Autonomous
Lunar Geophysical
Experiment Package (ALGEP)

In response to

Call for White Papers for the Voyage 2050 long-term plan in the ESA Science Program

Context

1 Project Overview

1.1 Introduction

The geophysical exploration of the Moon, particularly its interior structure and processes, has been recognized as a high scientific priority from the time of the Apollo project planning to the present (see, e.g., Finding 3 of the NRC Space Studies Board Interim Report on *The Scientific Context for the Exploration of the Moon*: "Determine the composition and structure of the lunar interior", 2007). Recently, ESA published "*ESA Strategy for Science at the Moon*" (2019), where they address "deployment of geophysical instruments and build up a global geophysics network" and "characterization of the internal structure and thermal structure of the lunar interior" as one of the key activities that needs to be performed in the near future. This confirms that the questions addressed more than 10 years ago is still under investigations today and that there is a global interest to the subject from the scientific community.

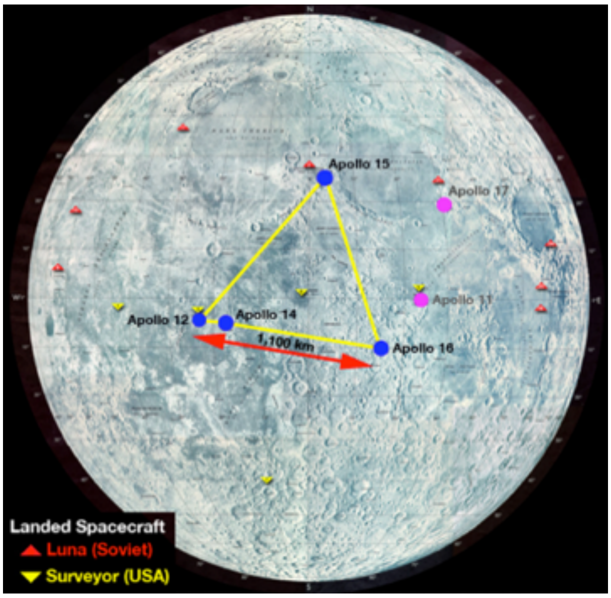

Figure 1-1: Apollo landing sites. ALSEP

The Apollo Lunar Surface Experiments Package (ALSEP) that was deployed by the later Apollo missions was enormously successful in furthering our understanding of the Moon and its history through seismic, magnetic, and geothermal measurements. Along with lunar sample analyses, these data, now nearly 50 years old, still largely define our knowledge of the Moon beneath its visible surface. By modern standards, however, this information is quite limited due both to the technology of the instrumentation available at the time and by the limited geographic extent of the Apollo landing sites (Figure 1-1).

We propose to develop a suite of instruments that function as a modern follow-on to ALSEP. This will be a standardized and robust geophysical package that can be reconfigured depending on various launch opportunities including those by private sectors. We investigate and develop some key instruments to uncover the lunar interior. It comprises a comprehensive suite of geophysical instruments, such as a seismometer covering both long and short period bands, a shallow seismic sounder, a magnetometer, a heat flow probe and a laser retroreflector. This package would enable the extended exploration of the lunar interior, from the upper few meters of the regolith to the core. At the same time, we develop a central station and long-living survival module that will commonly be used by the instruments. The central station and the survival module should be designed to have a standardized interface with the instruments so that the payloads can be reconfigured depending on constraints on the launch opportunities.

Although such instruments can produce useful information from a single installation, the full value comes from a network of such stations distributed across the Moon’s surface operating simultaneously for an extended period of time. Thus, to maximize the achievement of the geophysical observations, we need to consider all the possible launch opportunities and establish a global network. For this aim, it would be important that the instruments are designed so that they can be adapted and reconfigured with respect to the given constraints.

Our final goal will be to establish a global network on the Moon that carries out continuous observation. We aim to provide the geophysical package to all possible launch opportunities and expand as much as possible the network. Then we will use the geophysical data from the network to uncover the internal structure of the Moon. With payloads that are improved from Apollo and a network with improved global coverage, we will uncover the internal structure of the Moon from few meter depth to the center of the Moon. As the outcome of the mission, we will provide an improved view of the lunar interior and detailed inner structure model including its 3D structure. Knowledge of the inner structure of the Moon will surely contribute to uncover the mystery of the origin and evolution of the Moon. Furthermore, understanding the Moon will open a new window to explore the terrestrial planet and rocky satellites in the solar system in general.

1.2 Recent Trend of Lunar Exploration in the World

After 50 years from Apollo landing, the international community is once again targeting the Moon for their next field of exploration. Various space agencies are running lunar mission including future manned missions and construction of lunar bases.

One of the most active players in the lunar exploration is China who is carrying out the Chang’e program. In January 2019, Chang’e 4 has landed on the lunar farside for the first time in the human history and demonstrated their capability of landing operation through relay satellite. China is planning to launch Chang’e 5, which will be the first Chinese sample return mission. Chang’e program is planned until Chang’e 8 to be launched in 2027 and finally, they aim to launch a manned mission to the Moon in 2030.

NASA also announced their Artemis program to launch manned mission to the Moon by 2024. This program will send 2-4 astronauts to the Moon with new space launch system (SLS) and Orion crew vehicle. They will also establish a moon orbiting lunar outpost called Gateway to access the Moon. This will surely increase opportunities to access the lunar surface.

Japan is now planning to launch 2 landers to the Moon by early 2020s. The first is the SLIM which will be the launched in 2021. This will be an engineering mission to demonstrate the capability of high precision landing on the Moon. SLIM will be followed by Resource Prospector Mission which is planned to be launched early to mid 2020s. The mission aims to land on the lunar pole to search for subsurface ice and quantifying this.
India just launched the first lunar lander Chandrayaan-2 on July 2019. It is planned to land on the lunar south pole in September. They also plan another polar landing mission in mid 2020s.
ESA is working with the Canadian and Japanese space agencies to prepare the Heracles robotic mission to the Moon in the mid-to-late-2020s. The mission plans to use the NASA Gateway as a halfway point and land on the Moon with a rover to perform a sample return. ESA is also contributing to the development of Orion crew vehicle and is participating to Gateway project.
Finally, private sectors have now play an important role in the lunar exploration. As a part of Artemis program, NASA selected the first 12 new science and technology payloads that will go to the Moon on future flights through NASA's Commercial Lunar Payload Services (CLPS) project. CLPS will be delivering constantly payloads to the lunar surface until 2028. This will open a new possibility to establish new stations on the Moon and the possibility should be closely investigated.
All of these launch opportunities will be good candidates to deploy geophysical stations on the Moon. At the same time, all launch opportunities have their own constraints, concepts and aims. Thus, the geophysical package shall be adapted for each mission. There is also another constraint on manned and robotic missions. This will be a strong constraint on the instrument deployment and we need to develop a system that can be deployed (or deployment system that can be added if necessary) in both manned and robotic missions. To maximize the launch opportunities, the payloads should have a robust and universal design that can be adapted to such various constraints.

