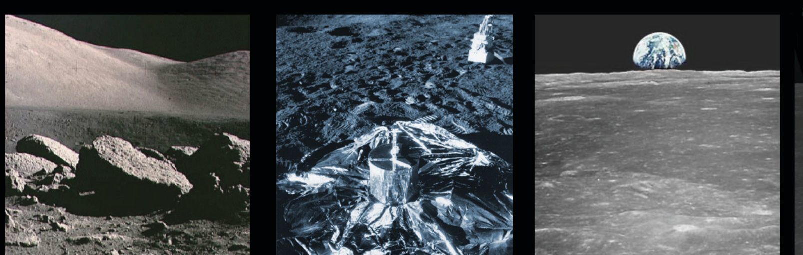
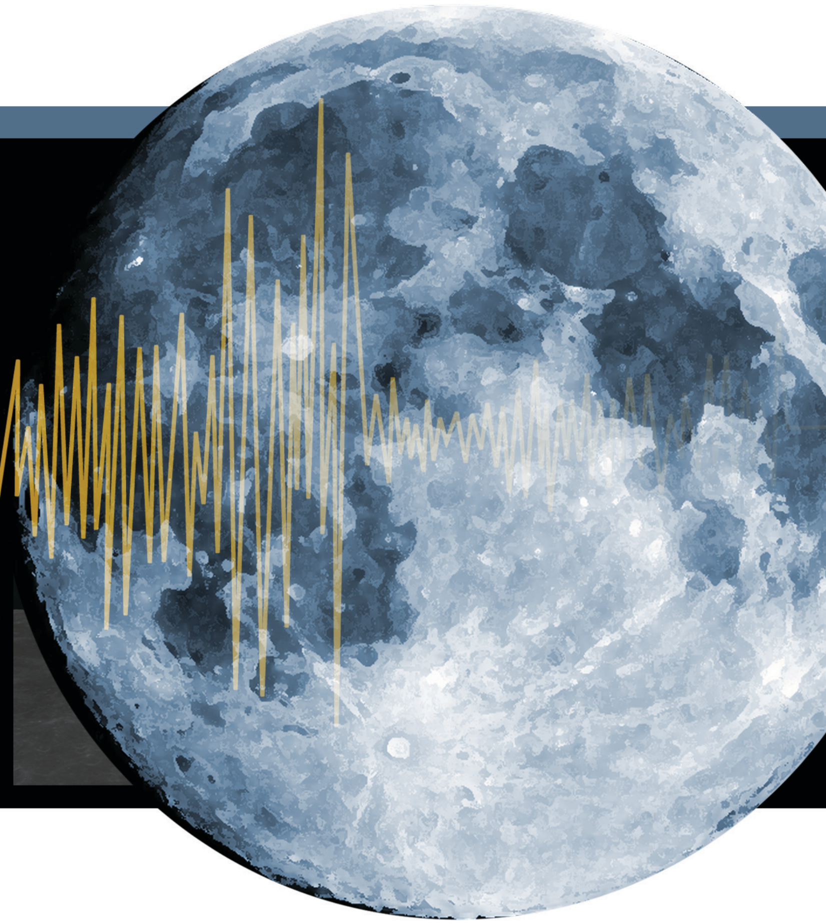
National Aeronautics and Space Administration

ILN Final Report

Science Definition Team for the ILN Anchor Nodes

January 2009





Outline

1.0 Executive Summary

The moon provides an important window into the early history of the Earth and all terrestrial planets. Its interior is a treasure-trove of information about its initial composition, differentiation, crustal formation, and subsequent magmatic evolution. In spite of more than four decades of intensive study, many aspects of the moon, especially detailed information about its interior, remain to be determined. Geophysical measurements provide the optimum means of obtaining this essential information.

A new line of lunar science flight projects was introduced under the Lunar Quest Program in NASA's Science Mission Directorate's (SMD's) proposed 2009 budget to accomplish outstanding lunar science objectives embodied in the National Academies report *The Scientific Context for Exploration of the Moon* (2007) and the NASA Advisory Council-sponsored *Workshop on Science Associated with the Lunar Exploration Architecture* (2007). A major element of NASA's lunar flight projects is the International Lunar Network (ILN), a network of small geophysical nodes on the lunar surface. NASA plans to provide the first two nodes in the 2012–2014 timeframe, and is looking to international involvement to provide additional nodes. A second pair of US nodes is envisioned for launch in the 2016–2017 timeframe. Ultimately, this network could comprise 8–10 or more nodes operating simultaneously. NASA's contribution to the ILN is referred to as the Anchor Nodes missions in this report.

The next generation of geophysical measurements on the moon must improve upon data obtained during the Apollo missions by the Apollo Lunar Surface Experiment Packages (ALSEPs) deployed at the landing sites. Valuable as these data are, in most cases they have significant limitations that can be overcome by the deployment of more advanced geophysical instruments. The goal of a next-generation lunar geophysical network is to improve our understanding of the interior structure and composition of the moon.

The ILN Anchor Nodes Science Definition Team (SDT) examined the opportunities and challenges associated with implementing a next-generation lunar geophysical network. The ILN SDT concludes that seismometry is the essential element of any surface network, enabled by simultaneously-operating nodes and best able to address the highest-priority science goals of a lunar geophysical mission. Direct measurement of the lunar heat flow is the most highly desirable secondary objective. Electromagnetic sounding and laser ranging are desirable measurements that provide additional information at each site about the shallow substructure and deep interior.

The ILN SDT advocates exploring lateral heterogeneity in the lunar crust and mantle as a major goal of a new network mission. The SDT defined a Network Science Baseline Mission (Box 1) to meet this goal, requiring a minimum of four nodes, carrying a seismometer plus other complementary instruments, globally distributed, including nodes on the lunar farside. The lifetime requirement of the network (simultaneous operation) is one lunar tidal cycle of 6 years. Specific instrument characteristics and measurements are summarized in Table A1.

Box 1: US ILN Anchor Node Baseline and Floor Science Definitions

Network Science Baseline Mission

Mission Attributes

Four stations, concurrently active, with lifetime of 6 years, stations no closer than ~2000 km; to the extent possible, stations should be placed unambiguously in each of the major terranes; farside coverage desirable, otherwise front-side stations within ~20° of the limb.

Instrumentation (in priority order)

1. Three axis broadband seismometer
2. Temperature and thermal conductivity measurements to depths >3 m
3. Electromagnetic sounding
4. Laser ranging experiment

Science Floor Mission

Mission Attributes

Two stations, concurrently active, with lifetime of 2+ years, stations no closer than ~2000 km; to the extent possible, stations placed relative to A33 moonquake nest hypocenter.

Instrumentation

1. Three axis broadband seismometer

From the Network Science Baseline mission, the SDT defined graceful descopes, including instrument requirements, number and type of instruments, and number of nodes (discussed further in Section 5), that reduce the science return but still provide an improvement over Apollo data. The SDT then defined a minimal acceptable science mission (Science Floor Mission; Box 1) that would focus on determining the deep interior velocity structure of the moon and placing constraints on the core size/density through seismic measurements by operating two broadband seismometers simultaneously and continuously for 2 years. A mission of this type must strategically locate the two nodes at sites relative to known moonquake locations to provide new information to address whether there is a central core deep inside the moon and answer some unresolved questions about lunar seismic activity. However, two nodes are insufficient for achieving major new lunar science. Therefore, the SDT strongly advocates a Network Science Baseline Mission, where two initial nodes are joined with at least two additional nodes (ideally located on the lunar farside) to form a larger network for a combined 6-year minimum operational lifetime.

In summary the SDT concluded that:

1. An International Lunar Network can deliver essential new science that will enhance our understanding of the moon.
2. Of the major measurement objectives, the implementation of one—heat flow measurements to a depth of approximately 3 meters—will benefit from immediate investment to determine the relative merits of at least three possible implementations (mole, drill, penetrator).

3. Although some ILN Anchor Nodes goals can be achieved without a nuclear power source, full realization of the objectives on a minimum-mass lander is enabled by a nuclear power system such as the Advanced Stirling-cycle Radioisotope Generator (ASRG), or its lower-powered derivative (DASRG).
4. The SDT felt that the given task was overspecified by
   a. Insisting on excellent science,
   b. Specifying an extremely low cost,
   c. Specifying very small landers to be launched on vehicles under development and of uncertain performance.

The SDT concludes that at least one of these constraints must be relaxed. It cannot be (a).

2.0 A Lunar Geophysical Network

One of the key motivations for studying the moon is to better understand the origin of the planets of the inner solar system in general and that of Earth in particular. The origin of the moon is inextricably linked to that of Earth. The precise mode of formation affected the composition and early thermal state of both bodies and, therefore, affected the subsequent geologic evolution. Because the moon's geologic engine largely shut down long ago, its deep interior is a vault containing a treasure-trove of information about its initial composition, differentiation, crustal formation, and subsequent magmatic evolution. Data concerning interior structure and dynamics are difficult to obtain but are worth considerable effort to do so. Geophysical measurements are often the best, and only, way to obtain information about the composition and structure of the deep lunar crust, mantle, and core.

The National Research Council report, *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003) (the Planetary Science Decadal Survey), is the principal roadmap for solar system exploration, providing a community-based weighting of science priorities across the solar system, including the Earth's moon. In this document, the Inner Planets Panel asserted that the inner solar system affords the opportunity to address broad objectives for understanding the history, current state, and potential future of habitable planets. Landed geophysical networks were recommended by the panel for all the terrestrial planets—Mars, Venus, Mercury, and the moon—in order to address multiple key aspects of inner solar system science (see Table 2.1 of that report). Although the panel did not specifically recommend them for the 2003–2013 decade, it stated that efforts in the subsequent decade should focus on essential network science, involving the establishment of multiple surface nodes operating concurrently.

The Decadal Survey preceded the announcement of the 2004 Vision for Space Exploration (VSE) that set the nation on a course to return to the moon. A new National Academies effort was commissioned to examine the possibilities for science provided by the VSE. The National Academies report, *The Scientific Context for Exploration of the Moon* (2007) (SCEM report), supplements the scientific weighting of the Decadal Survey by examining the additional opportunities for achieving those scientific objectives within the VSE. One of the major science discussions in the SCEM report is the need to understand the interior structure and composition of the moon. Of the eleven near-term highest-priority activities listed in the SCEM, four are particularly addressable by a lunar geophysical network. The SCEM report also provided an independently-formulated "Candidate Lunar Research Strategy for the Near Term," in order to balance the highest integrated science implementation priorities with the feasibility of implementing them during the time interval 2010–2022. The third highest priority on the list (following dedicated research and analysis programs and an atmosphere and polar volatile mission that will be partially addressed by LCROSS and LADEE) is to:

3. Emplace a geophysical network to include, at a minimum, seismic and heat flow experiments, environmental sensors, and new laser ranging retroreflectors. Such a program should be coordinated with those of other countries that are likely to include lunar landed missions in their space exploration strategies. The minimum number of landed sites should be four, more or less equidistantly placed, including at least one farside site (no retroflector required). (SCEM p. 53)

The NASA Advisory Council sponsored a Workshop on Science Associated with the Lunar Exploration Architecture in Tempe, Arizona, and subsequently prepared a set of recommendations to the NASA Administrator in a *Final Report* (2007). Recommendation S-07-PSS-2 concluded that "Geophysical networks are needed to accomplish exploration and high-priority science and operational objectives such as investigating the lunar interior and understanding the lunar surface seismic environment. Such networks need to be long-lived (>6 years to encompass one lunar tidal cycle and >10 years to survive until other nodes come on line) which requires the development of a power source that can function over such long duration. Networks could be built up in partnership with other space agencies provided that a framework for compatible timing and data standards is established." The discussion of a network mission at this meeting additionally emphasized its importance for understanding safe site selection for human landings and understanding seismic activity that affects long-term habitat design and construction.

In 2008, NASA asked the National Research Council to provide criteria and guiding principles for determining the list of candidate missions for the next New Frontiers mission competition. The report, *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008), followed the guidance of the Decadal Survey in recommending missions, reinforcing the importance of geophysical network science and recommending its inclusion for consideration in the New Frontiers project line. The New Frontiers report also provided additional perspective on the role of network missions as a tool for understanding the interiors of the inner planets.

3.0 Science Definition Team

A new lunar science flight projects line, the Lunar Quest Program, has been introduced within NASA's Science Mission Directorate's (SMD)'s proposed 2009 budget. Lunar Quest missions are designed to accomplish key scientific objectives and, when possible, provide results useful to the Exploration Systems Mission Directorate (ESMD) and the Space Operations Mission Directorate (SOMD) in their planning work for returning humans to the moon. The first mission in this line will be the Lunar Reconnaissance Orbiter, an initially ESMD mission that will acquire key information for humanity's return to the moon that will transition after one year of operations to the SMD Lunar Science Program for an additional 2-year nominal science mission. The second mission, the Lunar Atmosphere and Dust Environment Explorer (LADEE) will launch in 2011. The third major element in this new SMD program is the International Lunar Network (ILN), a network of small geophysical stations on the lunar surface designed for lunar surface and interior science deployed to multiple sites. NASA's Science Mission Directorate and Exploration Systems Mission Directorate (ESMD) have partnered to provide NASA's first two nodes in the 2012–2014 timeframe, and hopes to see international involvement to provide additional nodes in the network. A second pair of US nodes is envisioned for launch in the 2016–2017 timeframe.

The International Lunar Network is intended to establish a global lunar geophysical network that fulfills a long-standing desire from the scientific community (see Section 2). The ILN could provide the desired global coverage by involving US and international landed missions as individual nodes working together to deploy 8–10 or more nodes operating simultaneously, while minimizing the required contribution from each space agency. Indian, Russian, Japanese, and British landed missions are currently being formulated and SMD is actively seeking partnership with these and other space agencies to establish the full ILN.

