Accessing the Lunar Underground: The LAva-TUbe iNvestigAtion (LA-TUNA) Mission Concept.

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Introduction: With an increasing interest in returning to (and staying on) the Moon, there is a growing interest in both exploring intact lava tubes scientifically and using them as settlement locations, e.g. [1]. Lava tubes can be created by a variety of mechanism following surface or subsurface lava flows [1], leaving behind hollow underground tunnels. A natural limitation in the lava tube diameter comes from the structural stability of the lava tube roof, which, however, allows larger diameters at smaller gravities, i.e. on the Moon and Mars. Generally, intact lava tubes can be accessed via collapsed parts of the tube roof [2] or vertically via a lunar pit as proposed by e.g. [3].

Here, we present the LAva-Tube iNvestigAtion (LA-TUNA) mission concept for a robotic Lunar underground exploration mission, the first mission ever to access an extra-terrestrial lava tube. While different underground missions have been proposed before, we emphasize the proposed payload suite, capable not only to well characterize the tube interior, but also the overlying near-surface material. This mission concept was first proposed in response to the ESA call for ideas for the European Large Logistic Lander (EL3), while the concept can be included in any Lunar mission, both robotic and human, that includes a landing element. Entering an intact lava tube opens the door to a new world. Broad scientific investigations will allow detailed characterization of the lava tubes, but also the overlying materials. Such a mission will not only contribute to better understanding the history of the Moon and its volcanism, but it is also a prerequisite to consider using lava tubes as part of a human settlement architecture.

The primary mission goal is the investigation of the cave interior with respect to composition, environmental conditions, structure and habitability.

The mission concept is based on a tethered vehicle equipped with scientific payloads and supplemented with further payloads on the Lunar lander, located ideally in the proximity of the lava tube entrance. After the deployment of the vehicle from the lander, it will traverse towards the lava tube entrance on a trajectory that maximizes coverage of the lava tube from the top, i.e. it follows the lava tube roof. Like this, sequential measurements at the same location, first from above and then from below the lava tube roof can be conducted. This will be a valuable asset, e.g. to gravimetry, allowing differential measurements. A tethered connection between the lander and the vehicle ensures continuous power supply and data connection.

The investigation of the cave interior is done with a full payload suite consisting of:

- Environmental package (temperature, radiation, dust conditions, thermal inertia, etc.)
- LiDAR
- Gravimeter
- Acoustic tomography (source and receiver)
- Spectrometer
- Ground-penetrating radar
- Stereo Navigation Camera
- Optional: Sampling payload for case of collapsed rille entrance: deliver to other side

Exploration Targets: As stated above, there are two options to enter the target lava tube. A preference is given to using the intersection of intact and collapsed tube [2], as a later habitat will not require means of vertical transport, i.e. an elevator. Furthermore, the intact part of the lava tube can have two entrances (as in [2]), allowing the vehicle to enter from one side and potentially to exit on the other side. The latter even allows considering a sample return from the underground. Two sides to exit will also be a true benefit to safety engineering of an underground habitat.

Alternatively, a lunar pit (also: “sky hole”) such as the Marius Hills Hole, thought to be created by a limited (circular) collapse of an intact lave tube roof, can be considered for entering a potentially intact lava tube [4]. This option allows detailed investigation of the lava tube roofs cross-section by performing experiments during the descent [3].

Mission benefits: The mission concept provides benefits to three fields of spaceflight listed below:

Science at the Moon: Lunar history, volcanism, mapping and exploration of lava tubes, composition and structure of top lunar layer. “Comparable geophysics”: lava tubes are also present on the Earth, comparing and transferring knowledge between Moon and Earth is huge benefit for investigations, also for other bodies such as Mars [1].

Human Exploration (Lunar settlement): Understand structural stability of the lava tube roofs for lunar settlement architecture, radiation level inside cave (habitat, equipment storage, astronaut exploration, solar storm shelter, etc.). Understanding the stability and structure of the covering material is crucial to avoid catastrophic events. If permanent stability cannot be guaranteed, other solutions need to be developed for habitation, while maintaining the tubes as a shelter for equipment, or as a fallback as a solar storm shelter.

In-situ resource utilization (ISRU): Map the composition and structure of accessible materials (top surface layer, deeper material reachable via rilles/craters, possible presence of water in lava tubes, etc.).

Mission details: The mission scenario formulates two main demands to the lander:

Firstly, the lava tube exploration rover shall be deployed from the lander. A tethered connection between the lander and vehicle is required to ensure power supply and communication of the vehicle, which is imperative once underground. The tether will also be used for descent into the rille/sky hole, where it might be necessary to subdivide the tether using deployable winches. Night survival and data relaying to Earth will be done via the lander.

Secondly, the lander will carry duplicates of some of the payloads carried by the vehicle. A radiation sensor will allow to compare the radiation levels and possibly the compositions simultaneously above and below ground. One part of the acoustic tomography experiment (source/ receiver) will be part of the lander.

The introductory payload list would mostly include experiments that have flown before on missions or are under development (e.g. space gravimeter [5]). For acoustic tomography, a new system, also including an active source (e.g. hammering, micro-explosions, etc.) needs to be developed for the Moon. Most experiments can be performed sequentially at every vehicle position to limit peak power and data. Where applicable, the benefit of complementary measurements performed by the Lunar Lander on the landing site and/or of the measurements performed during the traverse from the lander to the lava tube entrance is added.

The first introduced payload is the environmental package. The temperature conditions and variations inside a lava tube provide information on the insulation properties of the overlying material. The expected better temperature stability is an important information for designing thermal control unit of equipment or habitats. Radiation measurements will be performed prior to entering and, as stated above, also on the lander, simultaneous to the underground measurements. With this, the absorption of the lava tube roofs can be assessed, which, if sufficient, makes a strong point for setting up habitats underground, or building solar storm shelters. Further analysis will include Lunar dust conditions, and thermal inertia measurements.

The cross-section and relief of both the lava tube floor and ceiling is mapped using a LiDAR. Knowledge of the empty underground space is also important for the gravimetric measurements. For this, a gravimeter will be used to survey both, the surface of the lava tube roof and the underground. Free-air and Bouguer anomaly corrections can be applied between these two differential measurements. The interesting and novel aspect of the underground measurement, however, is that it also contains the roof's gravity "pulling upwards", which allows well constraining the roof's density. This does not only constrain the composition and structure from a scientific point but is also key in determining the structural stability of the lava tube as a candidate to host human habitats.

Constraining of the top surface layer is also done by acoustic tomography: Measurement of speed of sound in solids in the material overlaying the lava tube: While sound can obviously not travel in vacuum, it can well travel through solid and granular material. Measuring the propagation speed between the vehicle and the lander, we can reveal more insights on the material structure and its coarseness, which influences the speed of sound in solids.

The payload suite will be complemented by spectroscopy and ground penetrating radar, to further improve the subsurface structures and understand the lava tube compositions. Spectroscopy will answer the question of the possible presence of water in lunar lava tubes.

As an option, we consider a payload to collect a sample for delivery aboveground for further investigation.

Summarizing, the LA-TUNA mission provides a scientific mission concept to investigate intact lunar surface layers. The outcome of this mission is, however, not limited to science return alone, but these findings explicitly form the foundation for preparing a permanent human presence on the Moon. In particular, the possibility of integrating such underground structures to settlement architecture and implications for ISRU will be derived.

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