1.3 Mission Concept

The aim of the mission will be to prepare a suite of instrument that would be ready to fly on the opportunities described above. This will be a strawman payload that can be reconfigured with respect to the requirements of each mission. Specific configuration and payloads for each mission should be selected and defined through open application opportunity. For this, we shall prepare a standardized central station and long term survival module with common interface. By fixing the interface, we can reconfigure the geophysical package by simply plugging and unplugging the selected instrument. Such standardization will be helpful not only to facilitate the mission design but also to simplify the instrument development.

In the framework of the mission we will develop some key geophysical payloads that will be described in the following section. Establishment of global network would be a key aspect for some geophysical observations, such as seismic and geodetic observation. It would be important that we thoroughly review such instruments and develop these instruments to be ready for the future missions.

In addition to such payloads, we will develop a standardized central station and long living survival module. Such system will be required for all geophysical station on the Moon and there is an urgent need for the development. At the same time, all the system should be designed so that they can be adapted to various launch opportunities. It is highly possible that future launch opportunities vary in its mass availabilities and mission duration. While some mission may be capable of delivering 10s of kilograms of payloads, others may have more limited availability. However, to establish a global network on the Moon, we need to take advantage of all the opportunities and we should adapt and design the package so that this can be reconfigured to fit in the requirement of the mission. This is the same for the mission duration. Not all mission will be designed to survive the lunar day and night cycle. It will be critical for a geophysical station to be in simultaneous operation with other stations. This will require long term operation of the station and we need a stand-alone system that can operate even after the mother spacecraft finishes to function.

The objective of the project will be to first discuss these functionalities necessary for the geophysical package to define the requirements to be met. This includes the discussion of interface between subsystems. The next step will be to develop each subsystem that meets the requirements by using the heritage from the previous missions such as InSight. It is clear from the example of InSight, we have already some high TRL instruments developed in the community. It would be also important to collect such information to make clear the heritage we have already and list the new development that needs to be done.

2 Scientific Background and Approach

Geophysical analyses typically utilize distributed data collected over the surface of a planet (e.g., seismic, magnetic, gravity, topography) to determine such properties as composition, density and temperature of the materials located in its inaccessible depths. Although all such determinations are non-unique, combining different data sets can be particularly effective in removing ambiguities. Thus, the combination of geophysical measurements envisioned for ALGEP will be much more powerful than the sum of the individual investigations.

In the following sections, we summarize the current knowledge and projected improvement we can expect from the some of the key payloads considered for ALGEP.

2.1 Seismometer

The Apollo Moon landing missions (1969-1972) performed two types of seismic experiments: Active and Passive. The Active Seismic Experiment (ASE) on Apollos 14 and 16 utilized arrays of three geophones, grenades and thumpers to investigate the shallow regolith structure, while another active experiment (LSPE: Lunar Surface Profiling Experiment) on Apollo 17 used an array of four geophones and explosive packages to probe shallow structure during the mission as well as to listen to high-frequency signals for an extended time after the mission.

Active seismic measurements conducted during the Apollo missions [*Kovach et al.,* 1971, 1972, 1973] provide a detailed view of the shallow seismic structure of the lunar regolith. A surface layer, ranging from 2 to 20 meters thick, has a very low P-wave velocity of about 110 m s^{-1} and consists of unconsolidated, fine grained soil with a bulk density of about 1500 kg m^{-3} [*Mark and Sutton,* 1975; *Lognonné and Mosser*, 1993]. The second layer has a speed of 250 ± 50 m s^{-1} (indicating less porosity) and a thickness of tens of meters. Below this is a layer with a speed of about 1200 m s^{-1}, approaching velocities for poorly consolidated rock.

Much of the recent history of the surface of the Moon is recorded in or hidden by the regolith, the layer of broken rock and “soil” that covers the surface. The regolith forms by processes including impact cratering and radiation weathering, and the physical characteristics of the regolith retain clues about these processes. The subsurface contains a long-lived record (in composition, lithology, stratigraphy) of the regional geologic history and the processes that have shaped the surface. To begin unraveling this record, it is necessary to determine the location, orientation, and physical characteristics of layering in the subsurface arising from variations in grain size and compaction.

In addition to its scientific interest, regolith structure will be important for astronaut activities. The geotechnical parameters will play a key role in construction of lunar structures (as a foundation, if not a building material) and the processing of any in situ lunar resources.

The Passive Seismic Experiment (PSE) consisted of a network of seismic stations deployed during Apollo missions 11, 12, 14, 15 and 16. All but the Apollo 11 instrument operated for up to eight years until the data acquisition was terminated in 1977. The main purpose of PSE was to investigate the Moon's natural seismic activity and to infer its internal structure.

Four major types of seismic activity were discovered: thermal moonquakes, meteoroid impacts, deep moonquakes and shallow moonquakes. *Thermal moonquakes* are small, high frequency events that occur at the surface of the Moon near sunrise and sunset [*Duennebier and Sutton*, 1974]. They represent minute but repeated mechanical changes on the lunar surface in response to temperature changes. *Impacts* are observed when meteoroids in Earth-crossing orbits collide with the Moon. More than 1700 such impacts were cataloged during the eight years of observation, and they tell us the distribution and possible orbits of such objects in the neighborhood of the Earth-Moon system [e.g., *Oberst and Nakamura*, 1991]. *Deep moonquakes* are small (M_b<2) but are the most numerous (>7000 identified) type of events. They concentrate in discrete locations (~240 identified) at depths between 800 and 1100 km. Their near-monthly occurrence suggests strong tidal influence of the Earth and the Sun [e.g., *Lammlein*, 1977]. *Shallow moonquakes* are rare (only 28 identified) but include some of the strongest (M_b>5) seismic events observed on the Moon [e.g., *Nakamura et al.,* 1979]. They have distinct spectral signatures [*Nakamura et al.,* 1974a], and are generally considered to be tectonic in origin. However, their origin is not completely understood [e.g., *Frohlich and Nakamura*, 2006].