To explore fully this opportunity, NASA formed a Science Definition Team (SDT) to consider NASA's initial contribution to the ILN, hereafter referred to as the Anchor Nodes mission. The focus of the SDT was to consider the science uniquely enabled by the synergy of a network. The SDT charter called for the team to a) Define and prioritize the scientific objectives for the ILN Anchor Nodes; b) Define measurements required to address the scientific objectives; c) Define instrumentation required to obtain the measurements; d) Define criteria for selection of the initial two sites; and e) Identify technical challenges. Though the SDT was charged to define potential instrumentation, it is expected that the instruments themselves will be obtained through a future Announcement of Opportunity.

In assessing scientific issues, the SDT worked within the broad context already provided by previous community-based activities such as *The Scientific Context for the Exploration of the Moon* (2007), the recommendations from the *Workshop on Science Associated with the Lunar Exploration Architecture* (2007), and *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008). The SDT was additionally charged to provide their analysis in the context of the nature of the US ILN nodes, which will be very small (<150 kg landed stations, no mobility, limited power and data rates).

The Anchor Nodes SDT was Co-Chaired by Dr. Barbara Cohen of Marshall Space Flight Center (MSFC) and Dr. Joseph Veverka of Cornell University, along with Dr. Thomas Morgan as the NASA Headquarters Study Scientist and John McDougal from MSFC as the Study Manager responsible for providing technical support to the SDT. A complete list of SDT members and their affiliations is provided in Appendix 1.

The Anchor Nodes SDT began work in March 2008 and met generally biweekly by telecon between mid-March and mid-August 2008. The team held two face-to-face meetings, May 21–22, 2008 in Huntsville AL and August 6–7, 2008 in Laurel MD. At both meetings, the team considered science objectives and implementation options and also held a joint technical interchange meeting with the Pre-Phase-A engineering team. Dr. Barbara Cohen presented interim findings on behalf of the SDT to Dr. James Green, Planetary Science Division Director, on July 17, 2008, and to the NASA Lunar Science Conference on July 21, 2008.

This document is the Final Report of the SDT, encompassing its assessment of the science that can be uniquely accomplished by a network and our best assessment of the measurements required to meet those objectives. Although the SDT members provided substantial support and guidance to the Pre-Phase-A design activities, the recommendations of this report are independent of specific design and/or implementation options.

4.0 Science Background

Summary: Constraints on the lunar crust, mantle and core structure are provided by spacecraft observations of topography, gravity, and magnetic fields, in situ seismicity and heat flow experiments, and Earth-based laser ranging measurements. Crustal thickness models, based on gravity and topography data, indicate thick crust beneath the lunar highlands and thinning beneath large basins. Models for seismic velocity as a function of depth show a discontinuity interpreted as the crust-mantle boundary, and allow investigation of mantle structure to about 1200 km depth. The lack of seismic imaging of depths below 1200 km means that core size and composition are poorly constrained, although laser ranging data suggest a fluid, or partly fluid state. The measured lunar heat flow is consistent with its small size, which favors rapid, early cooling of the interior, but variability among lunar terranes is unconstrained.

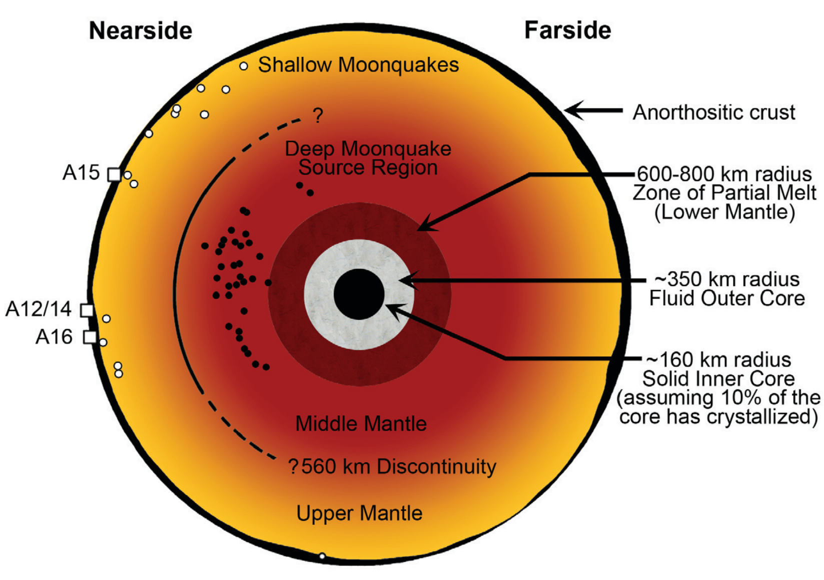


Figure 1. Notional view of lunar interior showing the thin crust, mantle and possible inner and outer cores. Also illustrated are the locations of the Apollo seismometers and the distribution of shallow and deep moonquakes. After Wieczorek et al. (2006).

Our moon holds unique significance in the continuum of the evolution of rocky worlds. The moon today presents a record of geologic processes of early planetary evolution. Many of the more recent processes that shaped and modified the terrestrial planets are absent on the moon. Its crust has never been altered by plate tectonics, which continually recycles Earth's crust; by planet-wide volcanism, which resurfaced Venus a little more than half a billion years ago; or by the action of wind and water, which have transformed the surfaces of both Earth and Mars. Its airless surface also provides a continuous record of solar-terrestrial processes.

Most importantly for the ILN, the lunar interior retains a record of the initial stages of planetary evolution, starting from the formation of the Earth and moon 4.5 Gy ago. At that time, it has been proposed that a Mars-sized body likely impacted the proto-Earth during the last stages of planetary accretion. Most of the impactor was accreted to the Earth, but its outer, rocky layer predominantly went into Earth orbit and eventually accreted as the moon (Canup 2004).

The process of formation and accretion of the moon was violent and energetic. Much of what became the moon was initially molten, forming a magma ocean at least several hundred kilometers deep. Differentiation of this vast magma body resulted in the formation of the plagioclase-rich crust and olivine-pyroxene mantle (and possibly metallic core). The lunar magma ocean hypothesis, formulated almost immediately after the return of the Apollo 11 samples (Smith et al. 1970, Wood et al. 1970), was a vital conceptual breakthrough in understanding the early formation of planetary crusts. The concept has provided a framework for understanding the early Earth, Mars, Mercury, and differentiated asteroids such as Vesta. However, the lunar magma ocean hypothesis is fundamentally a one-dimensional crystallization sequence, producing a traditional, dichotomous mare-highland classification that is inadequate in describing the structure and geologic evolution of the moon. Global remote sensing from the Clementine, Lunar Prospector, and Galileo missions of the 1990s and further sample analyses of returned rocks and lunar meteorites reveal a moon that varies both laterally and vertically in composition, age, and mode of emplacement, forcing scientists to rethink the simple lunar magma ocean hypothesis.

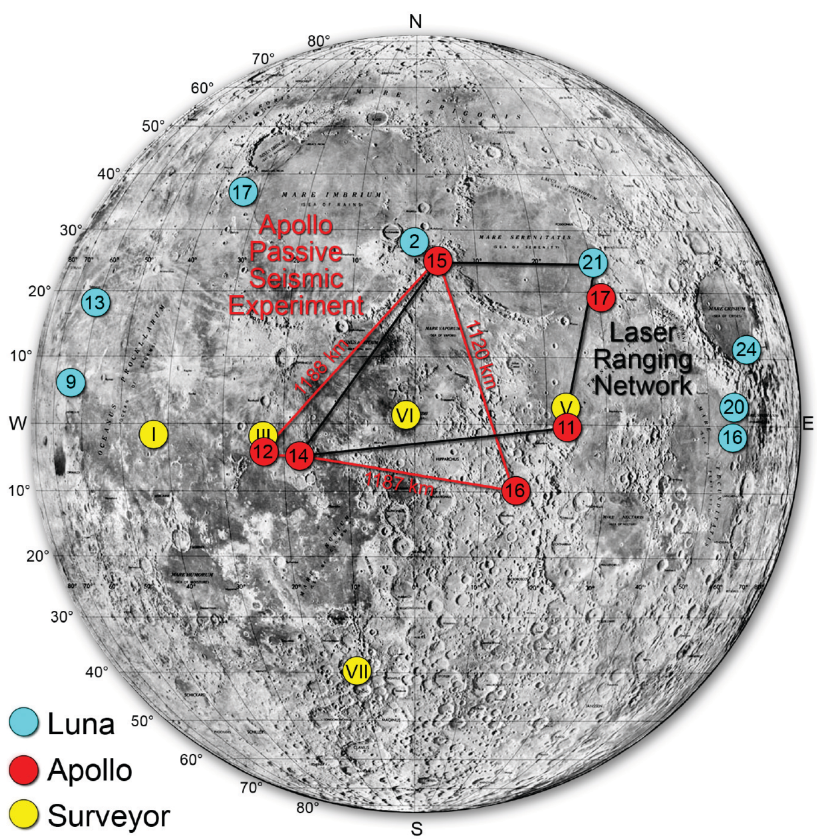


Figure 2. The locations of the Apollo, Surveyor and Luna landing sites. The red lines denote the Apollo passive seismic network (stations at the A12, A14, A15 and A16 sites); the black lines denote the laser retroreflector network. The small angular distances between stations (<1200 km) limited the ability of the seismic experiment to probe the deep lunar interior.

Compared to the Earth, little is known about the deep lunar interior, especially at depths greater than the deep moonquake zone at ~950 km. What we do know was gained primarily through the Apollo Lunar Surface Experiments Packages, or ALSEPs (at Apollo 12, 14, 15, 16, and 17), which contained a variety of different experiments that produced significant information regarding the nature of the lunar surface environment and lunar interior. Our current knowledge of the lunar interior, shown schematically in Fig. 1, includes several fundamental characteristics that make the moon an interesting and important target for a geophysical network: 1) the moon is a terrestrial body with the ability to shed light on the evolution of other terrestrial planets such as Mars and Venus; 2) the moon is a differentiated body, meaning it has become stratified into a crust, a mantle, and a core, and 3) the moon is an active body, releasing energy via seismic waves and radioactive decay. The experiments most relevant to the ILN, their results, and the questions still outstanding are described in the following sections.

4.1 Apollo Passive Seismic Experiment

The Apollo Passive Seismic Experiment (PSE) (Latham et al. 1969, Latham et al. 1970) deployed seismometers at every Apollo site except Apollo 17. The instrument at Apollo 11 failed after 20 days (Bates et al. 1979), presumably because it was not protected from the Sun's radiation by the thermal blanket that was incorporated into later versions. A network of four seismometers was completed in April 1972 (Fig. 2), and operated until they were all switched off on 30 September 1977. During the time the network was operational, it demonstrated that the moon was seismically active (Goins et al. 1981, Nakamura 1997). Four types of lunar seismic events have been defined from the Apollo PSE seismic database (Fig. 3):

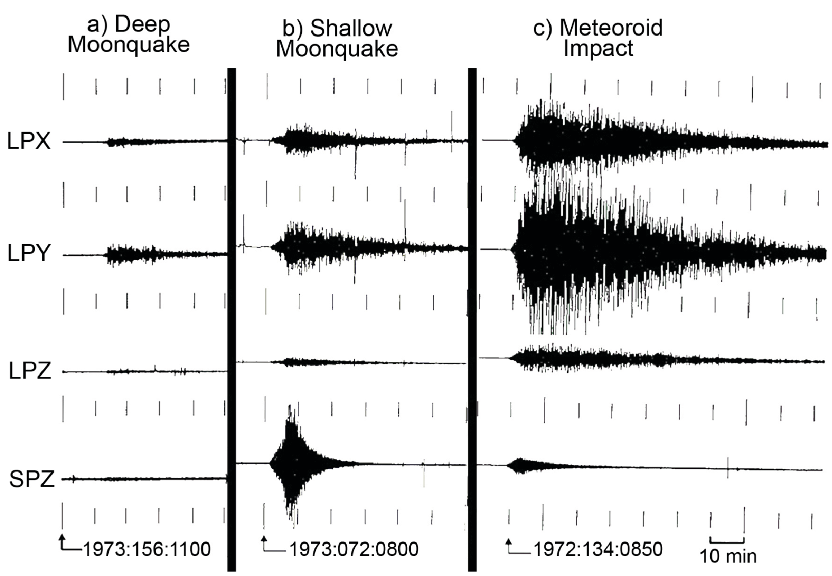


Figure 3. Compressed-timescale seismograms of a) a deep moonquake (category AI); b) a high-frequency teleseismic (HFT) or shallow moonquake event; and c) a meteoroid impact (from Nakamura et al. 1974). All of these seismograms were recorded at the Apollo 16 station. LPX, LPY, and LPZ are the three orthogonal (X, Y, and Z) components of a long-period (LP) instrument peaked at about 0.45 Hz, and SPZ is the short-period vertical component peaked at 8 Hz. The amplitude of the moonquake signal was amplified in playout by a factor of four relative to the other two signals.

1. Thermal moonquakes in the near-surface, which are related to diurnal temperature changes and are the smallest of all seismic events (Duennebier and Sutton 1974b).

2. Deep moonquakes (Fig. 3a), which originate at depths between 700–1,200 km (i.e., about halfway to the center of the moon) and are the most abundant (>7,000 events recognized) (Lammlein et al. 1974, Lammlein 1977, Nakamura 2003, Bulow et al. 2005, Nakamura 2005). These moonquakes have Richter scale magnitudes <3. While their origin is obviously related to tidal influences, there is no clear understanding of the mechanism that produces these seismic events.

3. Shallow moonquakes (Fig. 3b), which have inferred focal depths between 50 and 200 km and 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). These are also referred to as high frequency teleseismic (HFT) events because, relative to other lunar seismic events, these are richer in the higher frequencies (Fig. 4). They may represent the release of thermoelastic strain in the thick lunar lithosphere as the moon slowly cools (Wieczorek et al. 2006).

