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

Submitted to

The NRC Committee on the Scientific Context for the Exploration of the Moon

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INTRODUCTION

Geophysical observations of the Moon via a global and long-lived network of stations will yield a wealth of knowledge from regions heretofore inaccessible using the Apollo database. Data collected over a period of at least 6 years (covering one lunar tidal cycle) will yield information on the nature and evolution of the lunar interior using a combination of seismic, heat flow, and magnetic field data. 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 – see Fig. 1). The ALSEPs contained a variety of different experiments (Table 1) 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. This is particularly significant for understanding the nature of the deep lunar interior.

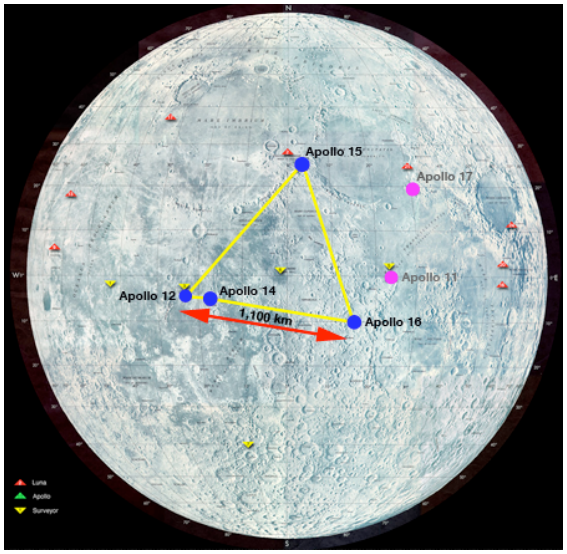

Figure 1: Location of lunar landing sites and the Apollo passive seismometer network.

Table 1: ALSEP Experiments and definitions by Apollo Landing Site

Acronym	Definition	Apollo Mission
ASE	Active Seismic Experiment	14, 16
CCIG	Cold Cathode Ion Gauge experiment	12, 14, 15
HFE	Heat Flow Experiment	15, 17
LACE	Lunar Atmospheric Composition Experiment	17
LDD	Lunar Dust Detector	12, 14, 15
LEAM	Lunar Ejecta And Meteorite (experiment)	17
LSG	Lunar Surface Gravimeter	17
LSM	Lunar Surface Magnetometer	12, 15, 16
LSP	Lunar Seismic Profiling experiment	17
PSE	Passive Seismic Experiment	11, 12, 14, 15, 16
SIDE	Suprathermal Ion Detection Experiment	12, 14, 15
SWS	Solar Wind Spectrometer	12, 15

This white paper is written in response to the questions raised by the NRC panel on Lunar Science Priorities and Goals after the recent meeting on June 21st, 2006. It focuses on the need for the deployment of a network of geophysical instruments to understand the nature and evolution of the Moons' interior from the crust to the core. These instruments will investigate lunar seismicity, heat flow, and magnetism.

BACKGROUND

Apollo Passive Seismic Experiment (PSE - see Latham et al., 1969, 1970): These seismometers were deployed at every Apollo site, except Apollo 17. However, the instrument at Apollo 11 failed after 21 days, presumably because it did not contain the thermal blanket that later versions did. A network of four seismometers was completed in April 1972 (Fig. 1), and operated until they were all switched off due to cost-cutting measures on 30 September 1977. During the time the network was operational, it clearly demonstrated that the Moon was seismically active, albeit on a smaller scale than Earth (e.g., Nakamura, 1980; Nakamura et al., 1982). However, the Moon exhibits seismic activity on a similar scale to that of an intraplate setting on Earth (Nakamura, 1980; Goins et al., 1981; Oberst, 1987; Oberst and Nakamura,

1992; see Fig. 2). Four types of lunar seismic events have been defined from the Apollo PSE seismic database:

