Rover-based system for Scouting and Mapping lava tubes from the Moon's surface using gravimetric surveying

OSIP Lunar Caves - System Studies

Executive Summary

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Document Description

This document is the Final report for the “Rover-based system for Scouting and Mapping lava tubes from the Moon's surface using gravimetric surveying” OSIP Lunar Caves System Study carried out by Canadensys and Queen’s University

APPROVALS

Rover-based system for Scouting and Mapping lava tubes from the Moon's surface using gravimetric surveying
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VERSION HISTORY

Revision #	Affected Pages	Reason for Revision
V.1	All	Draft for review
V.2	All	Final submitted version

Context

Gravity Geophysics: Gravity weighs you down. The *way* in which it does that, has been known ever since Sir Isaac Newton published his Theory of Universal Gravitation in his *Principia* in 1687. On the surface of the Earth, gravity exerts a downward force on you of about 9.8 newtons for every kilogram of your mass. If you stand on a more massive planet, then you will feel heavier, which is why lunar explorers will feel 83% lighter when standing on the Moon's surface than they are on Earth (because the Moon's mass is only about 1/6 that of Earth's).

However, you don't need an entire planet to create that weight. Some types of rock are more dense than others; for example, iron ore is more than twice as dense as basalt rock, and three times as dense as typical sandstone. If you were to stand on the ground above a large iron ore deposit, your weight would be higher than normal. Not a *lot* higher, not enough that you could feel the difference. But higher *enough* that it could be measured using a sensitive enough instrument.

The type of instrument used to make this sort of measurement is called, appropriately enough, a *gravimeter*. Geophysicists use gravimeters to conduct surveys of large areas of land, in order to measure the variations in gravity across the survey area, due to variations in the density of the rocks underlying the survey area. Deposits of high-density rock cause a "gravity high" signal on the surface above them, and deposits of low-density rock cause a "gravity low." Geologists can use maps of gravity strength versus latitude and longitude, to infer the subsurface composition and structure. This technique, which has been widely used for over 100 years, is one of the main methods used in searching for deposits of valuable natural resources — mineral ores, as well as oil & gas deposits — beneath the ground.

Another feature that can produce a gravity low is a *subsurface void space* — a cave. This is because a cave is like a deposit of "zero density rock" (or more accurately, the density of the air in the cave, but that is more than 1000 times smaller than the density of rock). The larger the cavity, the stronger will be the gravity-low on the surface above it. Ground-gravity surveying has been demonstrated on Earth to be capable of detecting the presence of even quite-small subsurface cavities, ones that are smaller than 20 m in diameter.

It is important to realize that the same principle applies on other planets — hence the term "Universal" in Newton's theory of gravitation. A gravimetry survey carried out on the surface of the Moon can be used to detect the gravity signature due to density variations below the Moon's surface, in the same way as on Earth.

Lunar Caves, Lava Tubes: Subsurface voids are one particularly interesting type of lunar subsurface feature. While there was speculation about the possible existence of natural lunar caves for many years, it was not until 2009 that the first lunar subsurface void was detected, using camera imaging from the Japanese Selene lunar orbiter spacecraft. This detected a "pit crater" in the Marius Hills region on the nearside of the Moon (Figure 1). Unlike most bowl-shaped lunar craters, the Marius Hills pit is clearly a hole punched through the lunar surface, to an underlying void-space.

Since that region shows many signs of past volcanic activity, it raises the possibility that the void might be a skylight into a *lunar lava tube*. Lava tubes are well-known features found in many volcanic areas of Earth, formed when a river of molten lava becomes "roofed over" as the top skin of the lava cools; the lava continues to flow in the now-covered-over tube until the volcanic eruption feeding that river ceases, at which point the remaining lava in the tube flows downhill, leaving the tube empty. The Marius Hills pit is located within a *lunar rille* feature — a long, shallow valley that is also thought to be a remnant of a once-flowing lava river. It seems plausible that this pit was formed at some point in the past when a meteoroid crashed into the Moon's surface just above a subsurface lava tube, collapsing the rocky roof of that tube and creating a tunnel from the surface into the tube.