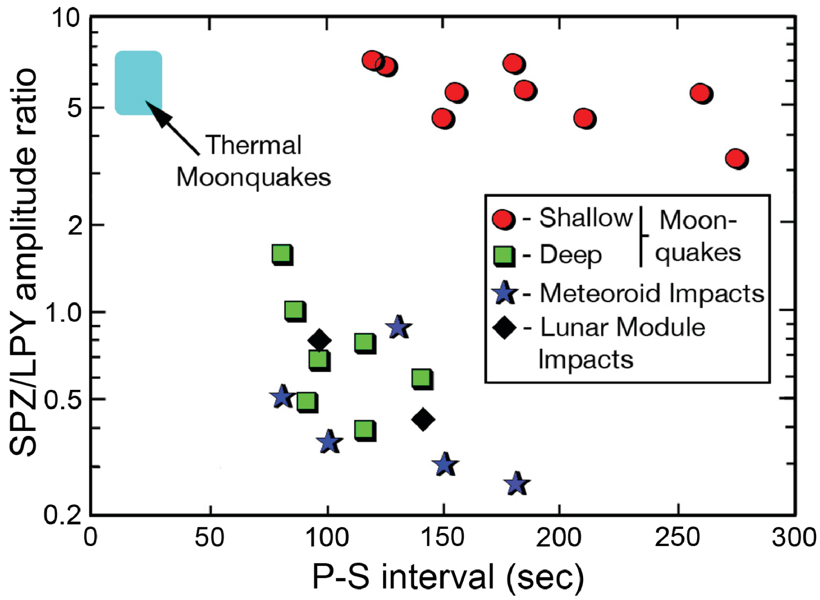


Figure 4. SPZ/LPY amplitude ratio versus S-P time interval of the shallow moonquake events and other selected events at the Apollo 14 station (from Nakamura et al. 1974). The vertical axis is the ratio of the vertical amplitude on the short period seismometer (SPZ) to horizontal amplitude from the long period seismometer (LPY) for a number of seismic events in various categories. Higher values indicate more high-frequency content in the wavetrain. The horizontal axis is the time interval between the P and S arrivals, a measure of the distance between the hypocenter and the seismometer; a large S-P time means a greater distance from the station. Deep moonquakes have characteristics similar to natural and artificial impacts; the shallow and thermal moonquakes are dominated by significant surface wave energy.

4. Meteoroid impacts (Fig. 3c) are surface seismic events that exhibit characteristic amplitude variations (similar to those of artificial impacts) with distance. More than 1,700 events representing meteoroid masses between 0.1 and 1,000 kg were recorded between 1969 and 1977 (Duennebier et al. 1975, Duennebier et al. 1976, Latham et al. 1978, Oberst and Nakamura 1989, 1991). Events generated by smaller impacts (Duennebier and Sutton 1974a) were too numerous to be counted.

Despite the wealth of data collected by the PSE network, major scientific questions remain unresolved primarily because the Apollo Passive Seismic Network was of limited spatial extent and confined to the lunar nearside (Fig. 2). The following key science questions remain unanswered:

a. Does the moon have a central metallic (molten) core, and if it does, how large is it and what is its composition? These are important questions that have direct relevance to the formation and evolution of the moon. The existence of a liquid lunar core having a radius of 350 km in radius is supported by the lunar moment of inertia and dissipation parameters derived from lunar laser ranging (Dickey et al. 1994, Hood and Jones 1987, Hood et al. 1999, Williams et al. 2008). Observations of the ancient lunar magnetic field via remanent magnetization in Apollo samples suggest (though not unequivocally) a fluid lunar core in the past (Fuller 1974, Fuller and Cisowski 1987, Stegman et al. 2003, Lawrence et al. 2008, Garrick-Bethell et al. 2009). Observations of the induced magnetic dipole require an electrically-conductive core at present, though the present data cannot distinguish whether it is liquid (metal or silicate) or solid iron (Hood et al. 1999). Seismic data would provide the most direct evidence for a central molten core and bound its size and composition. The small area covered by the PSE (Fig. 2) meant that comparisons could not be made between seismic waves (from the same event) that have ray paths through the deep interior of the moon with those that did not. The only unconfirmed seismic evidence for such a core came from a single observation of a large meteoroid impact near the antipode of the Apollo seismic network, which gave a possible size limit of 170–360 km and seismic P-wave velocity limit of 3.7–5.1 km/s (Nakamura et al. 1974b). Therefore, confirming, revising, and/or improving this result is critical for our understanding of how the moon evolved to its present state (Toksöz et al. 1974).

b. Is the lunar mantle homogeneous? An apparent seismic discontinuity at 500–600 km beneath the PSE sites could represent the base of the lunar magma ocean (LMO), but geochemical models suggest that the lunar mantle is layered, which might also explain the observed data. Estimating hypocenter locations for seismic events requires knowledge of the lunar mantle in terms of vertical and lateral mineralogical variations; the small areal extent of the Apollo PSE means that seismic interpretations are more poorly constrained with increasing depth. Re-analysis of the Apollo PSE data (Fig. 5) using different seismic events, seismic arrival times and analysis techniques may either validate the 550-km velocity change (Khan and Mosegaard 2002, Lognonné et al. 2003), or dispute it (Khan et al. 2007). The poor resolution of existing data leads to poorly constrained models for interpreting the seismic data in terms of mantle mineralogy. For example, seismic data have been interpreted to indicate the presence of garnet in the lower lunar mantle (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. 1974b, Nakamura 1983). The nature of heterogeneity in the lunar mantle, and whether such heterogeneity is globally observable, has important implications for our current understanding of the bulk composition of the moon and lunar evolution via a magma ocean.

c. How thick is the lunar crust and how does it vary across the moon? Variations in the lunar crust (mineralogical and thickness) away from the Apollo PSE network sites have been difficult to estimate. 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. It is also unknown whether the surface expression of the different lunar terranes (Jolliff et

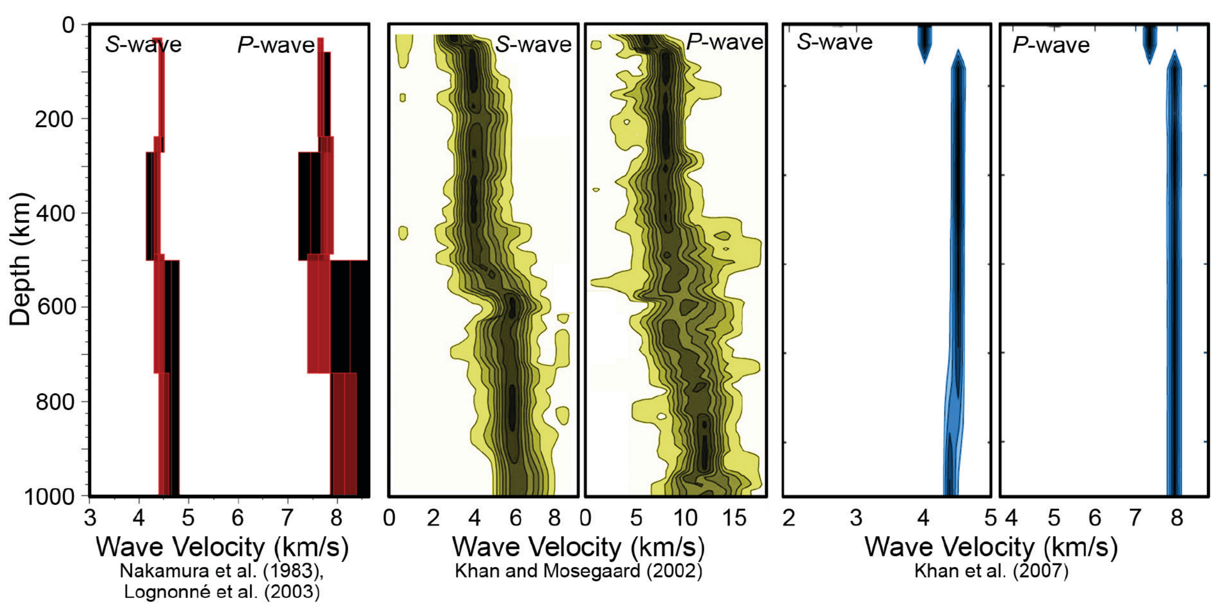


Figure 5. Three independent velocity models for the lunar interior derived from the Apollo PSE S and P wave dataset data analyzed by different methods (Nakamura et al. 1983, Khan and Mosegaard 2002, Lognonné et al. 2003, Khan et al. 2007). Some models show discrete layer boundaries; others do not. The range of modeled structure results from the limited data set.

al. 2000) extends deep into the crust, or indeed, into the upper/middle/lower mantle, and in what way the terranes themselves transition into one another.

d. What mechanism causes deep moonquakes? More than 7,000 deep moonquakes were recorded originating from >300 source regions, but of these, only three source regions undisputedly have hypocentral coordinates on the farside: A33, A282, and A285. There are many more whose coordinates could not be computed because there were insufficient data. Many (61) lack identifiable shear-wave arrivals at some stations. Because shear waves require rigid material for efficient propagation, the lack of shear wave arrivals from farside epicenters suggests there may be a plastic region in the lunar interior that prevents their transmission (Fig. 2). To propose a viable mechanism for deep moonquakes, is important to know whether deep moonquake nests are distributed globally, including nests that were not detectable by the Apollo PSE on the lunar farside. Alternatively, if a plastic zone exists, its nature and extent are sure to change our understanding of the lower mantle and core structure.

e. What controls the locations and origin(s) of shallow moonquakes? These events appear to be associated with boundaries between dissimilar surface features, such as impact basin rims (Nakamura et al. 1974a, Nakamura et al. 1979), and may be tectonic events caused by differential stress. Alternatively, shallow moonquakes may originate from interaction of the moon with high-energy particles (“strange quark matter”) originating from a fixed source outside the solar system (Banerdt et al. 2006; Frohlich and Nakamura 2006). There was, on average, at least one event per year of body wave magnitude 5 or greater during the time the PSE was active (Fig. 6). As these shallow moonquakes are the largest of the lunar seismic events and may have implications for any permanent lunar habitat, this is an important scientific objective, but also important for exploration initiatives (i.e., whether shallow moonquakes pose a risk to a lunar habitat).

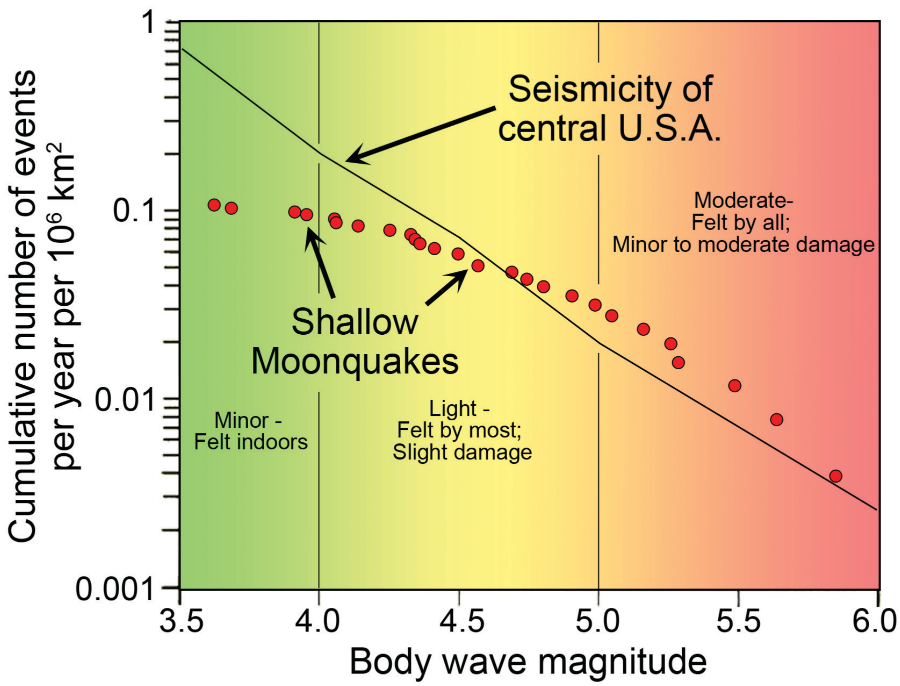


Figure 6. Seismicity of the Moon compared to that of the central United States, a region far from tectonic plate boundaries. Seismicity is a measure of the occurrence rate of quakes as a function of size. In this plot the size of a quake is denoted by its body-wave magnitude, which is proportional to the quake’s energy. Sampling is incomplete at small magnitudes, because amplitudes of small-magnitude events occurring at far distances fall below the detection threshold of the seismometers. The effects of various magnitudes of earthquakes are also shown. Shallow events are rare but can be high energy. Modified from Oberst and Nakamura (1992).

4.2 Apollo Heat Flow Experiment

Three heat flow experiments were attempted, at Apollo 15, Apollo 16, and Apollo 17 (Langseth et al. 1970, Langseth et al. 1976, Bates et al. 1979). The Apollo 15 and 17 experiments were successful, but the heat flow experiment at Apollo 16 failed due to a broken cable linking the two heat flow probes. All three instruments comprised 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. Figure 7 illustrates the resulting temperature profile versus depth from 3.5 years of data from Apollo 15 and 2 years of data from Apollo 17 (Langseth et al. 1976). These data show that the lunar surface (<100 cm) experiences large temperature variations as a result of the diurnal illumination changes, but below 100 cm, the temperatures largely reflect the geothermal gradient. More recently, Saito et al. (2007, 2008) reported the heat flow data from March 1, 1976 to September 30, 1977, showing that the temperature near the lunar surface was continuing to rise and had not stabilized as originally reported by Langseth and Keihm (1974) and Langseth et al. (1976) on the basis of the data between 1971 and 1975. Various hypotheses have been proposed to explain this temperature increase related to surface shadowing or lunar orbital oscillations (Wieczorek and Huang 2006, Saito et al. 2007, Saito et al. 2008). However, it is perhaps more likely that the slight surface temperature increase was due to a disturbance in either conductivity, albedo, or both caused by astronauts while emplacing the probes.