The near-surface zone of the Moon is highly pulverized with extremely low seismic velocities, as discussed above [see also *Cooper et al.,* 1974; *Horvath et al.,* 1980]. Below the regolith, seismic velocities gradually increase with depth, but normal rock velocity of V_p>4 km/s is reached only at depths greater than 1 km [*Cooper et. al.,* 1974]. The deeper interior of the Moon is differentiated with a clearly identifiable division between crust and mantle. The crustal thickness in the Fra Mauro region near the front center of the Moon was initially estimated to be about 60 km [e.g., *Toksöz et al.,* 1972], but more recent analyses find thicknesses around 40 km [e.g., *Lognonné et al.,* 2003]. The crustal thickness has been shown to vary [*Chenet et al.,* 2006], but no direct measurements are available other than from the Apollo landing sites. Thus, the nature and extent of the lateral variations are still poorly constrained. Seismic velocities in the lunar upper mantle are close to those found in the Earth's upper mantle at equivalent pressure ranges and are nearly constant or decrease slightly with increasing depth, both in original estimates [*Goins et al.,* 1981; *Nakamura*, 1983] and in more recent analyses [*Khan and Mosegaard*, 2002; *Lognonné et al.,* 2003]. There are reports of a distinct discontinuity that separates upper from middle mantle at around 600 km depth [e.g., *Khan* *and Mosegaard*, 2002], but its reality is uncertain. Below about 1000-1100 km (below the level where deep moonquakes occur) seismic shear waves are severely attenuated, suggesting that the lower mantle is either partially molten or contains significant amounts of volatiles [*Nakamura et al.,* 1973, 1974b]. Whether the Moon has a liquid core is uncertain from the seismic data alone. Although there was one far-side impact that suggested the existence of a molten core of radius ≤360 km [*Nakamura et al.,* 1974a], no additional observations have confirmed this result.

What the Apollo seismic data did not provide. Although the Apollo seismic experiments were highly successful and provided more information about the Moon than was anticipated, there remain several important unanswered questions:

1. Very deep interior: There is almost no reliable information on seismic velocities below ~800 km. What are the physical properties of the very deep interior of the Moon, in particular the lower mantle and core? Is there compositional layering in the lower mantle? What is the size, state and composition of the core?
2. Lateral heterogeneity: How do crustal and mantle structures vary from one region to another? Is there any correlation with surface compositional heterogeneity (e.g., PKT)?
3. Deep moonquakes: What is the true mechanism of deep moonquakes? How are they distributed globally (we only have data for the front side), and what does this distribution mean in terms of the lower mantle structure?
4. Shallow moonquakes: What causes shallow moonquakes? How deep are they? Do they pose any risk to future lunar bases?

These questions remain mainly because the Apollo seismic network was located near the front center of the Moon and its detectability limits did not extend much beyond. This fundamental limitation affects all five questions. Extending the station coverage, therefore, should be a primary consideration for the next generation of seismic observations on the Moon.

Increasing the number of stations is another important factor, especially for questions 2 and 4. The four stations that constituted the Apollo seismic network were only marginally sufficient to deduce parameters needed to define a radially symmetrical Moon model. It is imperative to have a sufficient number of stations to delineate at least the first-order lateral heterogeneity of the lunar interior, and thus to derive a more realistic lunar structural model, both radially and laterally. To determine the hypocenters of shallow moonquakes, close spacing of stations near the event is needed. For a global coverage, this translates to a large number of stations.

The Apollo seismic observational period was eight years, but the complete Passive Seismic Experiment (PSE) was only operational for ~6 years. This was barely long enough to cover a complete lunar tidal cycle for deep moonquake activity. A longer observational period helps to answer all the questions listed above by increasing the number of detected events. At the same time, this also increases the chance of recording rare large shallow moonquakes and infrequent seismic rays through the very deep interior of the Moon. These data are key for answering question 1.

Although the Apollo PSE seismometers were at least an order of magnitude more sensitive than any seismometer here on Earth, the general background noise on the Moon is sufficiently low so that we can usefully operate seismometers even more sensitive than those deployed during Apollo. This will sharply increase the number of detected events for a given observational period, thus greatly facilitating answers to all of the above questions.

Finally, observing surface waves and free oscillation of the Moon will help deduce the lateral heterogeneity (question 2) and structure of the deep interior (question 1). The Apollo PSE seismometers were too unstable to do this at very low frequencies, and modern VBB (Very Broad Band) seismometer technology can solve this problem.

2.2 Magnetometer

Electromagnetic subsurface sounding using natural geophysical signals (such as are generated by the passage of the Moon through the Earth's magnetotail) to provide the sounding energy is one of the oldest branches of geophysics. It exploits the fact that eddy currents are generated on the surface of a conductor when it is presented with a changing magnetic field. The eddy currents shield the interior of the conductor from the primary alternating field and generate their own magnetic field called the induction field, which is readily measured by ground or space instruments. The depth to which a signal can penetrate depends on its frequency and the conductivity of the probed material. By using multiple frequencies, electromagnetic sounding has been used successfully to probe the upper mantle of the Earth [see *Parkinson*, 1983; and references therein], place limits on the size of the lunar core [*Russell et al.,* 1981; *Hood et al.,* 1982] and more recently to discover liquid water oceans in the Galilean [*Khurana et al.,* 1998; *Kivelson et al.,* 1999, 2001]. The Apollo Moon landings and the accompanying missions in the late sixties and early seventies provided many opportunities for studying the interior of the Moon by using electromagnetic induction. Several orbiting spacecraft (Explorer 35, the subsatellites of Apollos 15 and 16) measured the magnetic field from low orbits. Three surface magnetometers (Apollos 12, 15 and 16) were operated simultaneously with orbiting spacecraft. An excellent summary of results from these investigations is provided by *Sonett* [1982].

Two different techniques were used to sound the deep interior of the Moon. *Sonett et al.* [1972], *Wiskerchen and Sonett* [1977] and *Hood et al.* [1982] utilized a surface magnetometer on the moon to characterize the total field (induction + primary) while obtaining the information on the primary field from a magnetometer onboard an orbiter. Observations were used only for those periods when the Moon was located either in the solar wind or in the Earth's magnetosheath. The second technique measured the response of the lunar core to the well-defined transients that the Moon encounters as it enters or exits the geomagnetic tail [*Russell et al*., 1974; *Dyal et al*., 1976]. Both techniques placed upper limits on the size of the lunar core between 360 km [*Hood et al*., 1982] and 439 km [*Russell et al*., 1974]. No direct evidence was obtained, however, for a highly conducting ($\sigma \geq 10$ S/m) core.

As the NRC Decadal Survey [2002] notes, one of the most important issues not yet addressable by the available lunar data concerns the uncertainty in the bulk composition of the Moon. Models of the impact generation of the Moon by the collision of a Mars size object with the Earth could be further constrained if the bulk composition of the moon were known more precisely. Further in situ sampling of the rocks from the lunar surface would help improve estimates of the bulk composition of the Moon, but a lack of sampling of the rocks from the deep interior thwarts efforts to fully characterize the bulk composition of the Moon.

