a surface magnetometer at the Descartes mountains site and the Reiner Gamma site would directly address the following questions: (i) What are the sources of lunar magnetic anomalies? (ii) What is the origin of the Reiner Gamma-type albedo markings? The first question has implications for the origin of the magnetizing field(s) since deep-seated sources would strongly suggest a core dynamo while surficial, rapidly forming sources would allow the possibility of transient fields (as well as a core dynamo). The second question has implications for the causes of optical maturation on airless silicate bodies in the inner solar system.

Lunar Laser Ranging: Although there have been 40 years of lunar laser ranging research, these measurements still do not have conclusive answers to such questions as what is the accurate size and density of the lunar core? Is there a solid inner core? What stimulates the free wobble, the Chandler wobble analog? These questions may be addressed if there were a wider geographical spread in ranging stations on the surface of the Moon, as it would improve the determination of three-dimensional rotation and tides and the geophysical quantities derived from them. New retroreflectors have been designed for more accurate ranges. Longer data spans benefit some solution parameters, including fluid core moment of inertia. Expanding the number of retroreflector sites and their geographical coverage will allow a better understanding of the fluid core/solid mantle boundary conditions as well as the presence/absence of a solid inner core [49,50], as well as address several fundamental physics questions. The fundamental physics questions are addressed in a separate white paper to the Inner Planets panel by Stephen Merkowitz et al. entitled “The Moon as a Test Body for General Relativity”.

SUMMARY AND CONCLUSION

This white paper demonstrates that a globally distributed, long-lived geophysical network on the lunar surface with each station containing a sensitive broad-band seismometer (about 10 times more sensitive than Apollo), heat flow probe(s), laser magnetometer, and retroreflector, will address many of the fundamental lunar science questions that remain. In addition, these data will also allow the fundamental solar system process of planetary differentiation to be investigated, which can be extrapolated to model the evolution of other inner solar system planets. This is because the Moon represents an end member in this process in that its evolution was effectively terminated early in its history. In addition, any future lunar geophysics network should use the Moon as a detector for extra-lunar materials, including but not limited to meteoroid impacts and strange quark matter. Whether this network is deployed via the proposed International Lunar Network (ILN SDT Report, 2009) remains to be seen, but the US contribution will in any case benefit from international collaboration and missions from JAXA and possibly ESA and RKA. It is critical to inner Solar System science that a geophysical network be established on the Moon.

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