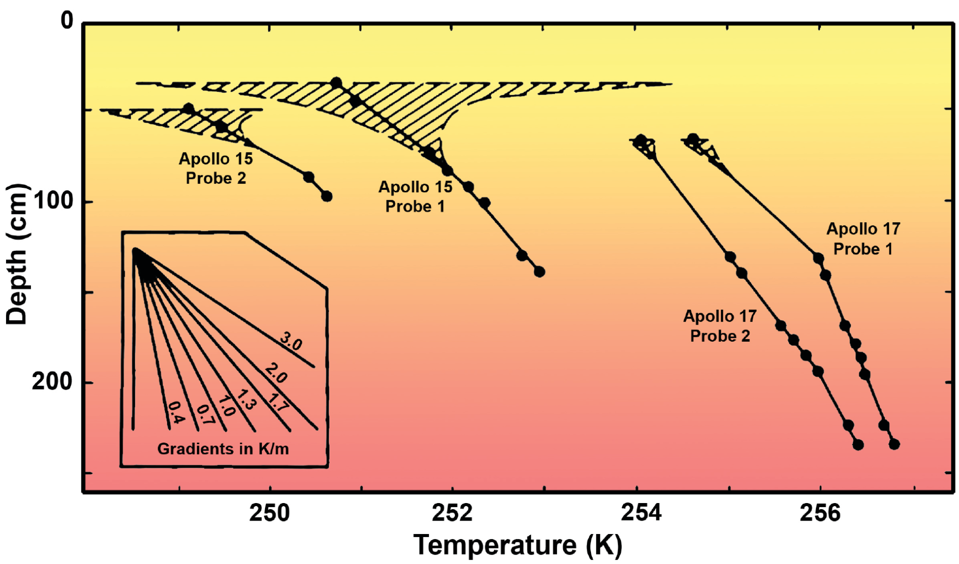


Figure 7. Temperature versus depth at the Apollo 15 and 17 sites. The striped areas at the shallow end of the curves illustrate the diurnal temperature variations, which extend to about 100 cm. The inset in the lower left shows the corresponding temperature gradient for different temperature profiles. Figure adapted from Heiken et al. 1991.

The results indicate that carefully planned and executed heat flow experiments still need to be conducted on the moon. Tens of thousands of terrestrial heat flow measurements have been made on land and in the ocean floor (Pollack et al. 1993). On Earth, variations are due to the effects of crustal composition and thickness, tectonic activity, terrane age, climatic effects, and hydrothermal circulation. Fortunately on the moon, the primary variations are likely to be due to differences in crustal composition and the thickness of the megaregolith and lithosphere. Even with reduced local effects in heat flow relative to Earth, measurements from only two locations on the moon (Langseth et al. 1976) do not adequately constrain lunar heat flow. Subsequent remote sensing data has shown that these two measurements straddle compositional terrane boundaries. Without additional measurements, variations in crustal heat production cannot be distinguished from mantle sources, and the global heat source abundance cannot be well constrained. More heat flow measurements should be made at depths that extend below the penetration depth of the annual thermal wave. Long duration measurements are needed to determine both the bulk thermal diffusivity, and the local depth of penetration of the annual wave. To help obtain straightforward results, heat flow measurements should be taken well away (> 100–200 km) from terrane boundaries.

The global heat budget of the moon needs to be determined more precisely to better constrain lunar thermal evolution and to answer several key outstanding questions:

a. What is the bulk composition of the moon in terms of heat-producing elements? The two measurements obtained by Apollo leave ample room for interpretation. Langseth et al. (1976) used heat flow to estimate that the moon has a uranium abundance of 46 ppm, much higher than that estimated for the Earth. Rasmussen and Warren (1985) instead suggested that variations in regolith and lithospheric thickness contributed to elevated heat flow at the Apollo sites, and that the moon's composition is actually much more similar to that of the Earth. Potential contributions from variations in local lithospheric structure emphasize that it is critical to combine heat flow and seismic measurements, which would allow for variations due to crustal and lithospheric thickness to be estimated.

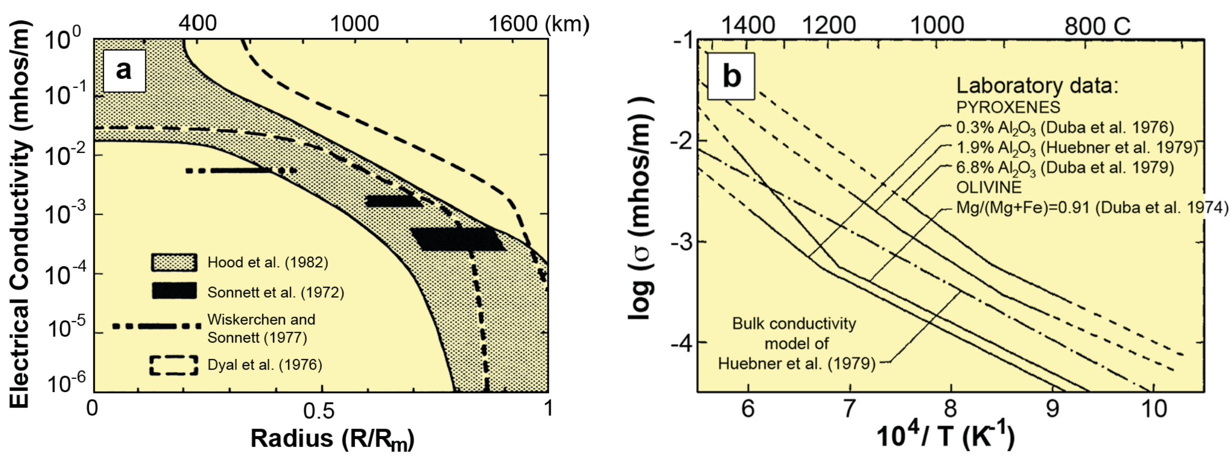
b. Do different lunar terranes have unique heat flow budgets, as suggested by the Apollo data? What are the implications of these differences for the chemical, thermal and magmatic evolution of the moon? While Apollo 17 landed in the Feldspathic Highlands Terrane, the heat flow was measured in a basaltic (mare) region. Thus the variation due to Procellarum KREEP terrane cannot be uniquely determined without additional measurements. Remote sensing measurement show that the KREEP terrane is enriched in U and Th at the surface, but it is not known to what extent these variations continue into the interior. Sufficient concentrations could account for mare volcanism (Wieczorek and Phillips 2000).

4.3 Lunar Surface Magnetometer

The Lunar Surface Magnetometer (LSM) (Dyal et al. 1970) was deployed as part of the ALSEP by the Apollo 12, 15 and 16 missions (Fig. 2). Science data were recorded until June 29, 1970 at Apollo 12, December 10, 1973 at Apollo 15, and March 3, 1975 at Apollo 16 (Bates et al. 1979). The LSMs, along with Explorer 35, were used to study the properties of the lunar interior and the lunar environment, specifically: a) electrical conductivity, temperature, and structure of the lunar mantle and core; (b) magnetic permeability and mantle iron abundance; (c) surface remnant magnetic fields; and (d) lunar environment (atmospheric, ionospheric, and interactions with the geomagnetic tail).

Data from the ALSEP magnetometers, in conjunction with the low-altitude orbital magnetometer measurements, revealed an unexpected magnetization in much of the lunar crust (Fuller 1974, Fuller and Cisowski 1987, Hood 1995). 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 (Dyal et al. 1974, Hood 1980, Halekas et al. 2001, Hood et al. 2001, Richmond et al. 2003, Hood and Artemieva 2008). Globally, anomalies are concentrated in regions antipodal to the four youngest large impact basins (Lin et al. 1988, Lin et al. 1998, Hood et al. 2001). The strongest individual anomalies often are coincident with unusual albedo markings of the Reiner Gamma class (Hood et al. 1979, Hood and Williams 1989). Paleointensity estimates for returned samples indicated the existence of a "high-field epoch" during the 3.6 to 3.9 Gy period (Cisowski et al. 1983, Fuller and Cisowski 1987). A major outstanding issue is distinguishing between surficial, impact-induced magnetization and deeper source fields due to crustal cooling in the presence of a core dynamo.

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. Although correlative studies suggest that basin ejecta are the sources of lunar magnetic anomalies, 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 sources of the magnetizing fields remains uncertain. As noted above, paleointensity estimates for returned samples indicate the existence of a core dynamo. However, if basin ejecta are the sources of lunar crustal fields, such sources would have formed relatively quickly (times up to 1 day) so that transient magnetic fields could have contributed importantly to the magnetization. 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). Unfortunately, each ILN node will only add a single point measurement of the remanent field and so the data will be of limited use for probing crustal magnetization compared to orbital and rover-based surveys.



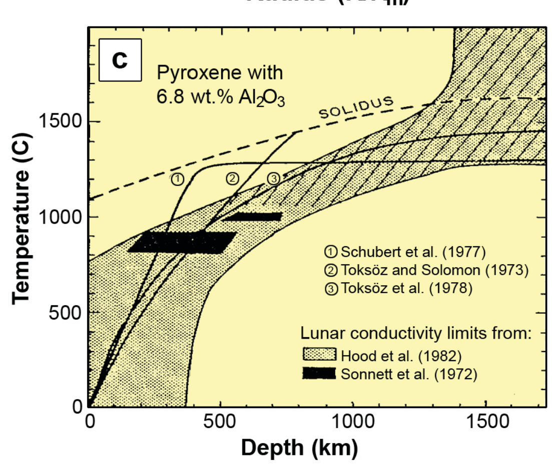


Figure 8. Lunar EM sounding interpreted using laboratory data (adapted from Hood and Sonett 1982): a) Estimated limits on electrical conductivity vs. radius based on simultaneous surface and orbital magnetometer data; b) Laboratory temperature-conductivity data for pyroxenes, olivines, and a bulk model for the lunar interior below several hundred km; c) Derived lunar temperature-depth profile. Shaded area represents range of temperature profiles based on electrical conductivity limits; solid lines are theoretical present day temperatures; dashed line is the anhydrous basalt solidus.

Natural-source electromagnetic (EM) sounding is another geophysical method used to sense the deep interior of the Earth and moon. EM measurements depend upon the principle of induction, in which a changing magnetic field induces eddy currents in an object, whose secondary EM field is in turn detected. Most prior lunar measurements used the transfer-function technique, comparing the magnetic fields in high lunar orbit (Explorer 35) to those at the surface (Apollo 12). These studies provided important constraints on core size, mantle free-iron and alumina abundance, and interior temperature and thermal evolution (Dyal et al. 1974, Goldstein and Phillips 1976, Dyal et al. 1977, Hood et al. 1982, Hood and Sonett 1982, Sonett 1982, Hobbs et al. 1983) (Fig. 8). Interpretation of electrical conductivity to temperature and composition is accomplished from laboratory measurements (e.g., Duba et al. 1974, Constable et al. 1992, Xu et al. 1998, Wang et al. 2006, Yoshino et al. 2006).

Electromagnetic sounding can be used to improve upon estimates of core size, deep mantle properties, and lateral heterogeneity in the upper crust and mantle. Greater bandwidth and higher resolution are required for the latter investigation, which may require new approaches beyond the transfer-function technique. New EM measurements would be complementary to seismology and heat flow in understanding the interior structure and thermal evolution of the moon.

4.4 Lunar Laser Ranging

Corner-cube retroreflector arrays were deployed at the Apollo 11, 14, and 15 sites as well as on the Soviet Lunokhod 1 and 2 rovers (the Luna 17 and 21 missions, respectively; Fig. 2) to allow lunar laser ranging (LLR). Four of these five instruments are still being used in studies of the moon and astrophysics (Lunokhod 1 can no longer be used). There are now 38 years of increasingly accurate laser ranging (Dickey et al. 1994, Merkowitz et al. 2007), providing 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., Williams et al. 2006, Ratcliff et al. 2008). However, there is still considerable uncertainty about the deep interior to which improved LLR data would significantly contribute.

LLR is sensitive to the fluid core moment of inertia, which depends on core density and radius. Analyses of tracking data on orbiting spacecraft give the second-degree gravity harmonics J_2 and $C_{2,2}$. LLR data analysis gives the moment of inertia combinations $(C-A)/B$ and $(B-A)/C$. Combining the two sets gives lunar C/MR^2, the polar moment C normalized with the mass M and radius R (Konopliv et al. 1998). LLR is also sensitive to the fluid core moment, indirectly through the dissipation at the fluid core/solid-mantle boundary and directly through the dynamics (Williams et al. 2001). Uncertainty in the fluid core moment is the main limitation to the uncertainty in the total moment. A solid inner core might exist inside the fluid core, but it has not yet been detected by any technique. Gravitational interaction between an inner core and the mantle would affect the mantle's three-axis rotation. Accurate determination of these quantities depends on a long time span of high accuracy range data.

Love numbers depend on the elastic properties of the interior including the deeper zones where the seismic information is weakest. Tidal distortion of the second-degree gravity potential and moments of inertia depends on the Love number k_2, but the major uncertainty to solutions for k_2 is flattening of the core-mantle boundary (CMB).

LLR detects CMB flattening, but currently the product of CMB oblateness and fluid core moment of inertia is determined more strongly than either separately. Elastic tidal displacements are characterized by the lunar second-degree Love numbers h_2 and l_2. LLR detects tidal displacements and determines h_2 with a 20% uncertainty with l_2 fixed, but k_2 is more accurately determined (12%) through rotation (Williams et al. 2001). The distribution of the Apollo retroreflector arrays is weak for determining tidal displacements. Future sites could strongly improve the determination.

The tidal specific dissipation *Q* depends on the radial distribution of the material *Q*s, a proxy for the internal layered structure. LLR detects tidal dissipation and infers a weak dependence of tidal *Q* on frequency. The tidal *Q*s are low, ~30 at a one month period and ~35 at one year. LLR does not distinguish the location of the low-*Q* material, but at seismic frequencies low-*Q* material, suspected of being a partial melt, has been inferred in the deep zone above the core. Future LLR sites would help increase the frequency span.

