LUVMI AND LUVMI-X: LUNAR VOLATILES MOBILE INSTRUMENTATION CONCEPT AND EXTENSION

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ABSTRACT

By making use of an innovative, low mass, mobile robotic payload following the Lunar Exploration Advisory Group (LEAG) recommendations, many of the international science community's objectives can be met at lower cost.

As a main objective LUVMI was designed specifically for operations at the South Pole of the Moon with a payload accommodated by an innovative lightweight rover with a range of several kilometres.

Over the past two years, the key LUVMI scientific instruments – a Volatiles Analyser (VA) and a Volatiles Sampler (VS), were successfully developed and validated (up to TRL 5-6), and new light field cameras were experimented. They were integrated onto a ground prototype of a purposely developed LUVMI rover and tested altogether in a series of outdoor trials, in rocky and sandy environments.

Based on these successful results, the recently started LUVMI-X project shall extend the LUVMI rover's capabilities to enable more comprehensive scientific investigations. Its suite of science instruments will be upgraded and extended, and a flexible and innovative payload infrastructure will create the foundation for commercial payload services.

1. MOTIVATION

Establishing a long-term presence on the Moon requires humanity to overcome several technological challenges. For lunar exploration—and eventually settlement—to be sustainable, we must address three central questions: How do we provide affordable yet reliable access to the lunar surface to a broad (scientific) community? How can we make use of locally available resources? How do we protect humans from the Moon's adverse environment?

The recent acceleration of NASA's plans for returning astronauts to the lunar surface and constructing a partially manned habitat in orbit may herald a new age of lunar exploration, but it also demands that we address open questions about sustaining a human presence quickly and thoroughly. Both the International Space Exploration Coordination Group (ISECG) [1] and the Lunar Exploration Analysis Group (LEAG) [2] have identified three general domains in which Strategic Knowledge Gaps (SKGs) associated with future human exploration missions to the Moon exist:

1. Understand the lunar resource potential.
2. Understand the lunar environment and its effect on human life.
3. Understand how to live and work on the lunar surface.

In each of these domains, the groups have identified several SKGs, of which only some have been addressed to date. In the latest edition of its Global Exploration Roadmap [3], the ISECG also states that future scientific activities shall not only meet exploration objectives through innovative and evolvable approaches, but also provide benefits to the general public and support the establishment of a human presence on the Moon.

By primarily addressing volatiles related science, and relying on a small to mid-size robotic platform, LUVMI and LUVMI-X are developing instruments having a strong scientific potential and the means to deploy them in relevant locations on the Moon.

In this paper, we describe the LUVMI mission's concept of operations, its instruments, and the rover platform. We summarize the results of the testing campaigns and validation activities performed.

The second part of the paper describes current activities that aim to upgrade the rover's capabilities and to extend its instrumentation. Called LUVMI-X, this new asset will be capable of performing much more comprehensive scientific measurements than its predecessor. At the same time, we intend to further optimize the size and mass of the system to increase its compatibility with planned European and international lander missions.

2. LUVMI CONCEPT OF OPERATION

The planning for initial surface operation is driven by finding the best compromise between engineering constraints (power, range, speed) and science goals (number of individual samples), though it may evolve as more information on landing site options are considered. The main operations to be performed on the surface include the following:

- Post landing check-out
- Rover egress
- Landing site survey
- Wide area survey for volatile hotspots
- Observations during a terminator passage
- Sampling in a Permanently Shadowed Region (PSR)

The baseline operations assume a short 14 days mission lifetime and are not assuming any particular landing site. The baseline operations consider a notional location with a number of nearby PSRs (approx. 1 to 2 km from the landing site). In this scenario, the key objectives would be to conduct operations in an increasing order of risk to allow science measurement to be obtained at an earliest opportunity prior to performing operations that may pose a risk to the rover. Access to PSRs and lava tubes will be provided through the deployment of instrumented projectable/ propellable packages.