Another high-priority question in lunar science concerns the sizes and the compositions of the lunar mantle and core, which are poorly known. The reason for the poor knowledge of the interior of the Moon is a general lack of reliable long-term simultaneous time series of the magnetic field from multiple sites on the moon. Even though the three Apollo magnetometers were often operated simultaneously, no extended simultaneous time series of the magnetic field is available because of telemetry and other infrastructural constraints.

Recent theoretical progress in modeling planetary composition and thermal state from inversion of long-period electromagnetic sounding data [see, e.g., *Khan et al.,* 2006] can be further leveraged by using data from several sites separated over global scales. The advantage of using multiple sites is that the data can be uniquely separated into internal (induction field) and external (inducing field) harmonics over multiple frequencies. New modeling techniques coupled with reliable long-duration time series from multiple sites would provide direct estimates of the chemical composition and the thermal state of the lunar interior.

Uncertainties in the inversion of magnetic and seismic data could be reduced by performing a joint inversion of the two data sets. Whereas magnetic data is sensitive to a global response from the interior of a body, seismic data are particularly sensitive to interfaces within the body. In regions where the mineralogy changes gradually or if an interface does not have large density contrast, magnetic data may be helpful in reducing the uncertainty of seismic data inversion. Similarly, the magnetic modeling, which suffers from intrinsic non-uniqueness, could be more objectively inverted by using specific information from seismic data about interfaces in the interior of the Moon.

2.3 Heat Flow Probe

The heat flow experiment measured the present day lunar heat flow, placing constraints on the bulk concentration of heat-producing elements and models of the Moon's thermal evolution [*Langseth, et al.*, 1972; *Langseth, et al.*, 1976]. Two heat-flow probes were deployed at each of the Apollo 15, 16 and 17 landing sites into the lunar regolith to measure the local subsurface temperature gradient and thermal conductivity (although an accident during astronaut deployment at Apollo 16 rendered that experiment useless). For each probe, a hollow fiberglass borestem was first drilled into the regolith, and heat flow probes containing temperature sensors and heaters were then inserted. Although the nominal emplacement depth was about three meters, problems with the design of the Apollo 15 borestem resulted in a maximum depth of only 1.5 m [*Langseth*, 1977]. After modifications, both Apollo 17 heat flow probes were inserted to depths of about 2.5 meters (Figure 1-2).

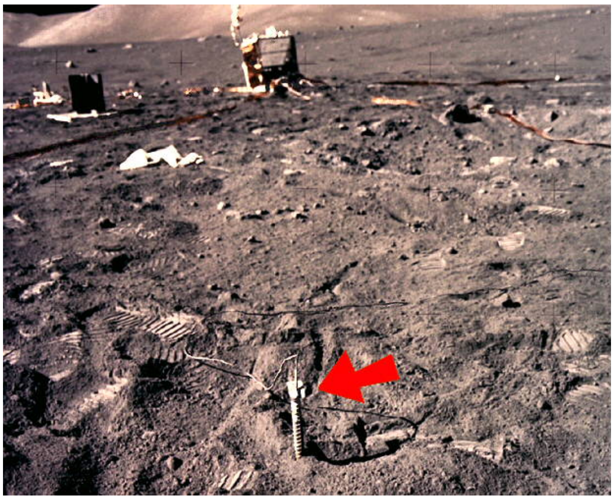

Figure 1-2: The Apollo 17 heat flow probe (arrow) was the only successful emplacement of that experiment (note raised cable that could catch an astronaut's boot). ALGEP will study packaging alternatives to reduce or eliminate cable trip hazards.

To derive the heat flow from the lunar interior, daily and annual signals must be removed to obtain the time-averaged temperature gradient. After removing this long-term signal, average temperature gradients in the range 0.79–2.52 K m^{-1} were obtained. Using these values, the heat flow at the Apollo 15 and 17 sites was finally estimated to be 21 and 16 mW m^{-2}, respectively, with estimated uncertainties of about 15%.

The Lunar Prospector mission revealed that incompatible elements were highly concentrated in only a single geologic province [*Haskin, et al.*, 2000; *Jolliff, et al.*, 2000; *Korotev*, 2000; *Lawrence, et al.*, 2000; *Wieczorek and Phillips*, 2000]. In retrospect, the Apollo 15 and 17 heat flow experiments were by chance performed in two of the most prominent geochemical provinces of the Moon: the Apollo 15 site lies within the Procellarum KREEP Terrane (PKT), which has elevated abundances of heat producing elements, whereas the Apollo 17 site lies in the more anorthositic and incompatible-poor

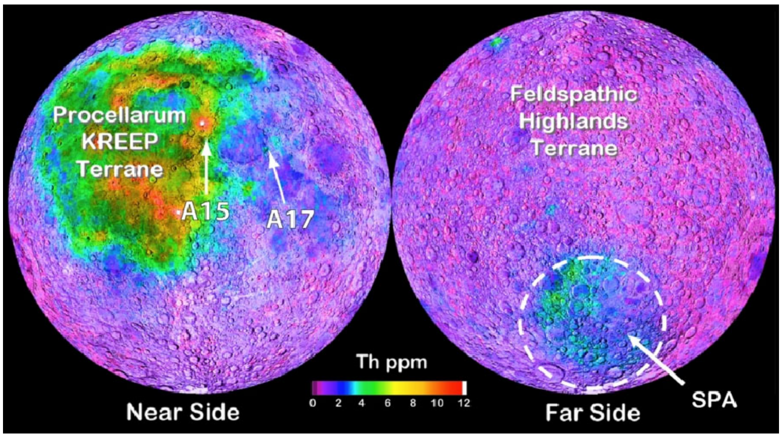

Figure 1-3. Thorium abundances at the lunar surface from Lunar Prospector [modified from *Wieczorek et al.*, 2006].

Feldspathic Highlands Terrane (Fig. 1-3).

Reliable heat flow data from the Moon, both globally and locally, will provide important input into four basic questions. 1) What is the internal thermal and associated mechanical structure of the Moon? 2) How does the Moon compare to the Earth and chondritic meteorites in its bulk content of the heat producing elements (U, Th, K), and if the Moon is significantly different, does this difference have implications for the origin of the Moon? 3) Are there regional variations in heat flow on the Moon associated with the major geological provinces, and do these variations record asymmetrical thermal evolution and chemical fractionation of the incompatible elements into the lunar crust? 4) Can long-term monitoring of near-surface lunar heat flow be used as a baseline to measure variations in external solar radiation at the Earth's location?