The accumulation of LLR data also allows tests of the Equivalence Principle, a fundamental tenet of Einstein's Theory of Relativity (Dickey et al. 1994). Einstein's Theory of Relativity does not predict a variable gravitational constant, *G*, but some other theories of gravity do. LLR data can be used to test a possible change in *G* with time because of the sensitivity of the lunar orbit to solar longitude. Results indicate that *G* does not show evidence of variation and thus the LLR tests are supportive of the theory of relativity.

5.0 Science Definition for the ILN Anchor Nodes

The narrow extent and instrumental limitations of the Apollo seismic, magnetometer, heat flow, and laser ranging network resulted in very little information regarding crustal variations, limited resolution of upper-mantle mineralogy, and few details about the lower mantle or the lunar core. Other geophysical methods also had limited coverage and resolution. The goal, therefore, of a next-generation lunar geophysical network will be to ***understand the interior structure and composition of the moon***. As a differentiated body, the moon provides fundamental information for our understanding of the evolution of terrestrial planets.

The SDT concluded that seismometry is the only technique that will satisfactorily provide the details of the deep lunar interior structure, including its velocity structure and dimensions, and that multiple nodes are required to achieve this goal. The SDT further concluded that direct measurement of the lunar heat flow is the second most critical measurement for this mission. Although heat flow is not a network experiment *per se*, the objectives addressable by heat-flow measurements are achievable only by making the measurements at multiple sites on the moon. Furthermore, heat-flow and seismic measurements work to substantiate each other by providing complementary information at the same location. The SDT further concluded that electromagnetic sounding and laser ranging are desirable measurements that provide new information. The SDT thereby defined the science objectives of the ILN Anchor Nodes (Box 2), in order of priority.

Box 2: Science Objectives for the ILN Anchor Nodes

1. Understand the current seismic state and determine the internal structure of the moon.
Rationale: Understanding the internal structure of the Moon is critical to unraveling its origin, evolution and differentiation. Only a seismic network has the ability to unequivocally deter-mine the presence, size, and material properties of the core and lower mantle. Detection of lunar tectonic events will enable determination of the internal structure and composition of a differentiated planetary body. Understanding how strong moonquakes are generated and where they occur has implications for lunar geology and for the siting of a lunar base.

2. Measure the interior lunar heat flow to characterize the temperature structure of the lunar interior.
Rationale: Heat flow measurements constrain the abundance of radiogenic elements, lateral variations in crustal and upper mantle composition, residual accretionary heating, and the nature of thermal evolution in a differentiated body.

3. Use electromagnetic sounding to measure the electrical conductivity structure of the lunar interior.
Rationale: Interior temperature and composition can be inferred from conductivity, allowing joint interpretation with seismology and heat flow. Additional measurements of crustal magnetization and the space-physics environment are auxiliary goals.

4. Use next-generation laser ranging to determine deep lunar structure and conduct tests of gravitational physics.
Rationale: Highly accurate laser ranging to the moon reveals small irregularities in the lunar rotation due to tidal changes of the moon's shape and motion of the lunar mantle and core. Ranging also enables tests of gravitational physics and improvement of the lunar orbit de-termination.

These science objectives address Concept 2 in *The Scientific Context for Exploration of the Moon:* "The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body." They also touch on several subgoals of the SCEM report, notably Goal 3a: "determine the extent and composition of the primary feldspathic crust, KREEP [potassium, rare-earth elements, and phosphorus] layer, and other products of planetary differentiation." Finally, this strategy is consistent with recommendations made both by the SCEM report ("Emplace a geophysical network to include, at a minimum, seismic and heat-flow experiments, environmental sensors, and new laser ranging retroreflectors") and the NASA Advisory Council Planetary Science Recommendation S-07-PSS-2 ("Emplace a geophysical network on the lunar surface, specifically a long-lived geophysical measurement node containing a seismometer, a heat-flow probe, a magnetometer, and possibly an optical retroreflector").

Starting from the science objectives, the SDT derived measurement requirements to meet each objective and made further recommendations for both the instrumentation and the mission. These recommendations are the source of the recommended science mission (Network Science Baseline), which is to understand the lunar interior structure and composition by using multiple geophysical analyses at each of four locations on the moon operating simultaneously and continuously for at least one 6-year lunar tidal cycle.

Figure 9 illustrates variations of this baseline mission in terms of descope options and establishes a floor mission below which no mission should be flown. To accomplish the full network science, a minimum of four nodes is needed. If all four cannot be accommodated, the descope tree should be followed downward to allow the greatest number of instruments to be flown. The divided boxes denote carrying either EM sounding or Laser Ranging, at the discretion of the mission. The Science Floor is defined as each node carrying only a seismometer.

The original guidance for the mission implementation was a mission of two geophysical packages at two different lunar sites with an operational lifetime of 2 years. In considering these mission constraints, the SDT defined the minimal acceptable (Floor) Science mission (Fig. 9), where the science objectives would be descoped solely to determining the deep interior velocity structure of the Moon and placing constraints on the core size/density by operating two broadband seismometers simultaneously and continuously for 2 years.

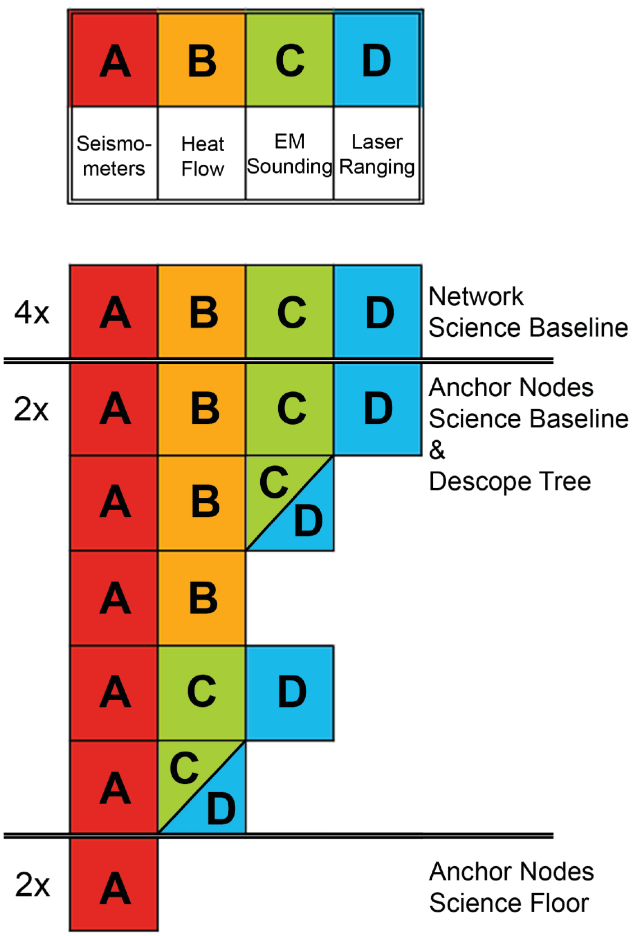


Figure 9. Prioritization of measurement goals and instrumentation for the Science Baseline and Science Floor mission definitions. To accomplish the full network science, a minimum of 4 nodes is needed. Within the scope of the Anchor Nodes (nodes 1 & 2), the SDT recommends a complement of four measurements, in order of priority: seismic > heat flow > EM > laser ranging. If all four cannot be accommodated, the descope tree should be followed downward to allow the greatest number of instruments to be flown. The divided boxes denote carrying either EM sounding or Laser Ranging, at the discretion of the mission. The Science Floor is defined as each node carrying only a seismometer.

These descoped science objectives can only be met by placing the nodes at specific nonpolar sites relative to known deep-moonquake nests, using the same strategy that was planned by the JAXA LUNAR-A mission (see section 7.2). However, this definition of a Science Floor mission was not unanimously accepted among the SDT members and the entire SDT very strongly recommends that any geophysical nodes have a lifetime much longer than 2 years and that they be a part of a larger network.

Effectively exploring the deep structure of the moon using the information available in seismic waves can only be accomplished with a minimum of four seismic nodes, globally distributed to provide definition of deep ray paths that will sample structural and seismic velocity variations (see section 7.1). The ILN network must have a much broader coverage than that of the Apollo network (see section 7.2). Many of the shortcomings of the Apollo seismic database stem from the lack of coverage beyond the central nearside of the moon. Therefore, extending coverage to the lunar farside is very strongly desired. The seismometers need to be simultaneously operational to receive data from each moonquake, leading to the mission requirement that nodes operate continuously (i.e., through lunar day and night cycles). The Apollo network recorded approximately one highly energetic (magnitude 5 or greater) shallow moonquake event per year and showed that deep moonquakes display cyclic behavior, leading to the lifetime requirement of one 6-year lunar tidal cycle (see section 7.3).

Any reduction from the recommended Network Science Baseline mission will affect its scientific impact. Although only seismometry is uniquely enabled by a network, other geophysical measurements at the same location greatly enhance interpretation of the seismic data. Reducing the number and variety of instruments at each site will limit our ability to understand the interior at each location. Scaling back on mission implementation also has serious consequences. If stations are widely distributed but operate only during lunar daytime, they would rarely be simultaneously operational. If the node lifetime is truncated at less than 6 years, the number and periodicity of observed moonquakes would be limited.

The four stations needed to accomplish the Network Science Baseline mission might consist of four US nodes, or two US nodes plus contributions from other Agencies. It is the SDT's opinion that the US should be responsible for ensuring that at least two stations carry an appropriate seismometer (Table A1) that will operate continuously for the lifetime of the network. This will ensure that the US nodes act as true Anchor Nodes in the sense that they allow other Agencies to fly missions that contribute to the goals of lunar network science without imposing limitations that are difficult for other missions to meet. For example, other nodes might operate only during sunlit times, have shorter lifetimes, have staggered delivery dates, fly less-sensitive instruments, or carry a different payload complement. If the US nodes act as Anchors in which to incorporate all other network data, then any of these alternative approaches would still help accomplish the goals of a geophysical network.

6.0 Science Measurements and Instrumentation

The Science Definition Team considered different experiments that would be most useful for probing the lunar interior and defined precision and accuracy of the measurements needed to achieve the science goals set for the Anchor Nodes (Table A1). The intention of this study is not to prescribe the exact payload for either the International Lunar Network or for the Anchor Nodes themselves, but rather to explore several ways that measurements of the deep lunar interior may be accomplished and to outline the sensitivities needed to achieve those goals. The SDT expects that the instrument payload will be competed and it will be incumbent on the proposers to demonstrate their ability to meet the ILN Anchor Nodes science goals.

6.1 Seismometry

Seismometry Measurement Goals: The goals of the ILN Anchor Nodes seismic investigation are to improve our knowledge of the structure of the crust, mantle and core, and to understand the distribution and causes of seismic activity. These goals can be described as follows:

1. Crust—Determine the mean crustal thickness and any large-scale compositional layering. To the extent possible, characterize local differences in velocity structure that can be related to lateral variations in crustal composition.
2. Mantle—Determine the vertical velocity structure of the mantle as a constraint on composition, particularly below 600 km, where the Apollo data provide little information. Characterize any global-scale layering and discontinuities due to chemical stratification or phase transitions.
3. Core—Determine the radius of the core and constrain its composition and state (liquid or solid). To the extent possible, determine the existence or absence of a solid inner core.

4. Seismicity—Characterize deep moonquake "nests," especially on the far side, and determine their source mechanisms and their relationships to tidal forces and other internal stresses. Determine the locations and causes of shallow moonquakes and their relationship, if any, to lunar tectonics. Characterize the lunar seismic background and determine the contributing sources such as meteoroid impact rate as a function of size, transient thermal stresses, etc.

Seismometry Measurement Requirements: The first measurement priority is to accurately detect various body wave arrivals ("phases") for small, distant quakes at multiple (at least four) well-spaced locations across the moon. These phases include the direct P and S waves, as well as reflected (e.g., pP, PcP), refracted (e.g., PKP) and converted (e.g., pS, SKIKP) phases that carry additional information on the internal structure. The detection at multiple, well-spaced locations is crucial for reconstructing the origin and path of the rays, from which the velocity structure and the locations of internal boundaries can be determined. Equally crucial is the detection of the most distant quakes, as these provide ray paths that travel deep in the planet, revealing the innermost structure.

The identification of these arrivals is complicated by attenuation (particularly at high frequencies), strong scattering within the crust, and the exceedingly small magnitude of most moonquakes. These challenges can be overcome by extremely sensitive, three-axis broad-band measurements that enable the utilization of sophisticated digital signal processing techniques that have been developed for terrestrial seismology over the past five decades. Spectral analysis of the seismic waves provides a direct measure of the elastic properties and density at various depths. In the case of surface waves, this information, derived from the velocity dispersion, is specific to the wave's path from its source to the receiver, providing localized information. For normal modes, the globally averaged structure determines the frequencies of the resonance peaks. Thus, it is important to extend seismic measurements to lower frequencies to search for surface waves (~0.05–0.01 Hz) and normal modes (~0.01–0.001 Hz).

Seismometry Instrument Requirements: The seismometers must provide vector measurement (i.e., measure displacement on three orthogonal axes) covering a dynamic range of ~24 bits (Apollo was limited to 10 bits) in order to characterize the lunar background as well as seismic events. The seismometer effective sensitivity requirements are stated in terms of the acceleration power spectral density (PSD, units of $m/sec^2/Hz^{1/2}$) of the instrument noise in three frequency bands, *f*:

a. $f > 1.0$ Hz: The sensitivity should be about the same as or slightly better than PSD $\approx 10^{-9}f^2$ (the Apollo SP), with a high-frequency cutoff no lower than 20 Hz.
b. $0.1 < f < 1.0$ Hz: The sensitivity should be at least an order of magnitude better than the Apollo LP (peaked mode). This corresponds approximately to PSD $\approx 10^{-10}f$.
c. $0.001 < f < 0.1$ Hz: The sensitivity should be at least an order of magnitude better than the Apollo LP (peaked mode). This corresponds to PSD $\approx 2\times10^{-11.5}/f^{1/2}$. In order to satisfy the objectives of detecting surface waves and normal modes, it is strongly desired that the low-frequency performance should attain a PSD $\leq 10^{-11}$ across the entire band.

