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ORIGINAL ARTICLE

# An autonomous lunar geophysical experiment package (ALGEP) for future space missions

## In response to Call for White Papers for the Voyage 2050 long-term plan in the ESA Science Program

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**Abstract**
Geophysical observations will provide key information about the inner structure of the planets and satellites and understanding the internal structure is a strong constraint on the bulk composition and thermal evolution of these bodies. Thus, geophysical observations are a key to uncovering the origin and evolution of the Moon. In this article, we propose the development of an autonomous lunar geophysical experiment package, composed of a suite of instruments and a central station with standardized interface, which can be installed on various future lunar missions. By fixing the interface between instruments and the central station, it would be possible to easily configure an appropriate experiment package for different missions. We describe here a series of geophysical instruments that may be included as part of the geophysical package: a seismometer, a magnetometer, a heat flow probe, and a laser reflector. These instruments will provide mechanical, thermal, and geodetic parameters of the Moon that are strongly related to the internal structure. We discuss the functionality required for future geophysical observations of the Moon, including the development of the central station that will be used commonly by different payloads.

**Keywords** Moon · Geophysics · Lunar exploration

## 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 National Research Council (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"

[46]). Recently, ESA published “ESA Strategy for Science at the Moon” (2019)[1], 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 among the key activities that need to be performed in the near future. This confirms that the questions addressed more than 15 years ago by the National Research Council [46] are still under investigation today and that there is global interest in the subject from the scientific community.

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, this is still the only geophysical station deployed on the lunar surface and still provide unique information which contribute significantly to our knowledge of the Moon beneath its visible surface. By modern standards, however, this information is quite limited both due to the technology of the instrumentation available at the time and by the limited geographic extent of the Apollo landing sites (Fig. 1).

We propose to develop a suite of instruments that function as a modern follow-up to ALSEP. This will consist of a standardized and robust geophysical package that can be reconfigured depending on various launch opportunities including those by private sectors. 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 would develop a central station and long-lived survival module that would 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 the proposed instrument suite can produce useful information from a single installation, the value can be greatly enhanced from a network of stations distributed across the Moon’s surface operating simultaneously for an extended period of time. Thus, to maximize what we can achieve by the geophysical observations, we need to consider all 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 given constraints imposed by different launch opportunities.

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 the network as much as possible. With payloads superior to Apollo instrumentation and a network with improved global coverage, we will uncover the internal structure of the Moon from a few meters depth to the center of the Moon leading to a detailed model of the interior structure. Knowledge of the inner structure of the Moon will surely contribute to uncover the mystery of

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[1] https://exploration.esa.int/s/WmMyaoW