3. LUVMI INSTRUMENTS

3.1. Volatiles Sampler (VS) and Volatiles Analyser (VA) instrument

One of the most-debated questions in lunar science is the possible existence of water or other volatiles in the lunar regolith, both because of their possible application as an in-situ resource for future exploration missions and because of wide-ranging implications for solar-system science. Lunar volatiles have been theorised to exist in frozen form in PSRs and chemically or physically bound states inside surface particles. Multiple remote-observation missions were conducted in lunar orbit in recent decades and provided encouraging results. Bistatic radar observations, infrared spectroscopy measurements, and neutron-spectroscopy data from Clementine [4], Lunar Prospector [5], Cassini [6], Deep Impact [7], Chandrayaan-1 [8] and the Lunar Reconnaissance Orbiter [9] missions suggest the existence of water on the Moon, with diurnal changes in the signal and increased concentrations towards higher latitudes. This is complemented by the results of the LCROSS impactor study [10], which indicated 5.6 +/- 2.9 % water in the ejecta plume of the Cabeus crater. However, only a surface mission can provide ground-truth data and investigate the actual state and distribution of lunar volatiles on the surface.

The VS/VA package is a small, light-weight integrated soil sampling, gas extraction and analysis instrument designed to investigate lunar volatiles at the Moon's polar regions. Figure 1 shows the instruments concept: A drill-like sample oven is inserted up to 20 cm into the ground. Once it is inserted, a central heating element heats the enclosed sample to release volatiles components. The released gas is lead to the VA for analysis. The VA is a quadrupole ion trap mass spectrometer, based on the Ptolemy ITMS instrument [11], with a mass range of m/z from 10 to 200, a resolution of 2 and a lower detection limit of 10^{-10} mbar.

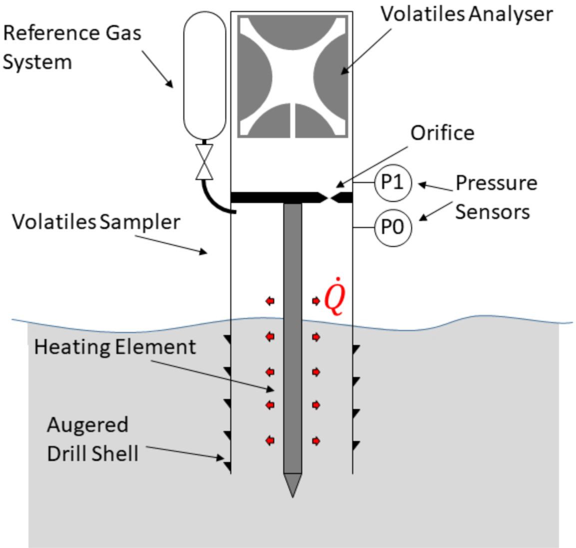

Figure 1: Schematic of the VS/VA instrument

During the LUVMI project, we developed an integrated prototype of the instrument, which is shown in Figure 2. The prototype was tested in a thermal-vacuum test setup that allowed the testing of mechanical insertion of the drill into frozen, hydrated samples of JSC-1A regolith simulant and subsequent gas extraction and analysis. Results showed successful release of water from the regolith and demonstrated that the VA is capable of determining water abundance in the regolith from and detection of characteristic mass spectra by the VA [12]. The total instrument mass is 1.9 kg with a top power consumption of 20 W.

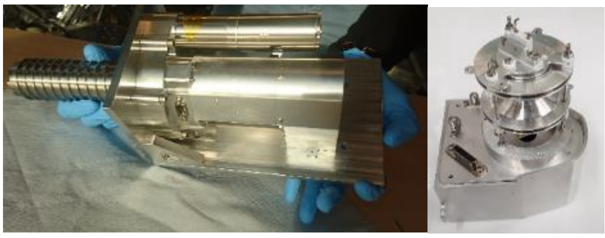

Figure 2: (left) integrated prototype of the VS/VA instrument (right) the VA ion trap mass spectrometer

3.2. Light Field Cameras

LUVMI is equipped with two camera imagers: a Navigational Camera (NavCam) supporting the navigation of the rover, and a Surface Camera (SurfCam) allowing to observe drilling and sampling activities (and possibly the rover tracks).

Both imagers are based upon light-field technology which offers a simple and robust 3D imaging solution with no moving parts.

Figure 3 shows a 3D point cloud and depth map of the LUVMI drill during operation.