Because of the high sensitivity requirements of the seismometer, the instrument must have the ability to maximize its thermal and mechanical stability and its emplacement on the surface.

Seismometry Mission Requirements: The mission must be responsible for isolating the seismometer from the vibrational and thermal interference of the spacecraft in the frequency range of interest (0.001-20 Hz), including such interferences as are passed from the spacecraft to the moon and back to the seismometer. Because interpretation of the seismic signals depends on the time the signals are received at the different nodes, the mission must have inter-station timing accuracy of ~5 msec or better (reconstructed), though the nodes do not need to communicate directly with each other. The seismometers must operate simultaneously. To capture a statistically significant number of events and characterize seismic activity over a lunar tidal cycle, the seismic nodes must remain operational for at least six years as part of a larger network.

In order to overcome the limitations of the Apollo network, the ILN requires a global distribution of nodes. The nodes should not be closer than ~2000 km. There is a strong science motivation to place at least one node on the farside. If this is not possible, there should be at least two nodes located within ~20° of the limb. To the extent possible, nodes should be placed unambiguously in each of the major terranes. There are special location considerations for the first two nodes of the network in order for it to be able to address high-priority goals in the absence of the full network (Section 7.2).

6.2 Heat Flow

Heat Flow Measurement Goals: Determining the heat flow in multiple locations on the surface of the moon will permit the characterization of radial and lateral variations in the distribution of radiogenic elements, as well as constrain the bulk abundance of these elements. Furthermore, joint inversion of lunar seismic data with the thermal structure of the moon will facilitate discrimination among the different models of internal structure. Therefore, the goal of a heat flow experiment on the ILN Anchor Nodes should be to measure the heat flow in multiple locations over the surface of the moon.

Heat Flow Measurement Requirements: Planetary heat flow at the surface is dependent on the thermal properties of the regolith and the temperature as a function of depth. Thus, determination of the lunar heat flow requires independent measurement of temperature and thermal conductivity as a function of depth.

The Apollo data indicate that the upper 1–1.5 m is strongly affected by propagation of the diurnal and annual thermal waves, thus necessitating measurement of temperatures below this depth range. As the near-surface thermal gradient is of order 1 K m^{-1}, measurement over depth spans of at least 1 m are required with a precision of 0.001 K. These factors control the experiment depth requirement of 3 m. Similarly because the thermal conductivity is known to vary with depth (e.g., Langseth et al. 1976), this parameter must also be measured at multiple depths along this 3-m length.

Heat Flow Instrument Requirements: The primary requirement for conducting a heat flow experiment is deployment to a depth of ~3 m. Apollo astronauts had difficulty achieving depths greater than 2 m with hand held drills, sometimes achieving considerably less. The lunar regolith is both very compacted and highly cohesive due the repeated comminution of fragments by impacts. Buried rocks pose additional obstacles to achieving sufficient depth. Furthermore, simply placing any device into the subsurface will alter the thermal environment by compacting the regolith adjacent to the drill, penetrator, mole, etc. If there is an open hole, regolith may fall back into the hole in an unknown manner. This can pose a challenge to making representative conductivity and temperature measurements.

The low conductivity regolith environment presents a further hurdle for accurate heat flow measurement. Any device emplaced into the subsurface is going to have a higher conductivity than the regolith. The challenge is to prevent the large surface temperature variations from being conducted to depth and disturbing the thermal environment. As discussed above, the lander itself disturbs the thermal environment. On Apollo, the surface was altered by astronaut activity, and the borestem sticking up above the ground may have thermally affected the surrounding regolith. Thus the calibration of the thermal environment for the heat flow experiment is important, although the disturbance of the thermal environment may be modeled post facto (e.g., Langseth et al. 1976).

Measuring the thermal conductivity in a low conductivity environment is also challenging. A heat pulse must be conducted into the regolith to a sufficient distance that the pulse is sampling undisturbed regolith. This requires both that the heater be in good contact with the regolith and that there be adequate time to monitor fully the decay of the heat pulse. The conductivity is known to vary with depth from Apollo, and thus must be measured at intervals comparable to that of the temperature measurements. On Apollo, in addition to an active heating method, the conductivity was estimated by examining the rate of propagation of the annual wave into the interior. This approach provides a good complement to active heating since it samples the bulk conductivity.

Heat Flow Mission Requirements: Heat flow measurement places constraints on lander operation and configuration. The presence of the lander creates a thermal disturbance that conducts hear into the interior and shadows the surface, potentially interfering with the thermal measurements. This effect can be mitigated by either deploying the heat flow experiment at approximately 1 lander diameter away from the lander or by deploying the heat flow experiment in a location such that the thermal effect of the lander can be readily modeled and removed. Deployment away from the lander is preferred since monitoring the propagation of the annual wave into the interior provides a complementary measurement of conductivity.

The thermal measurements should be made over a minimum 2-year period for several reasons. First, as demonstrated on Apollo, monitoring the propagation of the annual wave provides a reliable means of estimating the unperturbed, bulk conductivity of the regolith with depth, which complements the direct measurements of the conductivity. Estimates of the heat flow from Apollo data were reduced by 30–50% when thermal diffusivity estimates from the annual wave were incorporated (Langseth et al. 1976). Second, Apollo 15 and 17 measurements show an increase of at most a few ºC at all depths within the subsurface over several years. Although Langseth et al. (1976) attributed this increase to propagation of a surface disturbance due to astronaut activity, other ideas proposed to explain this increase include the effect of the 18.6-yr lunar libration (Wieczorek and Huang 2006), instrument drift, and topographic shadowing effects (Saito et al. 2008). Future measurements should be designed to mitigate both surface disturbance and electronics issues, thus making it possible to test other hypotheses. While it would be interesting to see if lunar cycles affect subsurface temperature, it should be emphasized that the observed increase in surface temperature does not compromise the measurement of the interior heat flux. If a similar increase is seen in future experiments, comparison with Apollo data should make it apparent whether the temperature variations are consistent with well-constrained lunar cycles. If so, the effects of these cycles can be extracted from lunar heat flow data. If not, surface temperature increases due to the emplacement of the experiment can be modeled as a surface transient. In either case, the effect on interior heat flow estimation is small. Third, monitoring one or more annual cycles ensures that the thermal gradient measurement is validated by correction for the annual wave, or by determining the gradient below the annual wave.

6.3 Electromagnetic (EM) Sounding

EM Sounding Measurement Goals: The overall objective of EM sounding from the ILN Anchor Nodes is to infer internal temperature and composition, complementing seismology and heat flow in pursuit of the general ILN goal of understanding the interior structure and thermal evolution of the moon. The primary goal of renewed EM sounding will be to determine the electrical conductivity structure of the outermost 500 km and its spatial variability. This region was poorly resolved in Apollo-era measurements. Understanding 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 (FHT, PKT, and SPA). Secondary goals of an EM investigation are to improve knowledge of the conductivity and composition of the lower mantle of the moon (~500–1400 km depth) and to assess the size and state of the core. An EM experiment also enables other investigations beyond the immediate scope of the ILN, as previously discussed.

EM Sounding Measurement Requirements: EM sounding using frequencies up to ~10 Hz would help resolve vertical and horizontal variations in the lunar structure. The earlier transfer-function approach (e.g., Hood et al. 1982) compared magnetic-field data acquired simultaneously by Explorer 35 in high lunar orbit (the inducing field) and by Apollo 12 on the lunar surface (the sum of the inducing and induced fields). The lunar response is well represented by a dipole at frequencies less than several mHz because wavelengths in the incident solar wind are much greater than the lunar radius. Multipole analysis extended the response to 40 mHz (Sonett et al. 1972) but this method requires assumptions for the wave-front incidence direction and speed. Extrapolation of this approach to significantly higher frequencies may restrict the reference magnetometer to a low lunar orbit so that the relevant short-wavelength parts of the source field can be analytically propagated to the surface with minimum error. This will limit soundings to the dayside in the solar wind, where the induced field is confined and orbiting spacecraft can still sense the free-stream plasma to within tens of kilometers of the surface. The time available for simultaneous EM measurements is then cut to some few orbits around the repeat interval of the ground track, which translates to efficiencies of just a few percent. Many passes over the ground station are necessary to separate the time-varying magnetic field from crustal magnetism. Finally, this approach would invoke orbital resources that are not specified as part of the ILN Anchor Nodes mission. However, the presently operating Japanese Kaguya spacecraft carries a magnetometer with accuracy <0.1 nT and useful bandwidth >1 Hz (http://www.kaguya.jaxa.jp/en/equipment/Image.htm); it may be reasonable to expect similar resources to become available in the next decade to support the ILN nodes. For the purposes of this report, however, the ILN Anchor Nodes are envisioned as stand-alone surface assets. Without the support of an orbiter carrying a magnetometer, the transfer-function approach is not viable; should an orbital asset become available, this approach could be reopened.

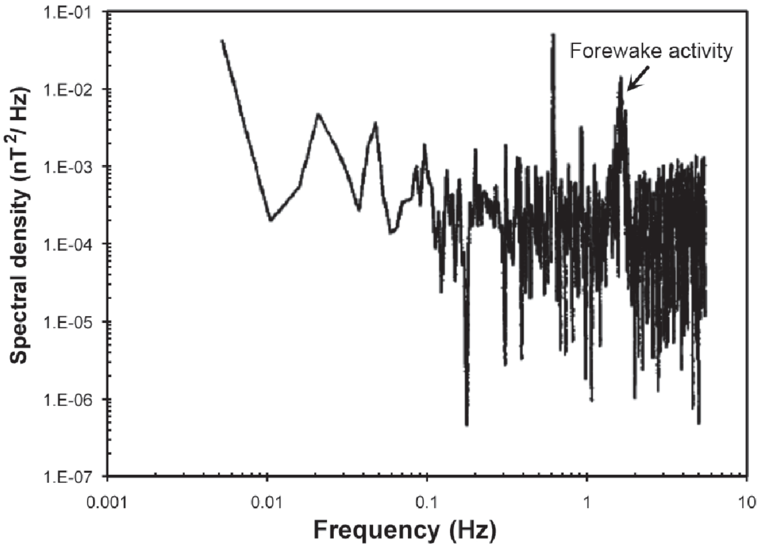


Figure 10. A single raw spectrum from the WIND magnetometer in the vicinity of the moon (Farrell et al. 1996), showing significant energy to >1 Hz. Magnetic fields in Earth-moon space fall steeply in the 10–100 Hz range (Gurnett 1985).

A complete EM sounding can be performed from an individual surface node by measuring orthogonal horizontal components of the time-varying magnetic and electric fields, i.e., by the magnetotelluric (MT) method (see Vozoff 1991 and Simpson and Bahr 2005 for reviews). Applicable frequencies are limited only by source strengths and sensor responses. Measurement of the solar-wind velocity is unnecessary and the method is insensitive to variations in incidence angle. The plane-wave impedances determined by MT are extendable to spherical geometry when wavelengths become comparable to the planetary radius (Weidelt 1972, Hobbs et al. 1983). MT naturally provides spatially independent measurements with horizontal resolution comparable to the EM skin depth.

Improved knowledge of the conductivity of the lower mantle (~500–1400 km depth) does not require additional bandwidth and associated changes in measurement techniques, but rather improved signal-to-noise ratio (SNR). By comparing results from different parts of the lunar orbit around the Earth and by acquiring data over many such orbits, the ILN Anchor Nodes EM experiment seeks to understand systematic differences evident in Apollo-era data and to reduce the random logarithmic error by a factor of three, i.e., to determine the conductivity to within a half decade. This would narrow the range of acceptable combinations of temperature and composition. For example, the uncertainty in lower-mantle temperature would be reduced from several hundred degrees to about ±75ºC for the composition specified in Figure 8. Assessment of heterogeneity in this region would be indicative of the past efficiency of convective mixing.

Finally, although core characterization is more readily performed using seismology, an EM investigation can help assess the size and state of the lunar core. A fluid (outer) core is suggested by laser ranging (Williams et al. 2001), but it is unknown whether this represents molten metal or silicate. The most recent estimate of the lunar core radius is 340±90 km using EM (Hood et al. 1999), in good agreement with an upper limit of 435 km previously determined by Hobbs et al. (1983). Compositional ambiguity again exists because both molten metal and silicate cores appear as perfect conductors at the lowest reliably measured frequency of ~50 μHz. In other words, eddy currents in both cases remain on the surface of the core at the frequencies considered. However, if the core is silicate, its conductivity will likely not exceed ~10 S/m (Simpson and Bahr 2005) and therefore frequencies <1-10 μHz would notably penetrate such a core and distinguish its response from metal. Careful instrument calibration is necessary to accurately measure these very long periods.

An ILN EM sounding experiment has implications for other investigations. The DC magnetic-field strength and direction is important for constraining downward continuation of orbital data, ultimately to understand whether magnetic anomalies have an impact or a crustal origin, with the latter perhaps related to an early core dynamo (Wieczorek et al. 2006). To test these hypotheses, lateral and/or vertical mobility is required to fully characterize local magnetic-field structures, but such assets are not available to the ILN Anchor Nodes. Plasma-surface interactions can be studied in more strongly magnetized regions. Long-term monitoring of the electromagnetic and plasma environment may be important for human spaceflight.

EM Sounding Instrument Requirements: Although all of the required measurements have been made previously in space, MT has not yet flown as a system. There are two new considerations to implementation of MT on the moon. The first is that the active plasma environment could affect local electric fields differently from magnetic fields and therefore bias the impedances. Standard characterization of the plasma environment will be important to identify any electro-static plasma effects. When inverting for subsurface conductivity, the plasma can be treated simply as a conducting layer, in analogy with ocean-bottom MT (Constable et al. 1998). The second consideration is that electric-field measurements must be made without depending on galvanic contact with the ground, and likely on a shorter baseline, than is done on Earth. For the moon, DC coupling of the sensors to the plasma will achieve electrical contact. Voltage probe separations of several meters (comparable to those used in ocean-bottom MT (Constable et al. 1998) should be sufficient to measure the relevant electric fields.