1) Thermal moonquakes – related to diurnal temperature changes and are the smallest of all seismic events (Dunnebier and Sutton, 1974a).
2) Deep moonquakes – originating between 700-1,200 km within the Moon and are the most abundant (>7,000 events recognized; e.g., Nakamura et al., 1974; Nakamura 2003, 2005; Bulow et al., 2004), with Richter scale magnitude <3. Their origin is unclear, but may be related to tidal influences, although there are no clear correlations between deep moonquakes and tidal effects.
3) Meteoroid impacts - these surface seismic events exhibit characteristic amplitude variations with distance and >1,700 events representing meteoroid masses between 0.1 and 1,000 kg were recorded between 1969 and 1977 (events generated by smaller impacts were too numerous to be counted - Duennebier and Sutton, 1974b; Duennebier et al., 1975, 1976; Latham et al., 1978; Oberst and Nakamura, 1989, 1991).
4) Shallow moonquakes (Fig. 2) – 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 (Nakamura et al., 1979: Nakamura, 1980; Oberst, 1987; Oberst and Nakamura, 1992).

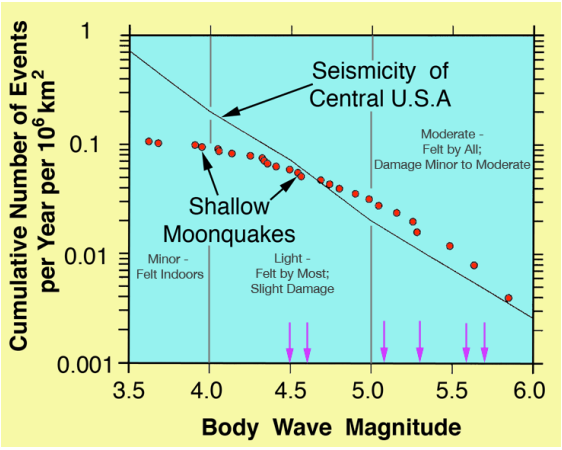

Figure 2: Comparison of shallow moonquake and intraplate earthquake activity. Modified from Oberst and Nakamura (1992).

While a lot of data were collected by the PSE network major scientific questions remain unresolved.

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 nature of the lower mantle and the existence, size, and composition of a lunar core remain to be unequivocally addressed (see Toksöz et al., 1974; Nakamura, 1983; Khan et al., 2000; Khan and Mosegaard, 2002; Logonné et al., 2003).

b. Estimating epicenter locations for seismic events requires knowledge of the lunar mantle in terms of vertical and lateral variations; the small areal extent of the APSE has resulted in reduced resolution of seismic interpretation the deeper one goes into the mantle. For example, seismic data have been interpreted to indicate the presence of garnet in the lower lunar mantle (e.g., Anderson, 1975; Hood, 1986; Hood and Jones, 1987). 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. While recent work by Chenet et al. (2006) employed a Markov chain Monte Carlo algorithm along with seismic wave arrival times from 7 artificial impacts and 19 meteoroid impacts to estimate crustal thicknesses variations, it should be noted that 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 (cf. Jolliff et al., 2000) remain unanswered.

d. Related to the last point is the nature of upper/middle/lower mantle from one terrane to another. Little is known about the variability and even the nature of the lunar mantle in a global sense.

e. While >7,000 deep moonquakes were recorded, only three are undisputedly from 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 APSE? 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 true mechanism for triggering deep moonquakes?

f. 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 – Nakamura et al., 1979), 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 (Nakamura and Frohlich, 2006). 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?

g. The seismic discontinuity at 500-600 km because the PSE sites could be reflecting the base of the lunar magma ocean (LMO), but is this a moon-wide feature? Answering this question has important implications for our current understanding of lunar evolution via a magma ocean. 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.

Heat Flow Experiment. (see Langseth et al., 1970). Three heat flow experiments were attempted – at Apollo 15, Apollo 16, and Apollo 17, (see Langseth et al., 1976; ALSEP Termination Report, 1979). The attempt to deploy the heat flow experiment at Apollo 16 failed due to a broken cable linking the two heat flow probes. The instruments were comprised of two 2.55 cm diameter hollow cylinders that were driven into the regolith and into which were placed a lower and upper heat flow probe (Fig. 3). The depths of penetration are also shown in Figure 3. The experiments lasted for 3.5 years (Apollo 15) and 2 years (Apollo 17). Significant results are shown in Table 2. Tens of thousands of

Table 2: Significant results from the Apollo Heat Flow Experiment. Taken from the ALSEP Termination Report (1979).