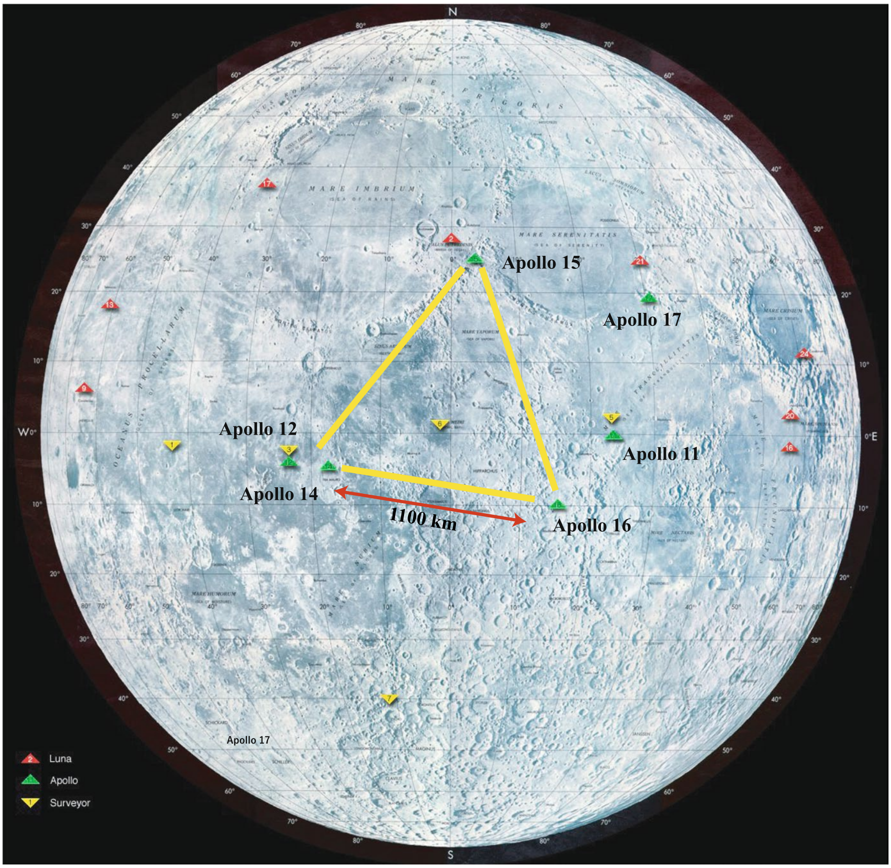

**Fig. 1** Apollo landing sites. The yellow triangle shows the seismic network of Apollo. Figure taken from Lunar Reconnaissance Orbiter project and modified by the authors (https://www.nasa.gov/mission_pages/LRO/multimedia/moonimg_07.html). Credit: National Space Science Data Center, NASA's Goddard Space Flight Center

the origin and evolution of the Moon. Furthermore, understanding the Moon will open a new window to explore terrestrial planets and rocky satellites in general.

### 1.1 Recent trends in lunar exploration

50 years after the first Apollo landing, the international community is once again targeting the Moon as their next exploration target. Various space agencies are planning lunar missions including crewed missions and the construction of a lunar base.

One of the most active players in lunar explorations is China which is carrying out the Chang'e program. In January 2019, Chang'e 4 landed on the lunar farside - the first such landing in human history - and demonstrated their capability of landing operations through a relay satellite. In November 2020, China launched Chang'e 5, the first Chinese sample return mission. Further Chang'e missions are planned up to Chang'e 8 in 2027 followed by the planned launch of a crewed mission to the Moon in 2030.

NASA also announced to launch a crewed mission to the Moon by 2024 as part of the Artemis program. This program will send 2-4 astronauts to the Moon, with a new space launch system (SLS) and the Orion crew vehicle. The Lunar Gateway, a planned station in lunar orbit led by NASA in collaboration with several international and commercial partners, will be established and pave the way for upcoming opportunities to access the lunar surface. ESA is contributing to the development of the Orion crew vehicle and is participating in the Gateway project.

Japan is planning to launch two landers to the Moon in the early 2020s. The first is the SLIM (Smart Lander for Investigating Moon) which will be launched in 2022. This will be an engineering mission to demonstrate the capability of high precision landing. SLIM will be followed by the 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 and quantify subsurface ice.

India launched the first lunar lander Chandrayaan-2 in July 2019, however contact was lost with the lander shortly before touchdown on the Moon. They also plan another polar landing missio, Chandrayaan-3, to be launched in August 2022.

ESA is developing a lunar lander that enables various types of mission, including the delivery of logistics in support of crewed mission or an independent high-profile scientific mission. The lander is known as European Large Logistic Lander or EL3 and is now in an intensive study phase. In this phase, ESA is gathering information from the community for possible payloads and experiments to be performed on the lunar surface. This phase is planned to be complete at the end of 2022.

Finally, the private sector has now started playing an important role in lunar exploration. As a part of the Artemis program, NASA selected the first 16 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 constantly be delivering payload to the lunar surface until 2028. This will open up possibilities to establish new stations on the Moon.