Instrument requirements for the ILN EM-sounding investigations can be developed by computing the wideband response of previously established conductivity bounds (Sonett et al. 1972, Hood et al. 1982; Fig. 8a). Good discrimination in the upper 500 km is established above 100 mHz (Grimm and Delory 2008). Measurements up to 100 Hz might be useful in detecting signatures of the crust, but strong, well-documented, EM fields are restricted to ≤10 Hz (Fig. 10). Sensitivity requirements are derived directly from Fig. 10 for magnetic fields B and from the computed apparent resistivity ρ_a (Grimm and Delory 2008) for electric fields, $E = B(\rho_a\omega/\mu_0)^{1/2}$, where ω is the angular frequency, and μ_0 is the free-space permeability. Both measurements have signal-to-noise ratio >10. MT is specified as the baseline investigation, but magnetometers alone could provide a measurement floor, assuming a low-orbiting magnetometer was available.

EM Sounding Mission Requirements: Mission requirements are imposed by the configuration and deployment of the sensors and the duration and variety of the measurements. Optimally, data should be acquired at a sufficiently large distance from the lander that intrinsic or induced signals from that spacecraft can be neglected, e.g., ballistic deployment to many lander diameters or more. Alternatively, booms could deploy the sensors to distances of order one lander diameter, and the different signals in two magnetometers at different radial distances used to subtract the lander offset (Ness et al. 1971, Leinweber et al. 2008). Plasma characterization could involve several additional sensors based on the lander. Data should be acquired during day, night, and magnetotail passages in order assess the different signals and boundary conditions imposed by these environments. The high-frequency measurements for the primary investigation could in principle then be completed in just one lunar orbit of the Earth. The lowest-frequency soundings for the secondary core investigation may require signals as long as a month, and therefore several such periods would be needed to derive a reliable spectrum. All told, one year of measurements should be sufficient.

6.4 Lunar Laser Ranging (LLR)

LLR Measurement Goals: A wider distribution of retroreflector sites will improve the determination of three-dimensional rotation and tides. Currently, the lunar laser ranging sites cover 25% of the north-south diameter and 38% of the east-west diameter of the moon (Fig. 2). A minimum of three sites is needed to be able to use the LLR data to probe the lunar interior. Expanding the number of LLR sites and their geographical coverage will improve the determination of lunar interior parameters, giving a better understanding of the fluid core/solid mantle boundary conditions as well as the presence/absence of a solid inner core (Williams et al. 2008), as well as address several fundamental physics questions.

LLR Measurement Requirements: New LLR equipment, whether active or passive, should enable measurements to be made with a precision comparable to or better than current abilities, which is about 2 cm position determination.

LLR Instrument Requirements: Current LLR science requires single photon detection due to r^4 signal loss (~10^{-21} photons lost over the 2 x 385,000 km round trip). For retroreflectors, even single photon returns require large (hundreds of cm^2) arrays pointed within a few degrees of the Earth. New LLR devices should be designed to reduce the scatter of the individual photons used to make a normal point. The current major source of error using LLR from lunar retroreflector arrays is scatter due to thermal flexing of the arrays, so one solution may be to thermally ground or actively control array temperature. Next-generation retroreflector arrays might employ hollow cubes which weigh much less than their solid counterparts so arrays could be made larger, or use new materials such as beryllium, which experiences smaller thermal distortions, so the cubes can be made larger without sacrificing optical performance (Merkowitz et al. 2007). Besides retroreflector arrays, laser transponders are also a possibility (Merkowitz et al. 2008, Turyshev et al. 2008). Transponders would give much brighter and more coherent signals that would be receivable by Earth-based assets over a broad geographic area, but they require power and pointing.

LLR Mission Requirements: New LLR sites on the moon could increase the north-south spread by a factor of 4 and the east-west spread by a factor of 2.6. Sensitivities to lunar science effects would increase by these factors. A larger north-south distribution would help determine fluid core moment and CMB flattening, and help look for free wobble stimulation. A wider east-west distribution would help look for free longitude libration stimulation. Both distributions help determine tidal *Q* vs. frequency and will aid the search for a solid inner core.

Important time scales for lunar science observations span 0.5 months to decades. A useful position for a new array or transponder could be determined with one to several months of tracking, though spans of years give the highest accuracy. Data spans of years are optimum for most lunar science applications but that would include continued accurate tracking of the four existing lunar retroreflector arrays.

7.0 Additional Mission Planning Considerations

7.1 Number of Nodes

The number of nodes is most directly tied to the seismology experiment and controls the science return by allowing for unequivocal location and timing of seismic events. The more nodes, the better the coverage and the more complete will be statistics for small magnitude events. With fewer than four nodes, the return is significantly decreased.

Four or More Nodes: Four seismometers are necessary for reliably deriving event location and timing and hence average radial structure. Four nodes will also provide definition of ray paths that will sample some lateral structural and seismic velocity variations. However, there is no clear lower limit to the number of seismic stations needed to do this. There have been some attempts even with the four-station Apollo network (e.g., Chenet et al. 2006 and references therein), but the larger the number of nodes, the more detailed the result will be. To obtain global distribution of structural and seismic velocity variations, a globally distributed array of seismic stations is required. If shallow moonquakes are clustered in a single region, a closely-spaced array of three stations could be built to characterize them, but to cover a larger area, an unrealistically large number of nodes may be required. The most effective plan may be 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.

Three Nodes: Three is the minimum number of nodes to locate and time each deep moonquake, assuming the radial structure is known well enough, or more simply that the P-S time difference can be extrapolated to time of origin. However, to accomplish more than what the Apollo data provided, including, in particular, the distribution of nests beyond the Earth-facing side of the moon, requires a global distribution of nodes. Also, data from three nodes will be sufficient to approximately determine meteoroid impact time and location. The smaller the node spacing, the smaller the impacts that can be detected by all three nodes, while the larger the node spacing, the larger area can be covered for detection. Finally, a minimum of three widely-spaced nodes 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 five nodes 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 on the locations of shallow moonquakes, and little information on crust/mantle heterogeneity.

Two Nodes: Two is the minimum number of seismometers that will give limited details on the nature of the lunar core and the deep lunar mantle. One seismometer should be close to a known source to obtain its origin time, and another near the source antipode to record the seismic signal from it through the very deep interior (see section 7.2). 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 or crust/mantle heterogeneity.

7.2 Site Selection Criteria and Accuracy

While the number of nodes necessary to form the next-generation lunar network is subject to scientific debate and programmatic realities, any network should have a broader coverage than that of the Apollo PSE network. Each of the measurements benefits from different criteria for site locations. The SDT expects that actual site selection would be recommended by the community, perhaps via a site selection workshop format. The importance of site selection can be somewhat mitigated by the increasing the number of nodes.

Seismometry: The SDT understood the constraints of the Anchor Nodes mission to be that two nodes will be deployed initially, and that there may or may not be an orbital communications asset at the time these nodes are active. If no orbital communication asset is available, farside nodes are not possible. Two nodes limits the amount and type of new science that can be accomplished with seismometry. Therefore, the SDT formulated a strategy that would maximize the amount of new information gained by initial deployment of two seismic stations.

The first two nodes can be located to ensure that seismic waves pass through the deep lunar interior, providing information to address whether there is a core, and if so, its properties. Because there will only be 2 nodes, we will have to take advantage of knowledge of seismic sources gained through the Apollo program. Deep moonquakes occur in isolated "nests", or epicenters of repeated energy release. Hypocentral coordinates of many of these nests, each <2 km in diameter, have been determined very precisely (Nakamura 2003); however, their accuracy is only as good as the internal model for the Moon, which is not yet known very well.

The SDT recommends deploying the first node near the antipode of the farside A33 deep moonquake nest (Nakamura 2005), and the second within approximately 60° of the A33 epicenter (Table 1; Fig. 11). This placement has the advantage of being able to place both nodes on the Earth-facing side of the Moon, in case a communications satellite is not available at the time of node placement. The A33 nest is expected to be inactive in 2012, but it is expected to be active from early 2013 to mid-2017 (Bulow et al. 2007). Furthermore, the occurrence of A33 deep moonquakes is very regular, being mostly near the Moon's apogee, giving confidence that they will be identifiable among many deep moonquakes expected to be recorded at a newly installed seismic station.

Table 1. Estimated coordinates of A1 and A33 nests and their uncertainties (from Nakamura, 2005).

Moonquake Nest	Latitude	Longitude	Depth (km)	Antipode Latitude	Antipode Longitude
A1	15.7 ± 2.4° S	36.6 ± 4.6° W	867 ± 29	15.7 ± 2.4° N	143.4 ± 4.6° E
A33	5.1 ± 2.6° N	115.8 ± 9.3° E	877 ± 112	5.1 ± 2.6° S	64.2 ± 9.3° W

A single node, located antipodal to a known moonquake nest, will give some ideas about the size and nature of the possible core. For example, the seismic travel time to a station located near the antipode of the hypocenter will give a range of core-radius/seismic-velocity combinations that will satisfy the observation. If the node is farther away from the antipode, however, lack of seismic arrivals at reasonably expected times may suggest that it is within a shadow zone created by a low-velocity core, and thus will give permissible ranges of core radius and seismic velocity within the possible core. Furthermore, if additional core phases, such as internally reflected arrival, equivalent of PKKP on Earth, are observed and identified, they will provide further constraints on both the radius and seismic velocity of a permissible core.

Assuming the seismic velocity gradient in the lower mantle is small, a core of 170 to 435 km radius will put the area within 17° to 37° of the antipode of the A33 nest behind the core as seen from the A33 hypocenter at 877 km depth. The outer part of this area will be in the shadow zone for direct P-wave arrivals as the seismic rays are bent inward due to a velocity contrast between the lower mantle and the core. How far the shadow zone extends depends on the velocity contrast. If the node is not in the shadow zone, the seismic arrivals through the core will provide information on the size and velocity of the core, whereas if the node is in the shadow zone, this observation alone may also give some information about the size and velocity of the core. Additional core phases mentioned earlier, if observed, certainly provide additional information about the size and properties of the core. Thus, the accuracy required for individual node placement is a few degrees, or ~100 km.

Uncertainty in the moonquake source location affects the estimates of the core size and velocity: The source location uncertainty on the order of 10 degrees is likely to affect interpretation of observed arrivals, but it is difficult to quantify at this point. A modeling study may help, but constructing a truly representative and useful model may be difficult considering so many variables. The depth uncertainty on the order of 100 km translates to an arrival time difference on the order of 10 seconds, while a velocity reduction of 8 to 5 km/s over a distance of 700 km translates to one greater than 50 seconds. Therefore, the depth uncertainty is unlikely to be a serious problem.

In addition to the A33 antipodal node, a second node must be located within a direct seismic range of the A33 nest to determine the origin time of each A33 event. To detect both P and S direct waves, the second node must be roughly within 60° of the A33 nest location. One possibility is the site of Apollo 16, which would confer the advantage on the node of being able to receive a well-characterized signal waveform from the A33 nest, reducing ambiguity in identification of the source. On the other hand, other locations closer to the A33 epicenter may have an advantage of providing additional arrival time data to improve the hypocenter location and thus

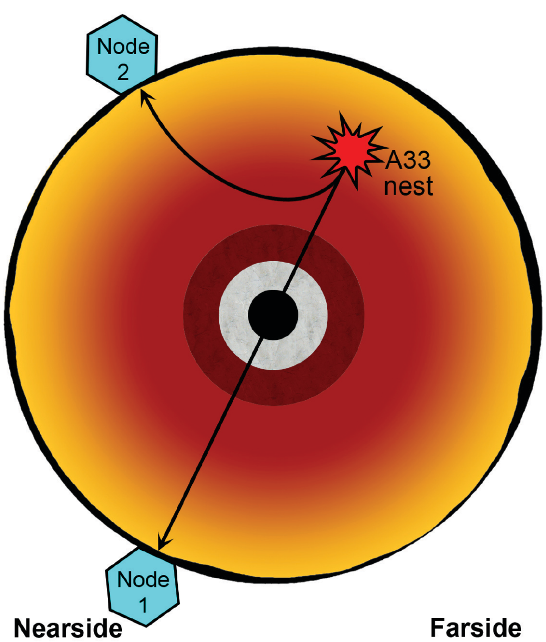


Figure 11. Cartoon showing the schematic location of seismic stations relative to the A33 moonquake nest (not to scale), if the nodes are to be deployed as pairs. The A33 nest is located over the east limb of the moon on the lunar farside. Node 1 should be placed antipodal to A33 to receive seismic waves that have passed through the core. Node 2 should be located within 60 degrees of A33. Both nodes may be located are on the lunar nearside if necessary, though farside coverage is strongly desired (see Fig. 12).

may be preferred. The location accuracy of this node is not critical as long as it is within a direct seismic range, about 60° or 1,800 km, of the A33 nest. Therefore, the selection of this site should be dictated by other experiments to be conducted at the site along with engineering considerations such as communications paths and landing trajectories.

If the US supplies a second pair of ILN nodes, they should form an approximate triangle, ~2000 km on a side, with one of the Anchor Nodes (Fig. 12). The SDT recommends that the second pair of nodes be located on the lunar farside, using a communications orbiter to relay data. In the event that farside communications cannot be established, the SDT recognizes that nearside nodes may still be deployed in the desired configuration with broader coverage than the Apollo network.