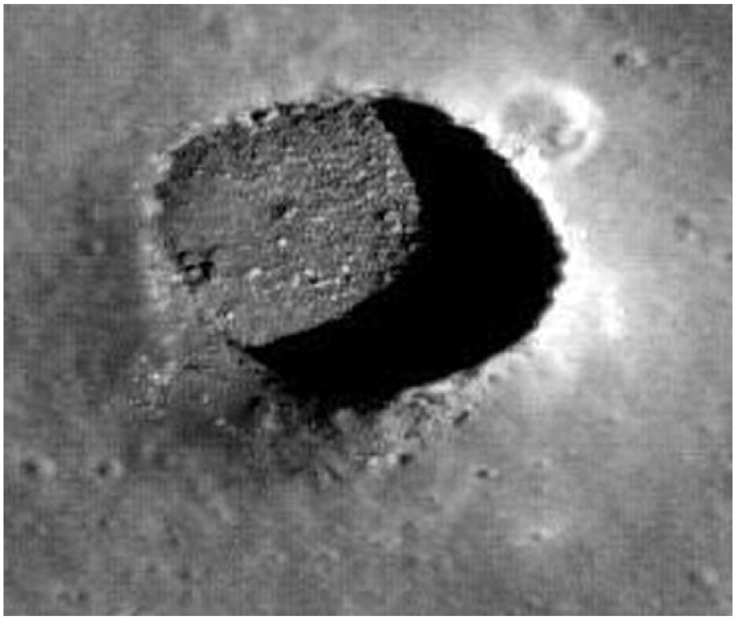


Figure 1: Composite image, combining two images of the Marius Hills pit taken by NASA's Lunar Reconnaissance Orbiter (courtesy of NASA's James Fincannon, from https://behindtheblack.com/behind-the-black/essays-and-commentaries/single-rope-techinque-on-the-moon/)

This is not an isolated feature on the Moon. Since the discovery of the Marius Hills pit in 2009, hundreds of other pit craters have been detected at locations distributed around the Moon. And while lava tubes on Earth are typically smaller than 20 m wide, some of the void-spaces underlying these lunar pits are much larger than that, with many being more than 100 m across. Current thinking is that lunar lava tubes may be abundant, and much larger than those on Earth; the reasons for their large size perhaps being linked to the Moon's low gravity, and the vacuum conditions under which ancient lava flowed.

These features are of strong potential scientific interest, because their interiors may preserve pristine records of the composition of lava flows on the Moon from far in the past. The surface of the Moon is continually being "weathered" by an incessant rain of micrometeoroids, irradiation by high-energy particles, and thermal stresses caused by the several-hundred-degree temperature swings between the lunar day-time and night-time. This causes all rocks exposed on the Moon's surface to crumble away with time, eventually into a very fine powder. The interior of a lunar cave, however, would be shielded from these effects, and may be essentially unchanged since first being formed, billions of years ago.

These features are also of huge potential interest from the perspective of human exploration and eventual settlement of the Moon, for a related reason. The same effects that cause "space weathering" of the lunar surface, also create hazards for people on the Moon's surface, and for the equipment they will use to land on the Moon, live there, move around the Moon's surface and leave the Moon to return to Earth. Ionizing radiation on the Moon's surface is much more intense than on Earth, and can lead to long-term health problems; occasional solar flares can even be immediately lethal. The rain of incoming micrometeoroids, small but impacting at speeds much higher than that of a rifle bullet, can damage equipment. The enormous temperature extremes greatly complicate the design of equipment that must survive on the Moon's surface for more than one lunar day, forcing that equipment to be designed to be more massive, and requiring hibernation through the 14-day long, cold lunar night. However, a lunar base located in a natural cave beneath the Moon's surface, potentially inside a lava tube, would be insulated from these effects. Lunar lava tubes might eventually become the most desirable locations for siting future crewed lunar bases.

Mission of Gravity: The voids underlying lunar pit craters *may* be lava tubes; however, the images that can be collected from lunar orbit cannot prove that to be the case. Lunar scientists have developed alternate explanations for these features, involving blobs of "impact melt" from material flung up from the Moon's surface during huge impact events. While a lava tube would be expected to be (like those on Earth) very large, long voids, an impact-melt feature might be much smaller, and entirely localized. Determining the nature of the voids beneath lunar pits is one of the top lunar scientific questions today.