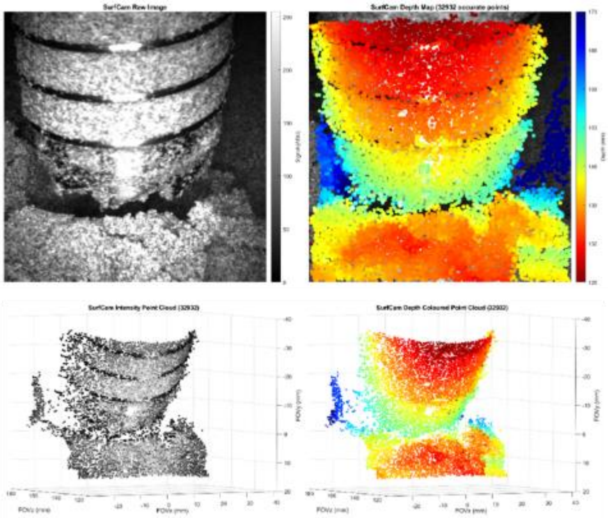

Figure 3: SurfCam image example of LUVMI drill

4. LUVMI ROVER PLATFORM

The LUVMI platform is based on a four wheels drive train and a chassis composed of aluminum frames, sandwich metal plates and 3D printed parts. The rover is capable of driving on slopes of up to 20 degrees while carrying payload of up to 30kg.

In its operational configuration, the rover is 1.4m long by 0.9m by 0.5m (w/o masts) and weighs approximately 60kg (ground prototype – Flight Model is expected to be 30% lighter).

The platform has four steerable wheels providing traction in all directions. The four wheels are controlled independently and allow executing complex driving patterns.

The rover also features a deployable, adjustable suspension offering the possibility to adjust the chassis height from 0 to 170mm (from ground). This is used to deploy or stow the rover (then fitting in a volume of 0.95m x 85 cm x 40 cm) and also allows adjusting the ground clearance to improve navigability on hazardous terrain. The same mechanism is exploited for on-spot drill positioning where the platform needs to touch the ground so that to obtain maximum depth with the drill.

Figure 4: Left - nominal chassis height for navigation. Right: lowered chassis to perform drilling operation.

In addition, a passive rocker-bogie mechanism provides the rover with a high obstacle clearance (up to 0.3m), while limiting the overall mass compared to a six wheels rover with similar capabilities. The rocker-bogie mechanism is implemented with an external differential bar located on top of the chassis. This system allows the rover to adapt passively the wheel positions so that, at all time, the four wheels contact with the ground is maximized.

Figure 5: LUVMI rover – highlighting the benefit of the passive rocker-bogie for obstacle clearance

The rover presented in this paper and shown above on Figure 4 and Figure 5 is a prototype that we developed for ground testing and instruments validation. Its mass, electric systems, power consumption and its thermal subsystem are thus not representative of a Flight Model[1].

5. LUVMI TESTING AND VALIDATION

The LUVMI platform and the VA/VS were extensively tested in 2018. The integrated VA/VS instrument was tested in thermal-vacuum conditions using the facilities of the Technical University of Munich. A functional test of the rover mated to the VS was performed using a gravity offloading system to ensure that the required penetration depth could be achieved in reduced gravity conditions. Finally, the integrated LUVMI platform was tested in an analogue environment to validate the mobility and operational requirements.

5.1. Integrated VA/VS Testing

To demonstrate the VA/VS assembly in a representative environment the instrument was mounted to a linear rail and placed in a thermal vaccum chamber. The test setup is presented in Figure 6. The test chamber is able to produce pressures as low a 2.0E-5mbar, much higher than the lunar exosphere, but several orders of magnitude smaller than the pressures created inside the drill shell and thus is considered sufficient.

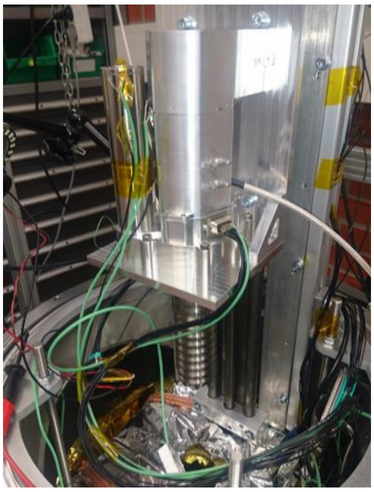

Figure 6: VS/VA assembly undergoing thermal-vacuum testing at TUM

To recreate the thermal conditions the chamber is placed in a cold shroud cooled down -100°C. Soil samples are prepared in 10L buckets of JSC-1A whose grain size reflects the thermal and gas permeability properties of lunar pole regolith. Moisturised samples with 0 to 5% water prepared and frozen.