All of these planned launches present opportunities for deploying geophysical stations on the Moon. At the same time, all launch opportunities might have individual constraints, concepts and aims. Thus, the geophysical package shall be adaptable for each mission. Because crewed and robotic missions have strict constraints on instrument deployment, we aim for the development of a system that can be deployed (with a deployment system that can be added if necessary) in both scenarios. To maximize the launch opportunities, the payload should have a robust and universal design that can be adapted to various constraints.

### 1.2 Mission concept

The aim of this Autonomous Lunar Geophysical Experiment Package (ALGEP) project is to prepare a suite of instruments that can be added, making use of launch opportunities described above. This requires a strawman payload that can be reconfigured depending on the constraints of each mission. The specific configuration and payloads for each mission can be selected and defined through an open application opportunity. As a base, we propose to develop a standardized central station and long-lived survival module with a common interface. By standardizing the interface, we can reconfigure the geophysical package by simply plugging and unplugging the selected instruments. Such standardization will be helpful not only to facilitate the mission design but also to simplify the instrument development.

Such a system will be required for all geophysical stations on the Moon and it is thus of urgent priority for development. At the same time, all systems should be designed in a timely manner so that they can be adapted to various launch opportunities. Future launch opportunities will vary in their mass availabilities and mission duration. While some missions may be capable of delivering tens of kilograms of payload, others may have more limited capabilities. However, to establish a global network on the Moon, we need to take advantage of all the opportunities and adapt and design the package in a way that it can be reconfigured to align with the requirements of the mission. This also applies to the mission duration. Not all missions will be designed to survive the lunar day and night cycle. However, it is critical for a geophysical station to simultaneously operate with other stations. This will require long-term station operations and thus a stand-alone system that can operate even after the mother spacecraft ceases to function. Our proposed activity considers the rare and pristine Lunar condition and plans to minimize its impact on the Lunar environment.

The objective of this project is to first discuss functionalities necessary for the geophysical package and to define the requirements that need to be met. This includes the discussion of interfaces between subsystems. The next step will be to develop each subsystem taking into account defined requirements by using heritage payload from previous missions such as InSight [1]. InSight is only one example of a mission with already existing instruments with high technology readiness level (TRL) and it is important to collect such information to gain clarity on heritage and required future development.

## 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 properties such 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 at distributed places across the planet, as 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 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 Apollo 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 and to listen to high-frequency signals for an extended time after the mission.

Active seismic measurements conducted during the Apollo missions [27–30] provide a detailed view of the shallow seismic structure of the lunar regolith. The surface layer, ranging from 2 m to 20 m thick, has a very low P-wave velocity of about 110 m/s and consists of unconsolidated, fine grained soil with a bulk density of about 1500 kg/m$^3$[38, 39]. The second layer has a P-wave velocity of 250 ± 50 m/s (indicating less porosity) and a thickness of tens of meters. Below this is a layer with a velocity of about 1200 m/s, 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 up 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. Geotechnical parameters will play a key role in the construction of lunar structures (as a foundation, if not a building material) and the harvesting and 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 instruments operated for up to eight years until the data acquisition was terminated in 1977. The main purpose of the 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 [6]. They represent minute-long 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 inform us on the distribution and possible orbits of objects in the neighborhood of the Earth-Moon system [e.g. 47]. Deep moonquakes are small (body wave magnitude<2) but are the most numerous (>7000 identified) type of events. They concentrate in discrete locations (~240 identified) at depths between 800 km and 1100 km. Their near-monthly occurrence suggests a strong tidal influence of the Earth and the Sun [e.g. 31]. Shallow moonquakes are rare (only 28 identified) but include some of the strongest (body wave magnitude>5) seismic events observed on the Moon [e.g. 45]. They have distinct spectral signatures [44], and are generally considered to be tectonic in origin, although this is not completely understood [e.g. 8].