Canadensys Aerospace Corporation, a small Canadian space-engineering company located near Toronto, working with Queen's University of Kingston, Ontario, has completed a study for a lunar exploration mission titled "Rover-based system for Scouting and Mapping lava tubes from the Moon's surface using gravimetric surveying," which was carried out under ESA's OSIP Lunar Caves Challenge. This study examined an exploration mission concept in which a ground-gravity survey, carried out on the Moon's surface in the vicinity of a pit crater, would measure and map the gravity anomalies due to the pit's associated subsurface void-space. The survey would be carried out by robotic lunar rover vehicle carrying a lunar-surface-compatible gravimeter instrument, which would be brought to the Moon's surface by a small robotic lunar lander, and controlled by radio-command by operators on Earth. Canadensys has developed multiple classes of lunar mobility in support of both government and commercial applications, with two classes in particular currently being built for the Canadian Space Agency, a sub-30 kg lunar "Micro-Rover" (similar to that illustrated in Figure 2), and a sub-10-kg lunar "Nano-Rover," and as well as a sub-2 kg space gravimeter (named "VEGA," shown in Figure 3) whose development is nearly complete. These developments, combined with the lunar landing capabilities being developed by several groups around the world, mean that a pit-crater gravity scouting mission is now a viable prospect within the next few year.

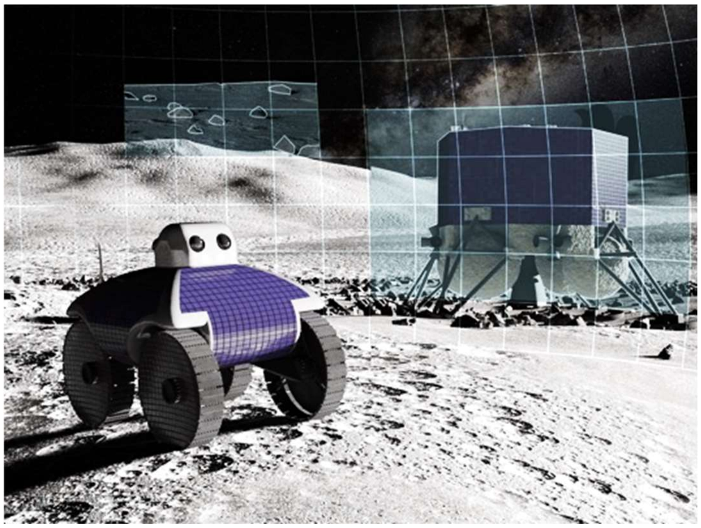


Figure 2: A concept for a robotic lunar Nano-Rover deployed from a lunar lander (credit: Canadensys Aerospace)

Objectives

The main Objectives of this study were:

- To carry out thorough analysis and modeling of the anomalous gravity fields expected from lunar lava tubes and other types of void spaces, of various sizes and depths. This work was carried out by geoscientists from Queen’s University.
- To define the Mission and System-Level Requirements for this exploration mission, derived from the scientific analysis of those expected gravity signals, and specifying feasible Mission and System-Level Designs, for a mission to scout the Marius Hills pit crater.
- An additional objective was to study the possible inclusion of another, auxiliary geophysical instrument aboard the rover — a Ground Penetrating Radar (GPR) — to produce subsurface imaging signals that would complement the gravity measurements.

Programme of Work

The work plan comprised two main areas of technical activity:

- **Science activities**, in which work would be done to understand the detailed nature of the geophysical signals (gravity and radar) that would be caused at the Moon’s surface by a subsurface lava tube.
- **Engineering activities,** in which a methodical space-engineering approach would be followed to define achievable requirements and designs at both the Mission and System levels, for a rover equipped with those geophysical instruments setting out to scout the Moon’s surface in the vicinity of the Marius Hills pit crater, to identify and map its subsurface void space.