Heat Flow: Site selection is also an essential consideration for the heat flow experiment. Ideally, a heat flow measurement would be obtained in the centers of each unique lunar terrane. Simple finite-element simulations performed for this report demonstrate that the thermal gradient (and hence heat flow) can be perturbed by greater than 5% within ~200 km of the boundary between regions with disparate thermal properties. Thus, the sites should be located farther than 200 km from terrane boundaries (the Apollo 15 and 17 heat flow measurements did not meet this requirement, and thus there is continuing ambiguity on how representative these measurements are; e.g., Rasmussen and Warren, 1985). Additionally, the sites should be in regions that are topographically smooth so that shadowing does not influence surface temperature.

Site selection for the ILN Anchor Nodes will be driven by the requirements of the seismic experiment, but the second node has more freedom, needing only to be within ~60° of the surface projection of the A33 nest. The SDT recommends placing the second anchor

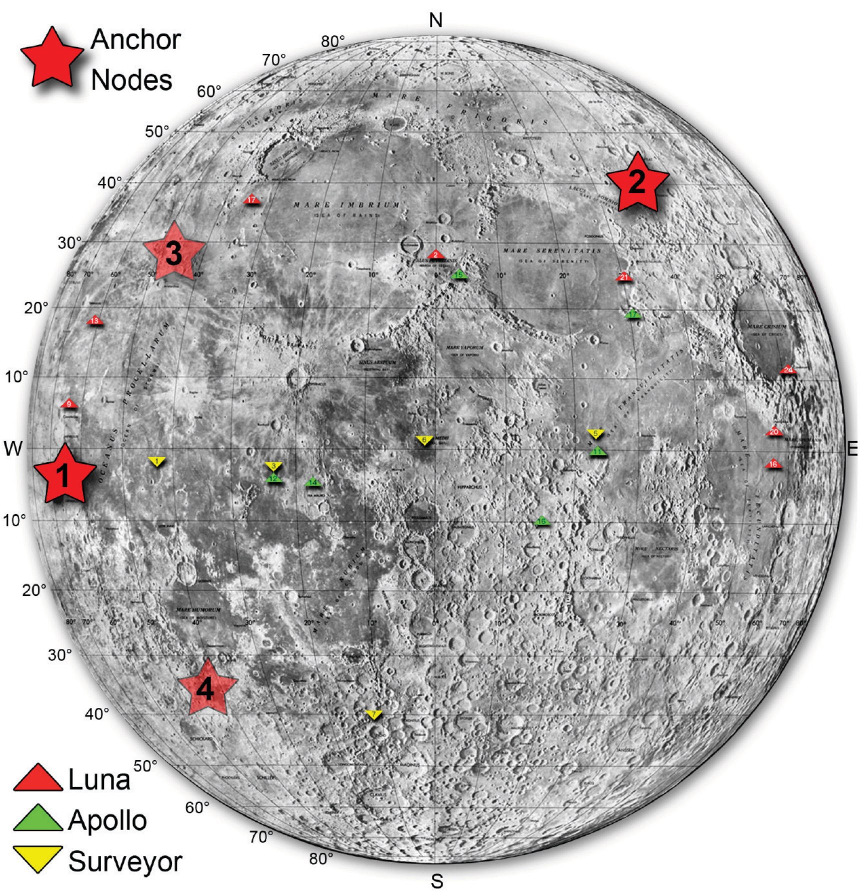


Figure 12. Stars mark the approximate recommended locations for emplacement of the Anchor Nodes, if they are to be deployed in pairs over multiple years. Nodes 1 and 2 are placed relative to the A33 moonquake nest; Nodes 3 and 4 should be placed on the lunar farside, ~2000 km from either of the first two nodes. More precise site selection should be conducted by the science community and engineering team, taking into account mission phasing, the experiments to be conducted at each site, and considerations such as communications paths and landing trajectories.

node within the feldspathic highlands, as it is the most common major terrane type on the moon but was not represented in the Apollo heat flow experiments.

Electromagnetics: Because the objectives of EM sounding are aligned with seismology and heat flow, there are no additional constraints other than colocation with these experiments. As the number of ILN nodes increases, crustal magnetism and plasmainteraction studies would benefit from measurements at sites of strong DC magnetization and/or albedo anomalies.

Lunar Laser Ranging: Site selection desires for LLR are that the sites expand the coverage offered by the three Apollo and one Luna sites that are currently available. Sites towards the limbs of the moon and the north and south poles would be most useful. Only nearside nodes need carry LLR experiments.

7.3 Lifetime Drivers

To achieve the outlined science goals, the ILN nodes need to operate simultaneously over an extended period of time. The nodes must observe and localize a sufficient number of strong, shallow moonquakes to understand their location and mechanisms. Such events are infrequent (~4 per year were recorded by the Apollo network, with ~1 per year having a body wave magnitude of ≥5), so the longer the observation period, the better the chance of detecting rare large events. The occurrence characteristics of the moonquakes from individual hypocenters are correlated with lunar tidal phases (Latham 1972), including the moon's rotation period and orbit around the earth (~1 month); the coincidence of lunar anomalistic and synodic phases—i.e., when a new moon coincides with lunar apogee, or a full moon with perigee (~7 months); the moon's period of libration (~6 years), and the precessional period of the lunar orbit (~18 years). ***The SDT recommends that the Anchor Nodes operate as part of a larger network for a minimum of six years*** to capture the 6-year lunar tidal period.

In the case of the floor science mission, the science objectives are limited to knowledge of the deep interior and core, where only information from deep moonquakes is useful. More of these will occur in a shorter time (e.g., 2 years), but the SDT does not endorse this reduced lifetime, because it virtually guarantees that the Anchor Nodes will not be part of a larger network operating over a full tidal cycle. Both the heat flow and EM experiments complete nominal operations on timescales of 2 years or less, so they do not drive lifetime requirements. However, if sufficient power and data capability are available to these instruments, longer monitoring would be advantageous, particularly for the heat flow experiment.

8.0 The Anchor Nodes in the Context of the International Lunar Network

The US Anchor Nodes are part of a larger effort aimed at maximizing the science return possible from the worldwide interest in returning to the moon. The concept of an International Lunar Network (ILN) was first presented to the international community by then NASA Associate Administrator of the Science Mission Directorate, Dr. Alan Stern, at a briefing to potential international partners at the Lunar and Planetary Science Institute in Houston, Texas, on March 12, 2008. Ten international partners were invited to this first meeting and eight attended. The ILN as proposed would address key science problems that could only be addressed by concurrent operations at multiple sites on the moon. Based on the expressions of interest by those present, a series of teleconferences were initiated to develop a more formal statement of the goals and approach for such an international network. Additional partners were invited to attend, as were those not present at the March 12 meeting. These teleconferences led to a meeting with representatives of nine space agencies (including NASA) on the 23rd and 24th of July 2008, at the NASA Lunar Science Institute in Mountain View, California, where a Statement of Intent was signed.

The top-level ILN group created by the Statement of Intent is known as the ILN Steering Group. The on-going work of the ILN is being carried out through a series of Working Groups. The first to be organized were the Core Instruments Working Group and the Communications and Navigation Working Group. A third working group, known as the Enabling Technologies Working Group has since been organized and is currently functioning. A fourth Working Group on Landing Sites will be organized in the future. The initial Working Groups for Core Instrumentation and Communication and Navigation hope to have reports out by the end of calendar year 2008. The ILN Steering Group expects to next meet in March 2009 in conjunction with the International Space Exploration Coordination Group (ISECG) meeting in Japan.

For the future, additional partners can be considered for the steering and working groups based on interest and expertise. Once the initial reports on core instrumentation and communications are received, implementation of the network will need to be considered, including potential bilateral and multilateral cooperative arrangements.

9.0 Programmatic Recommendations

In addition to scientific goals and measurement recommendations, the Anchor Nodes Science Definition Team feels that several other points need to be addressed by the Lunar Quest program, in order to enable the Anchor Nodes mission(s) to succeed.

a. The instrument procurement process for the Anchor Nodes should be competitive, not directed. Competing the individual instruments ensures that innovative and low-cost approaches to making important measurements will be achieved by members of the science community who best understand them. The SDT understands that the amount of money available to the instruments will be small, and therefore the science team supported by each instrument will be minimal. Therefore, the SDT further recommends that a general mission science team (or participating scientists) be supported in Phase E, in addition to the instrument teams.

b. The SDT recognized several significant technology challenges for the Anchor Nodes mission and recommends that early development and testing funding be directed to mitigate risks associated with implantation of a heat flow experiment, long-lived power sources (particularly the Advanced Stirling-cycle Radioisotope Generator), and a suitable launch vehicle for this class of mission.

c. NASA must continue its long-term partnership with the international community for the success of the entire International Lunar Network. The objectives for the US Anchor Nodes, as outlined in this report, should be integrated with the objectives defined by the ILN working groups. Opportunities for mission cooperation, such as hardware development, testing, or contribution, should be considered. It is also crucial to define an international plan for data standardization and cooperative data sharing with participant in all ILN nodes and the entire scientific community.

10.0 Summary

The ILN Anchor Nodes SDT was asked to provide answer five specific technical questions; short answers (supported at length in earlier sections) are given below.

Scientific Objectives of the US contribution to the ILN, in order of priority, should be:

1. Understand the current seismic state and determine the internal structure of the moon.
2. Measure the interior lunar heat flow to characterize the temperature structure of the lunar interior.
3. Use electromagnetic sounding to measure the electrical conductivity structure of the lunar interior.
4. Use next-generation laser ranging to determine deep lunar structure and conduct tests of gravitational physics.

The measurements required to address these scientific objectives are:

1. Measure lunar seismic energy over the frequency range 1 mHz–20 Hz at multiple at geometrically dispersed locations and for at least 6 years.
2. Measure the temperature and thermal conductivity at multiple depths at each location for 2 years.
3. Measure ambient electric and magnetic fields at each node for a minimum of 1 year. Quantify contribution to electromagnetic measurements by local plasma field.
4. Perform laser ranging to new sites with better than 2 cm range accuracy.

Instrumentation required to obtain the measurements given above are;

1. Three-axis Very Broad Band seismometer at each node with dynamic range of ~24 bits.
2. Temperature sensors with precision at or better than 0.05-0.001 K
3. 3-component magnetometers (10 $pT/Hz^{1/2}$) plus 2-component electrometer (100 $\mu V/m/Hz^{1/2}$) plus Langmuir probe (on a vertical mast; 500 K, 10 e/cm^3)
4. Laser-ranging instrumentation.

The principal criteria for selection of the initial two sites are:

1. Maximizing the probability of detection of seismic events from a known deep moonquake nest by placing one node at or near its antipode.
2. Nearside placement is acceptable, absent a relay satellite.

The major technical challenges are:

1. Acquisition (in the US at least) of lightweight broadband seismometers with necessary performance characteristics.
2. Surface deployment of seismometers.
3. Emplacement of thermal probes to depths of greater than 2 meters.
4. Node lifetime.

To insure that we obtain the very best science:

1. All instruments should be fully competed.
2. Science should be competed.

Appendices

Appendix 1—ILN Anchor Nodes Science Definition Team

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Appendix 2—ILN Anchor Nodes Measurements Matrix

Table A1. Science Objectives for the ILN Anchor Nodes Mission

Science Objective	Traceability to SCEM report	Measurement Requirements	Mission Requirements	Instrument Requirements
1. Understand the current seismic state and determine the internal structure of the moon	2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales. 2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle. 2c. Determine the size, composition, and state (solid/liquid) of the core of the moon. 3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.	Measure lunar seismicity over the frequency range 1mHz–20Hz at multiple, geometrically dispersed locations.	4 simultaneously operating nodes Continuous operation for 1 lunar tidal cycle (6 years) Inter-station timing accuracy ~5 msec Instrument attached to ground; spacecraft vibrationally isolated from ground Thermally isolate ground to ~1 m radius	Three-axis Very Broad Band seismometers Dynamic range of ~ 24 bits For $1.0 < f < 20$ Hz, PSD $\leq 10^{-9} f^{2}$ $m/s^2/Hz^{1/2}$ For $0.1 < f < 1.0$ Hz, PSD $\leq 10^{-10} f$ $m/s^2/Hz^{1/2}$ For $0.001 < f < 0.1$ Hz, PSD $\leq 2\times10^{-11.5/f1/2}$ $m/s^2/Hz^{1/2}$
2. Measure the interior lunar heat flow to characterize the temperature structure of the lunar interior	2d. Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine. 3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.	Measure the temperature gradient and thermal conductivity of the regolith at multiple depths to at least a depth of 3 m.	Temperature sensor array must extend to at least 3 m depth Thermal conductivity measurements require good contact with the regolith Minimize thermal effects of the spacecraft Placed 200–300 km from major terrane boundaries Continuous operation for 2 years	Record thermal conductivity for ≥1 lunar day Continuous monitoring T measurement every 6–12 hours Temperature sensor precision: 0.05–0.001 K Minimum 9 thermal conductivity and temperature locations Sensors spaced 30 cm from each other

Science Objective	Traceability to SCEM report	Measurement Requirements	Mission Requirements	Instrument Requirements
3. Use electromagnetic sounding to measure the electrical conductivity structure of the lunar interior.	2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales. 2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle. 2c. Determine the size, composition, and state (solid/liquid) of the core of the moon. 2d. Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine. 8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.	Measure ambient electric and magnetic fields at each node. Quantify contribution to electromagnetic measurements by local plasma field.	Continuous operation for 1 year Both magnetometers and one electrometer must be at least 2m away from spacecraft Magnetometers deployed in orthogonal directions Langmuir probe should be 0.5 m vertically from spacecraft	DC to 100 Hz 2 x 3-component magnetometers (10 $pT/Hz^{1/2}$) 1 x 2-component electrometer (100 $uV/m/Hz^{1/2}$) 1 x Langmuir probe (on a vertical mast; 500 K, 10 e/cm^3) Temperature sensor for calibration
4. Increase ability to determine deep lunar structure and conduct tests of gravitational physics by installing next-generation laser ranging capability.	2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle. 2c. Determine the size, composition, and state (solid/liquid) of the core of the moon.	Provide equipment that enables <2 cm ranging accuracy	Node separation >90° in latitude and/or longitude Only required on the near side	

Appendix 3—References

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