The near-surface zone of the Moon is highly pulverized with extremely low seismic velocities, as discussed above [see also 4, 16]. Below the regolith, seismic velocities gradually increase with depth, but recent re-analyses of Apollo 17 Lunar Seismic Profiling Experiment data found that low velocity of 1-2 km/s continues to 2 km depth [14]. 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. 57], but more recent analyses find thicknesses around 40 km [e.g. 37]. The lateral variation of crustal thickness were mainly studied using observation of gravity field, such as those obtained by GRAIL [e.g. 61]. Since the gravity field provides us with relative variation of crustal thickness, we need at least one anchor point. One of the observations frequently used as the anchor is the crustal thickness obtained at Appllo 12 site using receiver function analyse [58]. [3] also tried to further constrain the lateral variation by using impact events from different locations. While they succeeded in giving some seismological constraints on the lateral variation of the thickness of the crust, we still some discrepancy with GRAIL observation and further investigations are needed.

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 [11, 42] and in more recent analyses [20, 37]. There are reports of a distinct discontinuity that separates upper from middle mantle at around 600 km depth [e.g. 20], but this is somewhat controversial [9]. Below about 1000-1100 km (the depth at which deep moonquakes occur) seismic shear waves are severely attenuated, suggesting that the lower mantle is either partially molten or contains significant amounts of volatiles [43, 44]. Whether the Moon has a liquid core is uncertain from seismic data alone. The first seismic constraints on the molten core comes from one far-side impact that suggested existence of a molten core of a radius $\leq$ 360 km [44]. [59] also proposed a liquid outer core covered with partially molten layer while [10] was not able to constrain this using a similar approach. The strongest constraints on the molten core comes from geodesy [e.g. 12, 63] and in terms of seismic constraints on the liquid core, we still have discrepancies between different studies and further invetigations are needed.

Although the Apollo seismic experiments were highly successful and provided more information about the Moon than was anticipated, several important questions remain unanswered:

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., Procellarum KREEP Terrane, 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 four questions. Therefore, extending the areal coverage of stations 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 events 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 PSE network was only operational for about six years. This was barely long enough to cover a complete lunar tidal cycle for deep moonquake activity. A longer observational period allows for an increase in the number of detected events and at the same time, it also increases the chance of recording rare large shallow moonquakes and infrequent seismic rays travelling 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 operate seismometers even more sensitive than those deployed during Apollo. This will greatly increase the number of detected events for a given observational period, thus facilitating investigation of all of the above questions.

Finally, observing surface waves and free oscillations 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; 36] seismometer technology can solve this problem.

### 2.2 Magnetometer

Electromagnetic subsurface sounding using natural geophysical signals (such as those generated by the passage of the Moon through the Earth's magnetotail) to provide 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. Electrical conductivity in turn is sensitive to temperature and composition and thus complementary to the seismological and heat flow measurements proposed. By using multiple frequencies, electromagnetic sounding has been used successfully to probe the upper mantle of the Earth [see 56, Parkinson1983], place limits on the size of the lunar core [15, 50] and to discover liquid water oceans on Galilean moons [21–23].

The early Apollo program (specifically Apollo 12 and 14-16) placed several magnetometers on the lunar surface from 1970-1972 while Explorer 35 was measuring the magnetic field environment in orbit at the same time (1967-1973). Additionally, Lunar Prospector (1998-1999) and Kaguya (2007-2009) orbited the Moon each carrying a magnetic experiment [2, 18]. The lunar electrical conductivity structure has been the subject of many studies addressing the lunar core size as well as mantle structure[e.g. 15, 56, 54]. The three surface magnetometers (Apollos 12, 15, and 16) were operated simultaneously with orbiting spacecraft. An excellent summary of results from early investigations is provided by [55]. Generally, while the lower mantle is well characterized, the upper mantle and crust are poorly resolved with Apollo data due to the skin depth effect associated with the highest-resolution available data. The core size has been approximated as mentioned above; however, the core region is small and signals need to penetrate the full lunar body to sense it [55].