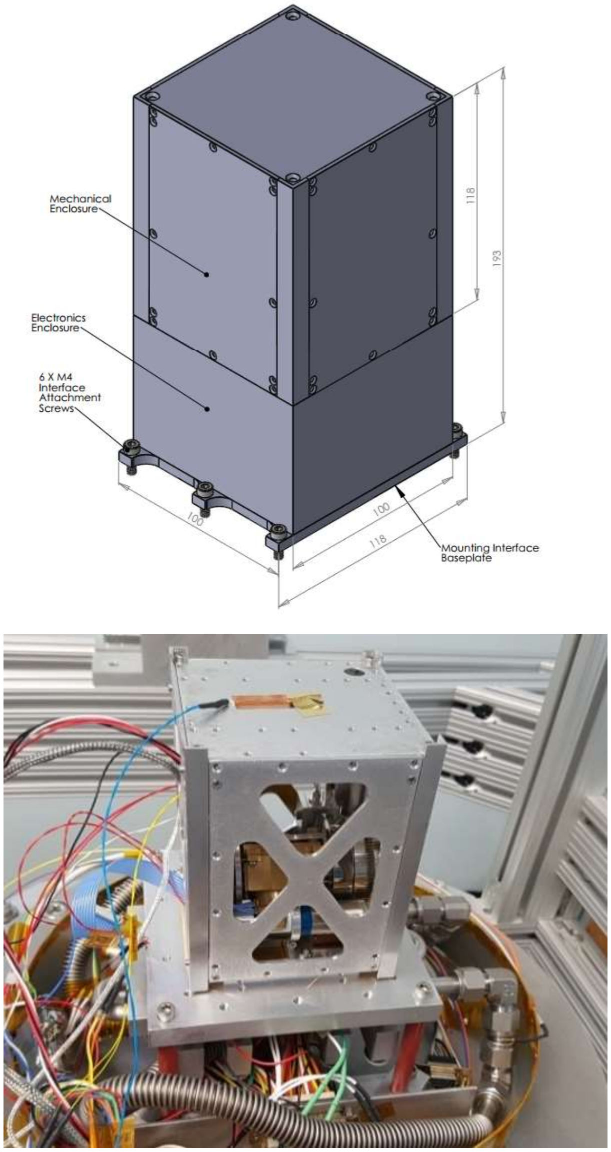


Figure 3: Drawing of the VEGA lunar surface gravimeter, and image of VEGA hardware undergoing thermal-vacuum testing (credit: Canadensys Aerospace)

Activities Performed

The main Science activities performed were:

- Studying available maps of the Marius Hills region to determine topographical context.
- Studying the nature (size, shape) of typical terrestrial lava tubes, to provide a basis for extrapolating possible lunar lava tube characteristics.
- Developing software tools to forward-model the gravity anomalies at the Moon's surface due to realistically sized and shaped lava tubes beneath the surface.
- Developing software tools to estimate the radar return signals from lunar lava tubes to a realistic ground penetrating radar instrument.
- Carrying out simulations using that software of various lava-tube scenarios, studying the geophysical signals at the surface as a function of lava-tube depth and size and shape.
- Performing numerical experiments with those simulations, to investigate various possible approaches to planning geophysical survey traverse paths, in order to assess how long a distance a rover would have to travel in order to sufficiently recover information on the characteristics of a given lava tube.

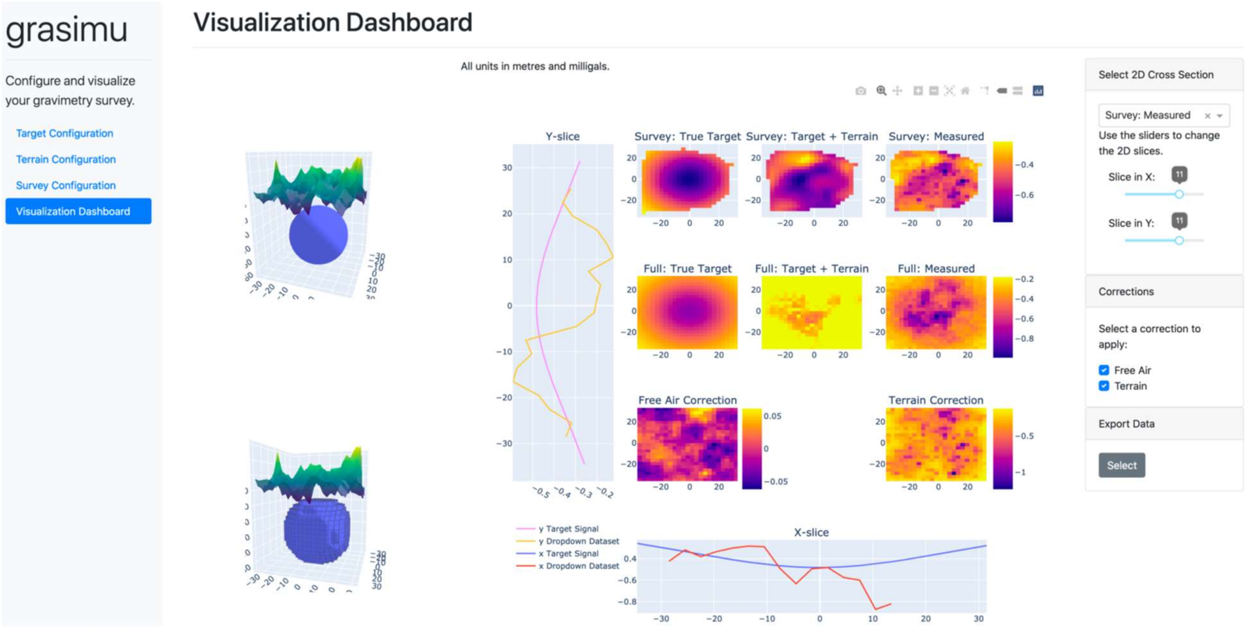
The main Engineering activities performed were:

- Identifying the main requirements at the Mission and System level that drive the design of a robotic rover mission to carry out this sort of survey, with the focus being on minimizing the size and mass (and hence flight cost) of the equipment in that system.
- Identifying the main system-level design characteristics of two different exploration rover systems — one carrying a gravimeter and the other a gravimeter plus a GPR — feasibly capable of carrying out the lava-tube scouting survey around the Marius Hills pit crater, while complying with those requirements.

Results

One of the main results of this work was the development by Queen's University of a gravity modeling and visualization software tool, called **grasimu**, to model a wide range of subsurface voids of different sizes, shapes and depths, with user-specified topography for the surface above that void-space, and to produce maps of the anomalous gravity on the surface above those voids. This software was used during the study to validate the expected magnitude of the gravity signals for a range of possible lava tube sizes and depths, verifying that Canadensys' VEGA gravimeter instrument is sensitive enough to detect and map these features; Figure 4 shows one of grasimu's output screens, illustrating the type of geophysical modeling results it produces. This software is portable, and is being made freely available as open-source code by Queen's.

Work done at the Mission-level was crucial, to develop an understanding of the constraints that end up driving the System-level design of the rover. The study assumed that determining the width of the void-space underlying the pit crater was a major science requirement; this requires that the rover carrying the gravimeter actually drive over the edge-wall of the void-space. If the void-space is a very localized compact one, not much larger than the diameter of the pit crater, this is easy to accomplish with a gravimetry survey confined to the immediate vicinity (within 100 metres or so) of the pit. However, if the void-space is a lava tube, then a major complicating factor is that lunar lava tubes are thought to be able to be *much* wider than terrestrial ones, possibly as wide as the *rille*



Visualization Dashboard

Configure and visualize your gravimetry survey.

All units in metres and milligals.

Survey: Measured

Use the sliders to change the 2D slices.

Slice in X: 11

Slice in Y: 11

Select a correction to apply:

☑ Free Air

☑ Terrain

Figure 4: Screenshot of the **grasimu** software modeling the gravity response to a compact localized void, with non-smooth surface topography above it

valley features observed in many places on the Moon. As the Marius Hills pit is located in the middle of a 900-metre-wide rille, it seems possible that a lava tube beneath that pit might be similarly wide. After considering several possible survey design strategies, a concept was developed for a 4-kilometre-long traverse design that has a strong likelihood of intersecting at least one edge of an underlying lava tube, within a 10-day survey carried out before the first lunar nightfall after the rover is deployed. Figure 5 shows this baseline survey path.