Datum	**Apollo 15**	**Apollo 17**
Thermal Conductivity (surface layer) mW m^{-1} K^{-1} (at 120 K)	1.2 ± 0.03	1.5 ± 0.03
Avg. Conductivity (>10 cm) mW m^{-1} K^{-1}	10 ± 10%	15 ± 10%
Lunation Temp. Wave Penetration Depth (m)	0.29	0.33
Annual Temp. Wave Penetration Depth (m)	1.35	1.48
Mean Vertical Temp. Gradient (K m^{-1})	1.85	1.35
Observed Surface Heat Flow (mW m^{-2})	21	16

terrestrial heat flow measurements have been made on the land and at ocean bottom (Pollack et al., 1993). In contrast there are only four measurements from the Moon (Langseth et al., 1976). To determine the interior heat flux to an accuracy of ±5 mW m^{-2}, 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 have some interest, but would also have very large error bars. On the moon, two heat flow measurements were made within several hundred meters of each other and differed by a factor of two (Langseth et al., 1976). Ideally three or more measurements should be made in holes spaced 10s to 100s of meters apart, at depths that extend below the penetration depth of the annual thermal wave (but to determine the geothermal gradient, these temperature measurements should also extend all the way to the surface).

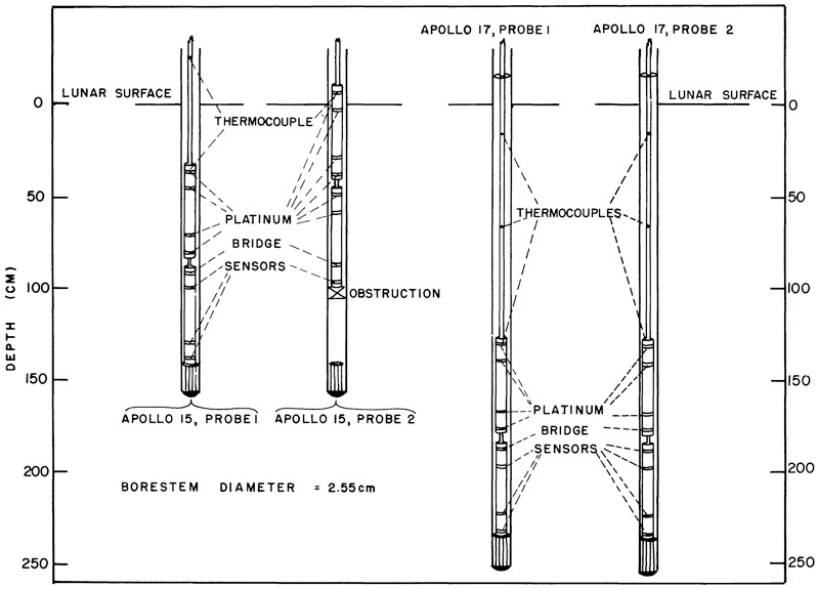

Figure 3: Details of the Apollo 15 & 17 heat flow experiments and instrumentation. From Langseth et al. (1976).

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 heat-producing elements:

- Are the two data points of lunar heat flow representative? Indeed, Langseth et al. (1976) emphasized the need for extended areal (global) coverage to define potential variations in heat flow.
- What is the heat flow from highlands regions? While Apollo 17 landed in the Feldspathic Highlands Terrane, the heat flow was measured in a maria.
- Is the Apollo 15 heat flow result representative of the Procellarum KREEP terrane?
- Do different lunar terranes have unique heat flow budgets?

Lunar Surface Magnetometer (LSM – see Dyal et al., 1970). The LSM was deployed as part of the ALSEP by the Apollo 12, 15 and 16 missions and the network was switched off on 14 June 1974. The LSMs, along with Apollo subsatellites, were used to study the properties of the lunar interior and the lunar environment, namely:

(a) Electrical conductivity, temperature, and structure of the lunar crust and deep interior;

(b) Lunar magnetic permeability and iron abundance (including estimation of the size of a highly conducting core);

(c) Lunar surface remnant magnetic fields (present day properties. Interaction with solar wind, and origin by thermoelectric generation;

(d) Lunar environment (lunar atmosphere and ionosphere on the geomagnetic tail, velocity and thickness of the magnetospheric boundaries.