Two different types of analyses were used to sound the deep interior of the Moon, one focusing on mantle structure, the other on the size of the core. Several authors [e.g. 56, 66, 15, 54] utilized the Apollo 12 surface magnetometer to characterize the total field (induction + primary), while obtaining information on the primary field from a magnetometer onboard the orbiter Explorer 35. Observations were used only for those periods when the Moon was located either in the solar wind or in the Earth's magnetosheath. We note that because the Moon is exposed to fluctuations of the solar wind lacking a protective core field or even a ionospheric envelope, orbital data selection for induction studies of this type is particularly important. Also, using this approach requires an orbiter equipped with a magnetometer; in the past temporal mission data overlaps limited the data that could be used for such studies greatly [e.g. 5, 54]. However, recently it was shown that when the Moon is in the geomagnetic tail, conductivity estimates of the lower and mid-mantle can be made with only one magnetometer [40]. The average conductivity structure was evaluated using this subset of satellite data leading to conductivities similar to what was found from local Apollo 12 estimates [40]. The second class of studies measured the response of the lunar core to the well-defined transients that the Moon encounters as it enters or exits the geomagnetic tail [7, 51, 54, 55]. Those studies approximate the core as a perfect conductor that is overlain by an insulating mantle leading to an upper limit core radius of ~400 km.

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-sized 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. 19] 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. This leaves behind magnetic remanent fields that could be in principle separated from the inducing fields [24, 25, 48]. 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.

Furthermore, by establishing several stations, no additional information from orbit is required, but investigation via geomagnetic depth sounding would be possible. Ideally, measuring the electric field in addition to the magnetic field would provide individual conductivity estimates at each landing site.

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 are sensitive to a global response from the interior of a body, seismic data are particularly sensitive to interfaces within the body. In regions where mineralogy changes gradually or if an interface does not have a large density contrast, magnetic data may be helpful in reducing the uncertainty of seismic data inversion. Similarly, the inversion of magnetic measurements, which suffers from intrinsic non-uniqueness, could be more tightly constrained 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 [33, 34]. 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

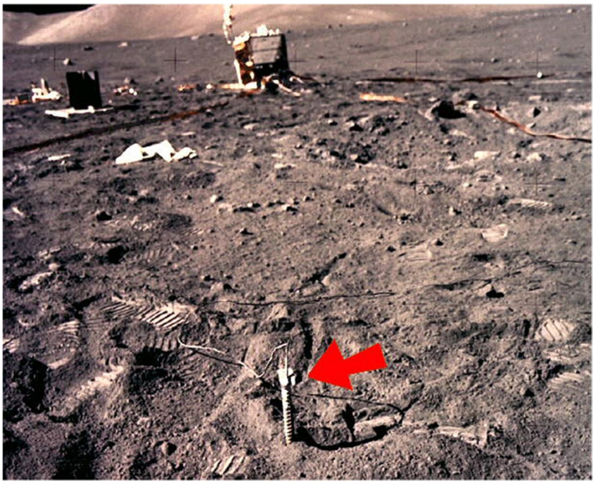

**Fig. 2** The Apollo 17 heat flow probe was the only successful emplacement of that experiment (note raised cable that could catch an astronaut's boot). ALGEP will study packaging alternatives to reduce or eliminate cable trip hazards.The image was taken from NASA's Project Apollo Archive (http://apolloarchive.com/apollo_archive.html) [AS17-134-20496]

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 [32]. After modifications, both Apollo 17 heat flow probes were inserted to depths of about 2.5 m (Fig. 2).

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 were obtained. Using these values, the heat flow at the Apollo 15 and 17 sites was finally estimated to be 21 $mW/m^{-2}$ and 16 $mW/m^{-2}$, respectively, with estimated uncertainties of about 15%.

The Lunar Prospector mission revealed that incompatible elements, such as K, P, or Th, were highly concentrated in only a single geologic province [13, 17, 26, 35, 62]. 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 PKT, which has elevated abundances of heat producing elements, whereas the Apollo 17 site lies in the Feldspathic Highlands Terrane, which is more anorthositic and poor in incompatible elements (Figs. 1, 2, and 3).