Additional heat flow measurements on the Moon are required for several reasons. First, the Apollo measurements were made in unrepresentative areas of the Moon bordering a geochemical province that is highly enriched in heat-producing elements. It is not clear if these estimates are representative of either the PKT or Feldspathic Highlands Terrane, nor how these measurements relate to the global heat flow of the Moon. Second, a debate currently exists as to whether the bulk silicate Moon has similar abundances of refractory elements as the Earth, or if it is enriched by a factor of two [see review in *Wieczorek, et al.*, 2006]. This debate could be settled by measuring the global heat flow of the Moon. However, in order to constrain the global heat flow, several measurements will be required within each of the major geological provinces of the Moon. Finally, by using representative values of the heat flow in each of the major geologic provinces, it will be possible to place constraints on the abundance of heat producing elements in the underlying crust and mantle. Lateral variations in these quantities will help constrain models concerning the asymmetric differentiation of the Moon, and these measurements will be indispensable for constraining thermal evolution models.

Measuring the interior heat flow and the crustal structure from heat flow are extremely complementary. Since little variation in the convective contribution from the lunar mantle is expected, regional variations in heat flow should be due to local changes in the radiogenic concentration in the crust. Lunar Prospector data provides on composition at the surface. Heat flow data provides information on the vertically integrated abundance of radiogenic elements. If heat flow data is acquired where the thickness of crustal layers is known, differences in heat flow from one location to the other can be attributed to crustal thickness or compositional variations. Without crustal thickness, there would be an ambiguity between thickness and radiogenic element concentration.

2.4 Lunar Laser Ranging(LLR)

Precision ranging to reflectors on the lunar surface provides information on lunar orbit, rotation, and solid-body tides (Williams et al., 1996). Lunar rotational variations have strong sensitivity to moments of inertia and gravity field while weaker variations, including tidal variations, give sensitivity to the interior structure, physical properties, and energy dissipation. Recent re-analyses of Apollo LLR data suggests 381±12 km [Viswanathan et al., 2019] A fluid core ~20% of the Moon's radius (~215 km) is indicated by the dissipation data. Second degree Love numbers are detected, most sensitively k2 [Williams et al., 2001]. The current LLR network was established by A11, A14, A17, and the Soviet Lunokhod Rovers (LR) 1 and 2 (Figure 1). LR1 could not be used for many years because its position was not known, but the Lunar Reconnaissance Orbiter Camera (LROC) recently rediscovered it. Even so, the LLR network is clustered in the center of the near-side Moon (Figure 1), a configuration that limits the sensitivity of the rotational measurement.

2.5 Other Possible Payloads

In the previous sections, we reviewed some key payloads that has already been discussed within the proposing team. However, it would be as important to explore other possibilities of payloads that can be included in the geophysical station. For example, mass spectrometer to investigate solar winds was included in ALSEP but this is not yet discussed in the team. Such instrument will be a good candidate for future discussion. We will plan to call for open discussion and accept new proposals from the community. This shall be done at the early stage of the project so that we can list the requirements for the central station and survival module, which is described in the following section. This will be important to maximize the capability and robustness of the geophysical station.

2.6 Central Station and Survival Module

Not all landers for future missions will be designed for long term observation. To realize simultaneous observation at multiple stations it would be mandatory to have a stand-alone system that enables the payloads to survive after the mother spacecraft stop its function. Development of such system will increase the number of launch opportunities that can install a geophysical station on the Moon and expand the lunar network. It would also be important that we also develop a central station that can be commonly used by the payloads. All payloads will be requiring some common functionality such as thermal control, power supply, and communication. A system that provides such functionalities will be required for all missions and standardizing such system will facilitate rapid development of the geophysical package.

2.7 Previous and on On-going Projects

2.7.1 Lunar Geophysical Network (LGN): NASA

Lunar Geophysical Network(LGN) was proposed to NASA New Frontier Program. In 2019, latest conceptual study was submitted to NASA which is now under investigation. the goal of the Lunar Geophysical Network (LGN) mission is to deploy four landers with instrumentation as described by the International Lunar Network report [ILN, 2009]: a broadband seismometer, heat flow probe, surface magnetometer/EM sounding, and laser retroreflector (at least for nearside landers). Four landers are baselined because of the LGN Concept Study conducted as part of the last decadal survey [Shearer & Tahu, 2013] as these can have a global distribution (including the far side) and allow for redundancy as a threshold of three landers can still achieve the goal of global coverage. The 4 landers will be long-lived (10 years) to maximize science and allow other nodes to be added by international and commercial partners during the lifetime of the mission, thus increasing the fidelity of the data obtained.

2.7.2 Development and Advancement of Lunar Instrumentation (DALI) Program: NASA

The project was funded by NASA to develop a flight heritage-based low-mass, low-power life-support system for the Moon that would wrap around and provide support (power, communications, thermal stability, shielding) to instruments like a seismometer, magnetometer, or mass spectrometer. This package would fly alongside as mass to any other flight efforts, be they commercial landers, astronauts, or other such payloads, similar to the autonomous CubeSat approach. These stations were investigated to be long-lived (2+ years) and be able to deploy themselves in small networks.

3 Technical Approach and Method

The proposed ALGEP activities will utilize science and engineering expertise to:

- Produce quantified Science objectives and an investigation baseline;
- Produce specific science-driven system requirements and constraints;
- Advance instrument designs for efficient incorporation into an integrated package;
- Identify environmental and operational challenges;
- Perform engineering trade studies and analyses to intelligently minimize mass, power, cost and astronaut impact while assuring reliability and performance;
- Produce an integrated ALGEP package concept in draft;
- Review and iterate specific analyses, as time allows, to improve the concept

.

3.1 Example Configuration of Geophysical Station

The broad ALGEP investigation concept is to install and monitor a distributed network of packages of geophysical instruments similar to (but greatly improved over) those deployed on the Moon in the Apollo Lunar Surface Experiment Package (ALSEP).

For reference, the geophysical instruments in the ALSEP were the Active Seismic Experiment (ASE), the Passive Seismic Experiment (PSE), the Lunar Surface Magnetometer (LSM), the Heat Flow Experiment (HFE) and the Laser Ranging Retroreflector (LRRR).

We will describe a possible configuration for the ALGEP concept. This will be one of the possible configurations and the details shall be discussed as the activity of the project.