Data from these magnetometers, in conjunction with the low-altitude orbital magnetometer measurements, revealed an unexpected magnetization of portions of the lunar crust (for reviews, see Fuller, 1974; Fuller and Cisowski, 1987; Hood, 1995). Paleointensity estimates for returned samples indicated the existence of a ``high-field epoch'' during the 3.6 to 3.9 Gyr period (Cisowski et al., 1983; Fuller and Cisowski, 1987). 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 (Dyal et al., 1974). 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 (Hood, 1980; Hood et al., 2001; Halekas et al., 2001; Richmond et al., 2003). The global distribution of orbital anomalies was characterized by large concentrations of strong anomalies in regions antipodal to the four youngest large impact basins (Lin et al., 1988; 1998; Hood et al., 2001). Correlative studies have also shown that the strongest individual anomalies often occur coincident with unusual albedo markings of the Reiner Gamma class (Hood et al., 1979; Hood and Williams, 1989).

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. Scientific questions that are unresolved with regard to lunar magnetism are as follows:

- Are basin ejecta the 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. Moreover, the identit(ies) of lunar magnetizing fields remain uncertain. As noted above, paleointensity estimates for returned samples indicate the existence of a ``high-field epoch'' suggesting a core dynamo. However, if basin ejecta are the sources of lunar crustal fields, such sources would have formed relatively quickly (times < 1 day) so that transient magnetic fields could have contributed importantly to the magnetization.
- What is (are) the origin(s) 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. One hypothesis for their existence therefore supposes that the solar wind ion bombardment plays a role in the darkening with time (``optical maturation'') of freshly exposed lunar surface materials such as crater rays (Hood and Schubert, 1980; Hood and Williams, 1989; Richmond et al., 2003; see also Vernazza et al., 2006). This hypothesis is based on calculations indicating 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 (e.g., Harnett and Winglee, 2000; Kurata et al., 2005). Another proposed hypothesis for the origin of the albedo markings is surface scouring by relatively recent (< 1 Myr) cometary coma impacts; the associated magnetic anomaly sources are then suggested to be surficial materials heated and exposed to transient magnetic fields during the coma impacts (Schultz and Srnka, 1980; Bell and Hawke, 1987). Deployment of a surface magnetometer at the Descartes mountains site and the Reiner Gamma site would directly address the following questions:
  - ⇒ What are the sources of lunar magnetic anomalies?
  - ⇒ 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.
- What is the electrical conductivity profile of the Moon? With laboratory data, this can be used to bound the temperature profile of the deep interior and thus integrate with the heat flow data, as

well as aid in the detection of a metallic core, thus integrating with the seismic data. For this deep electromagnetic sounding, new data are required over time for the same position of the Moon in the changing plasma environment.

It is evident that strategic deployment of instruments is required for any geophysical network to answer as many of the scientific questions posed above as possible.

DISCUSSION

The NRC panel on Lunar Science Priorities and Goals requested more information on the deployment of a lunar geophysical network that centers around four themes:

1) The need to develop long-lived power supplies (1-10 watts).
2) A list of recommendations for International Community involvement.
3) With regard to heat flow, how deep would the heat flow probe need to be to avoid the annual thermal wave?
4) Seismometer configurations - what scientific questions could/could not be answered with 2/4/6/8/10 seismometers?

1) The need to develop long-lived power supplies (1-10 watts).

The tidal influence on certain moonquakes requires that lunar seismicity be monitored over at least one lunar tidal cycle (6 years). In addition, the Apollo PSE detected only 28 shallow moonquakes over 5 years of operation. This data set is too small to perform a statistical analysis on correlating location with tectonic feature (and the epicenters were imprecisely located) to investigate a causal mechanism. This is particularly significant for a permanent lunar habitat as 7 shallow moonquakes were of magnitude 5 or greater – this means we can expected at least one moonquake of this magnitude per year. Without fully understanding the mechanism behind these, informed decisions (in terms of safety) about locating the permanent habitat cannot be made.

In terms of heat flow investigations Langseth et al. (1976) emphasized the need for extended areal (global) coverage to define potential variations in heat flow. This is required to minimize the uncertainties of global heat flow estimates. In addition, they also estimated that 5-7 years were required for the lowest probe to reequilibrate to the new steady-state regime.