Reliable heat flow data from the Moon, both globally and locally, will provide important input for four fundamental 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)? Is the Moon significantly different and does this difference have implications for the origin of the Moon?

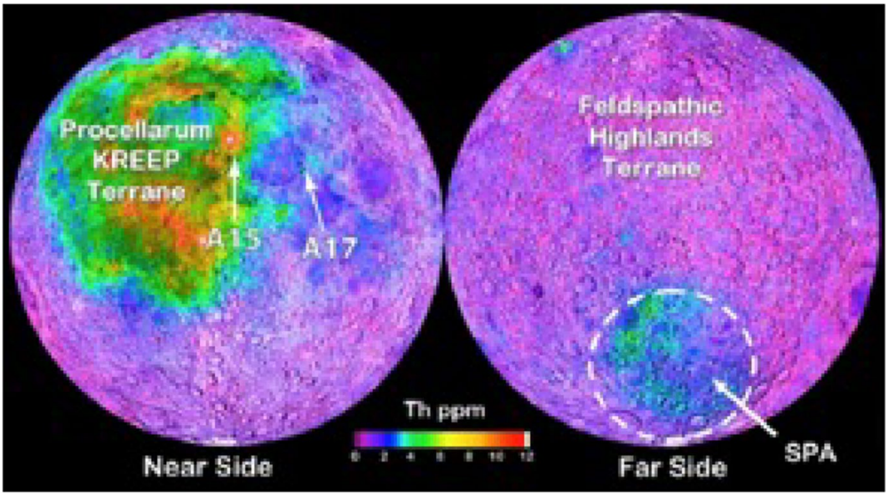

**Fig. 3** Thorium abundances at the lunar surface from Lunar Prospector [modified from Wieczorek et al., 2006]

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 60]. 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 information on composition at the surface. Heat flow data provides information on the vertically integrated abundance of radiogenic elements. If heat flow data are 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 [65]. Lunar rotational variations have strong sensitivity to moments of inertia and the gravity field while weaker variations, including tidal variations, are sensitive to the interior structure, physical properties, and energy dissipation. Second degree Love numbers are detected by LLR, most sensitively k2 [64]. A fluid core ~20% of the Moon's radius (~215 km) is consistent with the dissipation data. The current LLR network was established by Apollo 11, Apollo 14, Apollo 17, and the Soviet Lunokhod Rovers, (LR1 and LR2), see Fig. 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 in 2010 [41]. Even so, the LLR network is clustered in the center of the near-side Moon (Fig. 1), a configuration that limits the sensitivity of the rotational measurement.

### 2.5 Central station and survival module

Not all landers for future missions will be designed for long term observation. To realize simultaneous observations at multiple stations it is mandatory to have a standalone system that enables the payloads to survive after the mother spacecraft ceases to function. Development of such a system will increase the number of launch opportunities that can install a geophysical station on the Moon and expand the lunar network. It is also important that we develop a central station that can be commonly used by all instruments. 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 a system will facilitate rapid development of the geophysical package.

### 2.6 Previous and on-going projects

#### 2.6.1 Lunar geophysical network (LGN): NASA

The Lunar Geophysical Network (LGN) was proposed to the NASA New Frontier Program. In 2019, the latest conceptual study was submitted to NASA. LGN was selected as a part of New Frontier 5 call as announced in 2020 and is still under investigation[2]. The announcement of opportunity was planned during 2022 but this was postponed to 2023[2]. The goal of the LGN mission is to deploy four landers with instrumentation as described by the International Lunar Network report [52]: a broadband seismometer, heat flow probe, surface magnetometer/EM sounding, and laser retroreflector (at least for nearside landers). Four landers are baselined based on the LGN Concept Study conducted as part of the last decadal survey [53] because these can have a global distribution (including the far side) and allow for redundancy; a threshold of three landers can still achieve the goal of global coverage. The four landers would be long-lived (10 years) to maximize science return 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.