- An improved surface package including these updated instruments:
  - A very broad band 3-axis Seismometer (dc-100 Hz) in a thermally stabilized enclosure, well coupled to the ground.
  - A 3-axis vector fluxgate magnetometer
  - Heat flow probes: 1 to 3 strings of heatable temperature sensors deployed by astronauts to a depth of at least 3-m.
  - A seismic profiler: 5-10 sensors along a 20-m line, approximately 2-4 m apart, with a vibrator to induce repeatable seismic signals for measurement by the sensors.
- Isolation of instruments from interference by the rest of the package (mechanical motion, magnetic signals, heat, etc.)
- A number (notionally 4 to 8) of these installations distributed around the Moon.
- Long life: Minimum 6 years, goal 12 years.

- Optimized experiment infrastructure, including power, computing and telecommunications systems and thermal control.
- Mitigation of issues identified during Apollo and subsequently, including emplacement complexity, cable trip hazards and dust.

Notional descriptions of ALGEP resource impacts are provided so that reasonableness of the proposed study can be evaluated. However, it is expected that the study will produce improved values for all of these parameters.

<u>Notional ALGEP Concept Parameters</u>

- Mass: 70-125 kg.
  - based on past JPL experience with Mars surface studies adapted to lunar conditions.
  - assumed:
    - solar arrays and batteries, no RTG;
    - Direct-to-Earth S-band telecommunications, no orbiting relay;
    - thermal control using flight proven materials and approaches.
- Volume in transit (stowed) and deployed: To be studied.
  - Notionally all instruments plus power, thermal, computer and telecommunications will fit into one station, except deployed solar arrays, seismic profiler string, and heat flow probes.
- Power load (avg.): 12 - 25 W, assuming solar arrays and batteries, no RTG. Operational modes will be analyzed and specified in the Concept Report.
- Downlink notion:
  - Per Earth day: 30Mb (baseline), 150Mb (goal).
  - a trade study will determine the relative power/memory impact of continuous data storage system vs. daily telecom. The AO-specified resources will bound this study.
  - The impact of Direct-To-Earth telecom will be compared to UHF orbital relay, to determine impacts on power and cost. The AO-specified resources will again be essential to bounding this study.
- Astronaut intervention: Astronauts will be required, to perform some or all of these steps:
  - Place the seismic profiler sensors at meter-scale separations
  - Orient each seismic sensor, and implant them firmly into the site's surface material;
  - Create one to three vertical holes (at least 3 m deep) for the heat flow sensors
  - Place the unit according to any engineering constraints (e.g., minimize RF interference, control solar illumination, to place and assure thermal devices, etc.)
  - Emplace the unit according to science constraints (e.g., on firm soil, away from rims or rocks

that would interfere with measurements).

- After deployment, calibration will be required. Calibration based on astronaut-provided stimuli and verification would be studied.
- Lifetime of 6 years to over 12 years, depending on power source and environment.
- Operations: Initial calibrations and active measurements by seismic profiler and heat flow probe, followed by low-activity, continuous monitoring by the instruments, with data compression, filtering, and/or selection by the small processors in the passive seismometer, magnetometer and heat flow experiments.
  - Uplink commanding is expected infrequently, to adjust instrument data processing, and to re-level or re-orient devices (based on Apollo experience).
  - thermal, power and telecommunications will produce different system states through the lunar day/night extremes and telecom activities, which are the operating modes to be defined and analyzed for optimization.

3.2 Proposed Development Plan for Key Subsystems

To develop the ALGEP investigation concept, the proposed study will coordinate science, instrument and systems engineering analyses, with iterations to refine and integrate the concept for the Study Report.

Specific trade studies are proposed that are anticipated to retire the largest system-level uncertainties in the current ALGEP concept. These studies will also remove the largest risk to design and implementation approaches for the remaining design work.

- The Science team will quantify and bound the largest uncertainties related to the ALGEP network, and instrument performance.

The Apollo experience identified many of the constraints and opportunities for this type of geophysical science package in the context of a crewed sortie mission. The proposed concept study will take advantage of this experience. Analysis of the following three system-level issues is proposed:

- Packaging of geophysical instruments together on one “pallet” or around one “facility” with integrated power, thermal control, telecommunications, electronics and computing (instead of distributed instruments cabled to “central” resources, as with ALSEP). Assess astronaut installation and thermal impacts. Compare mass and cost of thermal, power, telecom and structural designs.
- Investigate seismic strings using low-power wireless RF communication instead of cables; evaluate trade based on development cost, risk reduction, increased reliability, mass and cost.

  - Include mass and cost of power and thermal protection for independent seismic sensors; assess radioisotope heater units (RHUs).
- Mitigation of dust deposition on thermal, solar-electric and other functionally active surfaces.

Four additional studies to retire the largest systems design impacts are proposed:

- Effect on science results from the incremental, years-long growth of the ALGEP network; and effect of placement and number of installations in the lunar ALGEP network.
  - Quantify fidelity of lunar interior and near-surface models based on sortie site possibilities for ALGEP installation, and on incremental installations over years.
- Determine power source trades: RTG or solar with batteries (current concept is based on solar arrays with batteries due to expected low power requirement of the instruments and thermal control approach).
- Determine thermal control methods: study active and passive alternatives, expected to require only flight-proven materials and methods. Use established thermal modeling tools and compare to Mars designs for verification.
- Study end-to-end data return tradeoff between number of telecom contacts and capability against data storage and automated transmission in the Command and Data Handling (C&DH) system; determine a robust and efficient integrated communications and computing/memory approach.

Other trades are required but can be performed later, so are not included in this proposed work. Based on JPL flight experience and related studies, the impact of these studies is limited and they are not required at this concept phase. In addition, they cannot be performed within the scope of the Concept Study. Examples of such important subsystem or detailed design tasks for future resolution include: study inclusion of slot for low-power sustained experiment (e.g. long duration cell culture); reduce mass and power further; examine trades between direct-to-Earth (DTE) and UHF relay (if available per the AO), since some ALGEP installations are needed on the far side of the Moon; identify resource sharing with compatible investigations (if possible); optimize astronaut interfaces (carrying configurations, deployment and installation timeline, installation techniques and tools, setup, calibration and operations verification); assess operability tradeoffs of astronaut time and task complexity compared to possible science gains and reduced risk; assess build strategy and economies from non-recurring cost for multiple ALGEP units.

An asset of the ALGEP Investigation is that the instruments and their installation can all be made with existing technology. Only modified applications of existing technology are anticipated, and proof of performance for flight. However, to enhance astronaut safety and operability, “wireless” connection of the 5 to 10 seismometers on the surface is proposed as a trade study. While not “new” technology, it would require development for lunar surface application, and the resulting independent seismometer installations would require their own thermal and power designs. A trade study will resolve this design choice. Otherwise, the ALGEP system will apply known technologies and methods to solve the lunar surface and astronaut interaction issues while achieving low-risk, long-term high-value science data return.