For surface magnetometer experiments, the maximum time interval that can be analyzed for sounding studies at a given time is relatively short (less than a week). This is because of the changing plasma environment of the Moon in its orbit (solar wind, geomagnetic tail lobes, magnetosheath). We can only compare deep eletromagnetic sounding data from one plasma environment like the tail lobes or the solar wind. However, analysis of many intervals over a period of years would allow very precise data to be produced, allowing more detailed conclusions of the lunar interior to be made, as well as making integration with the seismic and heat flow data more meaningful.

It is evident from the ALSEP results that geophysical instruments need to be active for periods of years, maybe even tens of years. The ALSEPs were powered by RTGs (Radioisotope Thermoelectric Generators) with a design output of 73 watts. On 30 September 1977, when the network was shut down, the lowest final power output was 36 watts (Apollo 15; ALSEP Termination Report, 1979). It has been estimated that, with advances in instrumentation, electronics, etc., since Apollo, a reliable power source in the range of 2-10 watts is required to power an instrument package containing a seismometer, heat flow probe and a surface magnetometer (Neal, 2006). It is unclear, however, whether electrical power in this range can be maintained for a minimum of 6 years using conventional solar/battery technology, given the long lunar night and mass constraints for remote/robotic instrument deployment. What is required is the

development of "mini-RPS" (Radioisotope Power System) units that supply between 0.1 and <10 watts of power. While this concept has been explored (Abelson et al., 2004), actual fabrication and testing of such units is not occurring nor are they planned to occur in the near future. *This is a major oversight for developing a long-lived geophysical network for the Moon or any planetary body*. However, the concepts presented by Abelson et al. (2004) are tantalizing for any mission that attempts to deploy a global geophysical network on an airless body. For example, the reduction in mass would be significant as the mass of the RPS unit would be between 4 kg and 6 kg, compared to 19.6 kg for the Apollo RTG units.

2) Recommendations for International Community involvement.

This issue raises the ugly topic of ITAR, which *must* be resolved if international collaboration is to advance. However, for the purposes of this document, this legislation is ignored. International community involvement in lunar missions and science has been occurring from the "bottom up" (i.e., at the individual scientist level). For example, the Russian "LEND" instrument is included on NASA's Lunar Reconnaissance Orbiter. Four instruments from Europe and two from the United States will be flown on India's Chandrayaan-1 mission in 2008. Indeed, for a project the author is involved with, it is an international group (US, Europe, and possibly Japan) that is trying to establish a geophysical network on the Moon. This "bottom up" approach appears to be working well, but could be enhanced from a "top down" approach if national space agencies cooperate in tackling a specific scientific/exploration problem. For example, understanding the nature of volatiles at the lunar poles, in addition to establishing a global lunar geophysical network, may also be a topic that could stimulate such cooperation.

3) With regard to heat flow, how deep would the heat flow probe need to be to avoid the annual thermal wave?

While the penetration depth of the annual thermal wave depends upon the nature of the regolith at a specific site, available data indicate that penetration does not occur more than 1.5 meters into the subsurface (please see Table 2). In addition, the lunar surface temperatures are strongly affected by the 18.6-year precession of the lunar orbit, which must be taken into account when correcting existing and future data (Wieczorek and Huang, 2006). However, a heat flow probe 3 meters in length should place two sensors below the depth of the annual thermal wave.

4) Seismometer configurations - what scientific questions could/could not be answered with 2/4/6/8/10 seismometers?

In general, the following points hold true with regard to the number of seismometers in a network and their distribution: the broader the coverage and the greater the number of seismometers, the more we will understand about the lunar interior. However, there are some important details and caveats to this general statement that are discussed below.

Two Seismometers. This is the absolute minimum number of seismometers that will give some details on the nature of the purported lunar core and the nature of the deep lunar mantle. One seismometer should be close to a known source, an A1 deep moonquake in particular (see Nakamura et al., 1982), to obtain its origin time, and another near the antipode to record the seismic signal from it through the very deep interior. This is the way the Japanese Lunar-A was intended to operate. However, it is preferable to have an array of at least three stations at one site to locate and time any source in one region and another array of any number of stations near the antipode to record seismic signals at various distances, all through the deep interior.