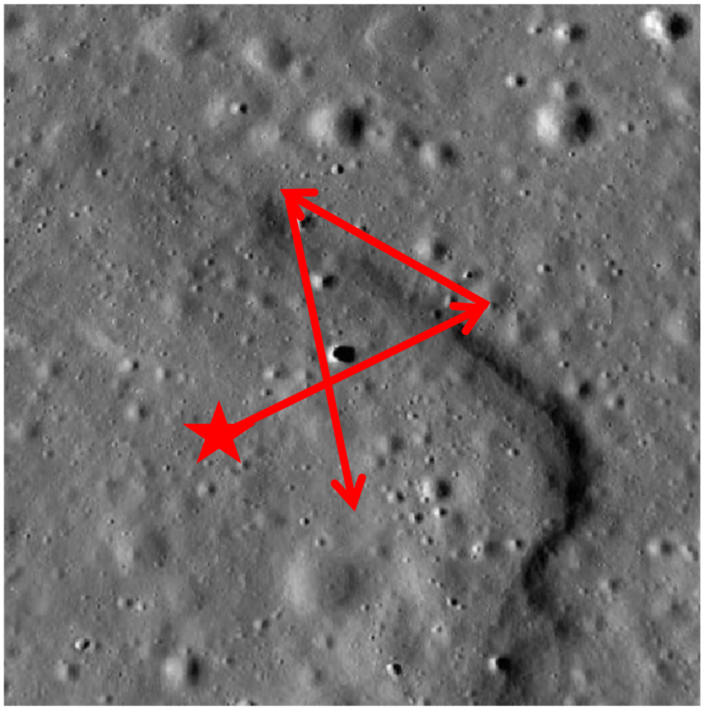


Figure 5: Baseline Marius Hills gravimetry survey traverse path

Another major result of this work was to determine the size of rover that would be needed for each of two versions of this mission: one in which only a gravimeter payload is carried by the rover, and the other in which the rover carries both a gravimeter and a 1.5 kg GPR instrument. Achieving this result took into account the mass and amount of power needed by each instrument, the amount of data produced by each instrument at each measurement location during a survey, and the amount of power needed to transmit that data back to Earth, which allowed the required power-generation capability for each rover to be specified, and hence the number of solar cells that each rover had to carry on each of its faces. This also took into account the total amount of distance that had to be covered for the planned surveys, and the speed that the rover would have to travel. The gravimeter-only mission can be carried out with a rover whose mass is under 8 kg, while the dual-instrument mission requires a slightly more massive rover, with a mass of under 12 kg. In each case, a total survey distance of 4 km was specified, to be carried out within 10 days of rover operations, requiring each rover to be able to achieve a speed-made-good of 500 metres per day. This verified that *the pit-crater gravimetry surveying mission is feasible to carry out using very small rovers*, based on lunar rover technology that Canadensys has already developed to an advanced level, which will be ready to support lunar flight missions within the next 2-3 years.

Canadensys is pioneering development of lunar rovers capable of surviving the extremely cold temperatures of the lunar night-time, and to wake up again the next morning to be able to continue operating, potentially for many lunar day/night cycles. That capability would clearly greatly enhance this mission, by allowing a much longer total traverse to be carried out, allowing a larger area of ground to be surveyed, or alternately allowing the same section of the Moon’s surface to be surveyed in much finer detail. In this study, the application of several different “flavours” of night-survivability technology were considered, to assess the impact on total rover mass of adding that capability.

Benefits and Next Steps

ESA’s OSIP Lunar Caves Challenge looks forward to a potential mission to actually send a “cave-diver” rover *inside of* a lunar pit crater, to explore its interior. This would be a challenging mission, likely requiring custom-development of quite-complex and expensive equipment. It would be very desirable to target such a mission towards a pit crater known to be as scientifically interesting as possible, preferably one that is *known to be a skylight into an extensive lava tube*. Because any given candidate pit crater might turn out to be a “dud” (with a disappointingly small void-space, not worthy of sending a cave-diver rover into), it might be necessary to scout out more than one such target before finding one worthy of further exploration. This study focused on defining a scouting mission with the lowest mass, and hence the lowest cost possible, so that multiple scouting missions would be affordable — applying a core feature of the Nanosatellite/Cubesat philosophy to this lunar surface exploration mission. The exploration technology studied, lunar surface gravimetry, is uniquely suited to carrying out this scouting function on the lowest possible cost basis. The study has shown that this robotic-rover based precursor scouting mission is technically feasible, and has established the main system design parameters for that mission, in particular determining the rover mass needed.

The next step for this mission is to complete the rover and gravimeter development work. Canadensys is doing that now, aiming to have this equipment ready to fly to the Moon by 2024. Following that, the next step would be to begin planning for one or more pit-crater gravimetry survey missions, which would involve actively engaging a science team to assess potential target pit craters, and to rank their priority for exploration. Programmatic activity should be carried out in parallel, to put approvals and budgets in place to pay for the lander rides to the lunar surface at selected pit crater locations, and for the rover and gravimeter instruments needed for the missions.

One potential lunar lander being planned, which could support one or more pit-crater scouting missions, is ESA’s European Large Lunar Lander (EL3), currently in its definition phase, aiming to begin flying missions to the Moon by 2028. Another next-step activity would be for the EL3 definition team to consider this pit-crater scouting mission amongst its early candidate missions.