4 Proposing Team

4.1 Contact Scientist

Taichi KAWAMURA

kawamura@ipgp.fr / +33 (0) 1 57 27 53 08

Institut de Physique du Globe de Paris (IPGP)

Bât. Lamarck - 7e étage - Bureau 722

35 rue Hélène Brion 75205 Paris CEDEX 13

4.2 Proposing Team

France

Philippe LOGNONNE, Institut de Physique du Globe de Paris (IPGP), lognonne@ipgp.fr

Eleonore Stutzmann, Institut de Physique du Globe de Paris (IPGP), stutz@ipgp.fr

Mélanie Drilleau, Institut de Physique du Globe de Paris (IPGP), drilleau@ipgp.fr

Sebastien de Raucourt, Institut de Physique du Globe de Paris (IPGP), deraucourt@ipgp.fr

Nobuaki Fuji, Institut de Physique du Globe de Paris (IPGP), nobuaki@ipgp.fr

Sebastien Rodriguez, Institut de Physique du Globe de Paris (IPGP), rodriguez@ipgp.fr

Pierre Delage, l'Ecole des Ponts ParisTech, pierre.delage@enpc.fr

Mark Wieczorek, Observatoire de la Côte d'Azur, mark.wieczorek@oca.eu

Germany

Martin Knapmeyer, German Aerospace Center, martin.knapmeyer@dlr.de

Matthias Grott, German Aerospace Center, matthias.grott@dlr.de

Sebastiano Padovan, German Aerospace Center, sebastiano.padovan@dlr.de

Ana-Catalina Plesa, German Aerospace Center, Ana.Plesa@dlr.de

Doris Breuer, German Aerospace Center, Doris.Breuer@dlr.de

Nicola Tosi, German Aerospace Center, nicola.tosi@dlr.de

Brigitte Knapmeyer-Endrun, University of Cologne, brigitte.knapmeyer-endrun@uni-koeln.de

Christos Vrettos, Technical University Kaiserslautern, christos.vrettos@bauing.uni-kl.de

Felix Bernauer, Munich University, fbernauer@geophysik.uni-muenchen.de

Switzerland

Luigi Ferraioli, Eidgenössische Technische Hochschule Zürich, luigi.ferraioli@erdw.ethz.ch

John Clinton, Eidgenössische Technische Hochschule Zürich, jclinton@sed.ethz.ch

Simon Stähler, Eidgenössische Technische Hochschule Zürich, simon.staehler@erdw.ethz.ch

Johan Robertsson, Eidgenössische Technische Hochschule Zürich, johan.robertsson@erdw.ethz.ch

UK

Anna Horleston, University of Bristol, Anna.Horleston@bristol.ac.uk

Nicholas Teanby, University of Bristol, N.Teanby@bristol.ac.uk

Belgium

Attilio Rivoldini , Royal Observatory of Belgium, Attilio.Rivoldini@oma.be

Czech Republic

Günther Kletetschka, Charles University, gk@natur.cuni.cz

4.3 Collaborators

USA

Clive Neal, University of Notre Dame, cneal@nd.edu

Bruce Banerdt, Jet Propulsion Laboratory, william.b.banerdt@jpl.nasa.gov

Seiichi Nagihara, Texas Tech University, seiichi.nagihara@ttu.edu

Jessica Irving, Princeton University, jirving@princeton.edu

Nicholas Schmerr, University of Maryland, nschmerr@umd.edu

China

Qian Huang, China University of Geoscience, qianhuang@cug.edu.cn

Shaobo Qu, HuazhongUniversity of Science and Technology, qushaobo@hust.edu.cn

Wenzhe Fa, Peking University, wzfa@pku.edu.cn

Japan

Takeshi Tsuji, Kyushu University, tsuji@i2cner.kyushu-u.ac.jp

Yoshiaki ISHIHARA, National Institute for Environmental Studies, ishihara.yoshiaki@nies.go.jp

Canada

Anna Mittelholz, The University of British Columbia, amittelh@eos.ubc.ca

Australia

Katarina MILJKOVIC, Curtin University, Katarina.Miljkovic@curtin.edu.au

5 References and Citations

Chenet, H., Lognonné, P., Wieczorek, M., Mizutani, H., 2006, Lateral variations of lunar crustal thickness from the Apollo seismic data set, Earth Planet. Sci. Lett., Volume 243, Issue 1-2, p. 1-14.

Cooper, M. R., R. L. Kovach and J. S. Watkins, Lunar near-surface structure, *Rev. Geophys. Space Phys*., **12**, 291-308, 1974.

Duennebier, F. and G. H. Sutton, Thermal moonquakes, *J. Geophys. Res*., **79**, 4351-4363, 1974.

Dyal, P., C. W. Parkin, and W. D. Daily, Structure of the lunar interior from magnetic field measurements, *Proc. Lunar Sci. Conf., 7th*, 3077, 1976.

ESA, 2019, *ESA Strategy for Science at the Moon*, (http://exploration.esa.int/moon/61371-esa-strategy-for-science-at-the-moon/#)

Frohlich, C. and Y. Nakamura, Possible extra-solar-system cause for certain lunar seismic events, *Icarus*, in press, 2006.

Goins, N. R., Dainty, A. M., Toksoz, M. N., 1981, Lunar seismology - The internal structure of the moon, J. Geophy. Res., vol. 86, June 10, 1981, p. 5061-5074.

Haskin, L. A., J. J. Gillis, R. L. Korotev, and B. L. Jolliff (2000), The materials of the lunar Procellarum KREEP Terrane: A synthesis of data from geomorphological mapping, remote sensing, and sample analyses, *J. Geophys. Res.*, *105*, 20,403-420,415.

Hood, L. L., F. Herbert, and C. P. Sonett The deep lunar electrical conductivity profile: Structure and thermal inferences, *J. Geophys. Res*., 87, 5311, 1982.

Horvath, P., G. V. Latham, Y. Nakamura and J. Dorman, Lunar near-surface shear wave velocities at the Apollo landing sites as inferred from spectral amplitude ratios, *J. Geophys. Res*., **85**, 6572-6578, 1980.

Jolliff, B. L., J. J. Gillis, L. Haskin, R. L. Korotev, and M. A. Wieczorek (2000), Major lunar crustal terranes: Surface expressions and crust-mantle origins, *J. Geophys. Res.*, *105*, 4197-4216.

Khan, A. and K. Mosegaard, An inquiry into the lunar interior: A nonlinear inversion of the Apollo lunar seismic data, *J. Geophys. Res*., **107**, 10.1029/2001JE001658, 2002.

Khan, A., J.A.D. Connolly, N. Olsen, and K. Mosegaard, Constraining the composition and thermal state of the moon from an inversion of electromagnetic lunar day-side transfer functions, Earth and Planet. Sci Lett, 248, 579, 2006.