A network of two seismometers will yield only approximate information on the locations of deep moonquakes, and little to no information on the origin of shallow moonquakes, crust/mantle heterogeneity.

Three Seismometers. This is the minimum number of stations to locate and time each deep moonquake. However, to accomplish anything more than what the Apollo data provided, including, in particular, the distribution of nests beyond the earth-facing side of the Moon, requires global distribution of stations. Also, data from three stations will be sufficient to approximately determine meteoroid impact time and location. The smaller the station spacing, the smaller the impacts that can be detected by all three stations, while the larger the station spacing, the larger area can be covered for detection. Finally, a minimum of three widely-spaced stations will be needed to determine the expected linear path of strange quark matter passage through the Moon, assuming that it will generate both P and S waves. If only the P wave is generated, a minimum of six stations will be required to determine its path and timing. Information obtained from a network of three seismometers will depend upon seismometer distribution.

A network of three seismometers will yield only approximate information at best on the locations of shallow moonquakes, and little information on crust/mantle heterogeneity

Four Seismometers. Exploring lateral heterogeneity in the lunar crust and mantle could be accomplished with a minimum of four seismometers. However, there is no clear limit to the number of seismic stations needed to do this. There have been some attempts even with the 4-station Apollo network (e.g., Chenet et al., 2006 and references therein), but the larger the number of stations, the more detailed the result will be. Also, to obtain global distribution of structural and seismic velocity variations, a globally distributed array of seismic stations is required. Also, it is theoretically possible that four stations placed at sites corresponding to the apexes of an equilateral tetrahedron may be sufficient to locate and time each deep moonquake, but a larger number of stations is definitely preferred.

More than Four Seismometers. A larger number of seismometers is required to determine a shallow depth of a source for a shallow moonquake because a smaller spacing of stations is needed relative to that required for deep sources. If we knew where shallow moonquakes are likely to occur, we could set up at such a location a closely spaced array of at least three stations, a required minimum, but to cover a large area spread out over the Moon, an unrealistically large number of stations may be required. What is required is to place clusters of seismometers at a number of the approximated shallow moonquake locations (Nakamura, 1977; Nakamura et al., 1979), as well as any proposed lunar habitat site. Obviously, the greater the number of stations that could be deployed, then at one location (at least) a cluster of three seismometers could be set up to answer some of the fine scale questions raised above.

While the number of seismometers is subject to scientific debate and programmatic realities, any network should have a broader coverage than that of the Apollo PSE network. Many of the shortcomings of the Apollo seismic database stem from the lack of station coverage beyond the near front-center of the moon. Thus, extending the station coverage should be the primary objective of our next lunar seismic observation. Also important is the length of observation. We were fortunate that the Apollo stations operated for five to eight years, long enough to record many moonquakes of various kinds. However, since large lunar seismic events do not occur often, it is important to have our next network of stations operating for at least as many years as the Apollo stations did (*minimum requirement*), but preferably for much longer (ten years and beyond). Finally, while deploying less than four seismometers will yield less information than that obtained by the Apollo missions, strategically locating these could answer ***some*** of the unresolved questions regarding seismic activity on the Moon and the nature of the lunar interior. However, the discussion above should demonstrate the need for having more than four of these stations strategically located around the Moon.

SYNOPSIS

As with the Apollo ALSEPs, it is likely that a geophysical network will be incrementally built up over a number of missions. This emphasizes even more the need for reliable, long-lived power supplies that will allow the initial packages to be "alive" when the subsequent packages arrive on the lunar surface so that they can be effectively networked with them. In addition, the results from the ALSEPs indicate the need for strategic deployment (e.g., in a variety of different terranes for heat flow; in areas of magnetic

anomalies; around known locations of shallow moonquakes, and on the lunar far side for deep moonquakes) that will produce a network that is more global in distribution. Creation of such a network that will generate data over a period of at least 6 years will dramatically enhance our knowledge regarding the internal structure and composition of the Moon, as well as yield input knowledge critical for the safe and efficient construction and maintenance of a permanent lunar habitat.

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