### 2.6.2 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 on any other flight efforts, be they commercial landers, crewed missions, or missions deploying other payloads, similar to the autonomous CubeSat approach. These stations are intended to be long-lived (2+ years) and be able to deploy themselves in small networks.

## 3 Technical approach and method

In this Section we outline a proposed way forward to develop an Autonomous Lunar Geophysical Experiment Package (ALGEP). 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.

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[2] https://newfrontiers.larc.nasa.gov/NF5/announcements.html

### 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 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). A possible configuration for the ALGEP concept could be:

- 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 indicated here, however, it is expected that the study will produce improved values for all of these parameters.

Notional ALGEP Concept Parameters:

- 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 control, computer and telecommunications will fit into one station, except deployed solar arrays, seismic profiler string, and heat flow probes.

- Power load (average): 12 - 25 *W*, assuming solar arrays and batteries, no RTG.
- Downlink notion:
  - Per Earth day: 30 *Mb* (baseline), 150 *Mb* (goal).
  - A trade study will determine the relative power/memory impact of a continuous data storage system and daily telecommunications. The resources specified in the Announcement of Opportunity (AO) for a mission that would carry ALGEP will provide bounds.
  - The impact of Direct-To-Earth telecommunications will be compared to UHF orbital relay, to determine impacts on power and cost. The AO-specified resources will again give essential bounds for this study.
- Astronaut intervention: Astronauts will be required to perform some or all of these steps:
  - Place the sensors along the seismic profile sensors at meter-scale separation
  - 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 radio-frequency (RF) interference, control solar illumination, to place and assure proper working of thermal devices, etc.)
  - Deploy 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 experience during the Apollo missions).
  - Thermal variability, power supply and usage, and telecommunications will produce different system states through the lunar day/night extremes and telecommunications 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, further study is required, coordinating science, instrument, and systems engineering analyses, with iterations to refine and integrate the concept. Specific trade studies should resolve 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 constrain the largest uncertainties related to the ALGEP network, and instrument performance.

The Apollo missions identified many of the constraints and opportunities for this type of geophysical science package in the context of a crewed surface mission with a possibility of extravehicular activities (EVA). 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, telecommunications, and structural designs.
- Investigate seismic strings using low-power wireless RF communication instead of cables; evaluate trade based on development costs, 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 assesss the largest system 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 site possibilities for ALGEP installation, and on incremental installations over years.
- Determine power source trades: RTG or solar arrays 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 telecommunication 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 trade studies are required but can be performed later, so they are not included in these lists of initial studies. Based on JPL flight experience and related studies, the impact of these studies is limited and they are not required at this concept phase. 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 should be investigated. While not novel technology in itself, it would require the development of an application for the lunar surface, 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 Conclusion

We presented our mission concept for an autonomous lunar geophysical experiment. This is a strawman payload which can be desigend and configured depending on the constraints of the spacecraft, landing site, or scientific objectives. We propose to develop a series of scientific instruments and a central station with standardized interface. The design will enable a flexible design tailored for each mission with small modification and development costs. With such a flexible and robust design, we will benefit from a wide variety of launch opportunities, including those of private sectors. The establishment of a network is the key for meaningful geophysical observations. By maximizing the opportunities to deploy geophysical stations on the Moon, we aim to perform quality observations and uncover the lunar internal structure.

We also presented examples of possible payloads for the geophysical experiment: a seismometer, a magnetometer, a laser ranging retroreflector, and a heat flow probe. These instruments were proposed to be high priority instruments whose developments are already underway. We welcome discussion at this early stage of development so that we can investigate our design in an optimized manner. At the same time, we should also encourage discussions for other possibilities for payloads. Such a flexible lunar surface experiment package may be used as a common infrastructure for various instrument as it was the case for ALSEP.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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