Khurana, K.K., M.G. Kivelson, D. J. Stevenson, and others Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto, *Nature*, 395, 749, 1998.

Kivelson, M.G., K.K. Khurana, and M. Volwerk, The Permanent and Inductive Magnetic Moments of Ganymede, Icarus, 2001.

Kivelson, M.G., Khurana, K. K., D. J. Stevenson, and others Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res*., 104, 4609, 1999.

Korotev, R. L. (2000), The great lunar hot spot and the composition and origin of the Apollo mafic ("LKFM") impact-melt breccias, *J. Geophys. Res.*, *105*, 4317-4345.

Kovach, R.L., J.S. Watkins, and P. Talwani, "Active seismic experiment," in Apollo 16 Preliminary Science Report, NASA SP-315, 10-1 to 10-14 (1972).

Kovach, R.L., J.S. Watkins, and T. Landers, "Active seismic experiment," in Apollo 14 Preliminary Science Report, NASA SP-272, 163-174 (1971).

Lammlein, D., Lunar seismicity and tectonics, *Phys. Earth Planet. Inter*., **14**, 224-273, 1977.

Langseth, M. G. (1977), Lunar heat-flow experiment: final technical report, 287 pp, Lamont-Doherty geological observatory of Columbia University, Palisades, NY.

Langseth, M. G., Jr., S. P. Clark, Jr., J. L. Chute, Jr., S. J. Keihm, and A. E. Wechsler (1972), The Apollo 15 lunar heat-flow measurement, *Earth Moon Planets*, *4*, 390-410.

Langseth, M. G., S. J. Keihm, and K. Peters (1976), Revised lunar heat-flow values, *Proc. Lunar Sci. Conf.*, *7th*, 3143-3171.

Lawrence, D. J., W. C. Feldman, B. L. Barraclough, A. B. Binder, R. C. Elphic, S. Maurice, M. C. Miller, and T. H. Prettyman (2000), Thorium abundances on the lunar surface, *J. Geophys. Res.*, *105*, 20,307-320,331.

Lognonné, P., and B. Mosser, "Planetary seismology," Surv. Geophys. 14, 239-302 (1993).

Lognonné, P., J. Gagnepain-Beyneix and H. Chenet, A new seismic model of the Moon: implications for structure, thermal evolution and formation of the Moon, *Earth Planet. Sci. Lett.*, **211**, 27-44, 2003.

Mark, N., and G.H. Sutton, "Lunar shear velocity structure at Apollo Sites 12, 14, and 15," J. Geophys. Res. 80, 4432-4938 (1975).

Nakamura, Y., 1983, Seismic velocity structure of the lunar mantle, J. Geophy. Res., vol. 88, Jan. 10, 1983, p. 677-686.

Nakamura, Y., D. Lammlein, G. Latham, M. Ewing, J. Dorman, F. Press and N. Toksöz, New seismic data on the state of the deep lunar interior, *Science*, **181**, 49-51, 1973.

Nakamura, Y., G. Latham, D. Lammlein, M. Ewing, F. Duennebier and J. Dorman, Deep lunar interior inferred from recent seismic data, *Geophys. Res. Lett*., **1**, 137-140, 1974.

Nakamura, Y., G. V. Latham, H. J. Dorman, A. K. Ibraham, J. Koyama and P. Horvath, Shallow moonquakes: Depth, distribution and implications as to the present state of the lunar interior, *Proc. Lunar Planet. Sci. Conf.* **10th**, 2299-2309, 1979.

National Research Council. 2007. *The Scientific Context for Exploration of the Moon*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11954.

Oberst, J. and Y. Nakamura, A search for clustering among the meteoroid impacts detected by the Apollo lunar seismic network, *Icarus*, **91**, 315-325, 1991.

Parkinson, W. D, *Introduction to Geomagnetism*, p. 308-340, Scottish Academic Press Ltd., Edinburgh, U. K., 1983.

Russell, C. T., P. J. Coleman, Jr., and B. E. Goldstein, Measurements of the lunar induced magnetic moment in the geomagnetic tail: Evidence for a lunar core?, *Proc. Lunar Planet. Sci. Conf. 12th*, 831-836, 1981.

Russell, C. T., P. J. Coleman, Jr., and G. Schubert, Lunar magnetic field: Permanent and induced dipole moments, *Science, 186,* 825, 1974.

Shearer C.K. and Tahu G. (2013) Mission Concept Study: Lunar Geophysical Network (LGN). NASA 40 pp. https://solarsystem.nasa.gov/studies/203/lunar-geophysical-network-lgn/

Sonett, C. P., B. F. Smith, D. S. Colburn, G. Schubert, and K. Schwartz, The induced magnetic field of the Moon: Conductivity profiles and inferred temperature, Proc. Lunar Sci. Conf., 3rd, 2309, 1972.

Sonett, C. P., Electromagnetic induction in the Moon, *Rev. Geophys. Space Phys., 20,* 411, 1982.

Toksöz, M. N., Press, F., Anderson, K., Dainty, A., Latham, G., Ewing, M., Dorman, J., Lammlein, D., Nakamura, Y., Sutton, G., Duennebier, F., 1972, Velocity structure and properties of the lunar crust, *Moon*, 4, 490– 504.

Viswanathan, V., Rambaux, N., Fienga, A., Laskar, J., & Gastineau, M. (2019). Observational constraint on the radius and oblateness of the lunar core-mantle boundary. Geophysical Research Letters, 46, 7295–7303. https://doi.org/10.1029/2019GL082677

Wieczorek, M. A., and R. J. Phillips (2000), The Procellarum KREEP terrane: Implications for mare volcanism and lunar evolution, *J. Geophys. Res.*, *105*, 20,417-420,430.

Wieczorek, M. A., B. J. Jolliff, A. Khan, M. E. Pritchard, B. J. Weiss, J. G. Williams, L. L. Hood, K. Righter, C. R. Neal, C. K. Shearer, I. S. McCallum, S. Tompkins, B. R. Hawke, C. Peterson, J. J. Gillis, and B. Bussey (2006), The constitution and structure of the lunar interior, in *New Views of the Moon*, edited by B. J. Jolliff, et al., pp. 221-364, Rev. Min. Geochem.

Williams, J.G., X.X. Newhall, and J.O. Dickey, 1996, Lunar Moments, Tides, Orientation, and Coordinate Frames. Planetary and Space Sci. 44, 1077-1080.

Wiskerchen, M.J., and C. P. Sonett, A lunar metal core?, Proc. Lunar Sci. Conf., 8th, 515, 1977.