A series of drilling and analysis tests were conducted with different regolith compositions and drill depths. Repeated tests showed that the instrument results were highly repeatable. In this campaign the instrument proved that it can determine the quantitative abundance if the released volatiles.

5.2. Partial Gravity Drilling Test

To validate that the required force on bit and drill depth could be achieved in the reduced gravity conditions of the moon a test with a gravity offloading system was performed. The reduced gravity reduces the weight of the rover which reduces the vertical force applied on the drill bit, consequently reducing the maximum achievable depth, and, by reducing the weight on each wheel decreases the contact forces between each wheel and the ground.

To reduce the effective weight of the rover a gravity offloading gantry was used. The gantry, positioned above the rover, held a pulley system through which a metal wire was passed. The wire connected a four point lifting system attached to the rover and a set of adjustable weights. These weights act as a counterweight to reduce the mass of the rover. To increase the representativeness of the test, the rover wheels were placed on regolith simulant as shown in Figure 7.

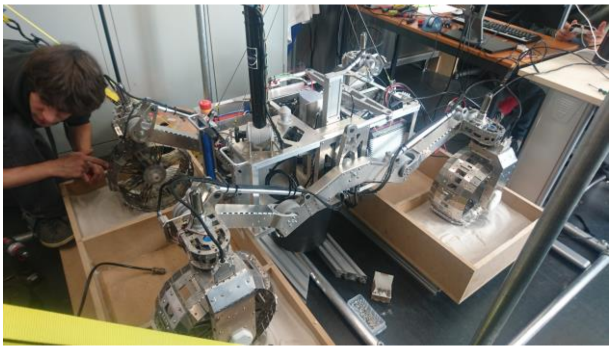

Figure 7: Partial gravity drilling test

The test campaign showed that the target drill depths were achievable even with an offloading approaching lunar gravity conditions. In all scenarios the rover was unaffected by the drilling and no corrective maneuvers were required to compensate for torques generated by the drill.

In addition the force sensor cells placed on the VA/VS assembly were shown to be precise enough to detect small obstacles in the path of the drill bit.

5.3. Mobility and End-To-End Drilling Test

The platform mobility tests were targeted towards end-to-end validation of the integrated systems. In test scenario, the rover had to perform a 50m traverse, stop to perform a drilling operation and drive back to the starting point. The tests were conducted at dusk requiring the

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[1] The LUVMI rover FM concept and characteristics (mass, power and thermal) analysis were well covered as part of the project, though not prototyped.

rover to use its floodlight to illuminate the scene for the camera. The entire test was conducted in teleoperated or semi-teleoperated (short distance way point) mode, without line of sight.

Figure 8: LUVMI platform mobility and drilling operation testing

The traverse demonstrated the rover driving and spot-turning abilities. Once the target was reached the rover deployment mechanism lowered the chassis to the ground. A complete drilling operation was performed and images of the drill bit and borehole were acquired by the surface camera. Finally, the deployment mechanism raised the chassis back to the nominal driving height and the rover returned to its starting location.

The end-to-end test was successful, and the complete drilling operation was performed without issue.

6. FROM LUVMI TO LUVMI-X

The LUVMI-Extended (LUVMI-X) project was established with the objectives being to enhance the rover's capabilities for characterizing lunar volatiles, to develop new payload and to make the platform more accessible for a wider range of payload developers. Specifically, LUVMI-X shall address several of the SKGs for lunar exploration identified by the ISECG, by:

1. Generating a deeper understanding of lunar resource potential by developing new instruments and new techniques to detect volatiles in new locations remote (and not directly accessible) from the rover;

2. Incorporate new instruments and techniques to study the lunar environment and its effects on human health (dust, radiation);

3. Preparing for a sustainable human presence on the lunar surface by making key measurements associated with in-situ resource utilisation (ISRU) and by developing an adaptable architecture that makes the lunar surface accessible to key enabling technologies, such as new instruments and power-generation techniques.

We are also working to optimize the rover's size and mass to make it compatible with a wider range of future institutional and commercial missions to the lunar surface, such as ESA's Heracles mission.

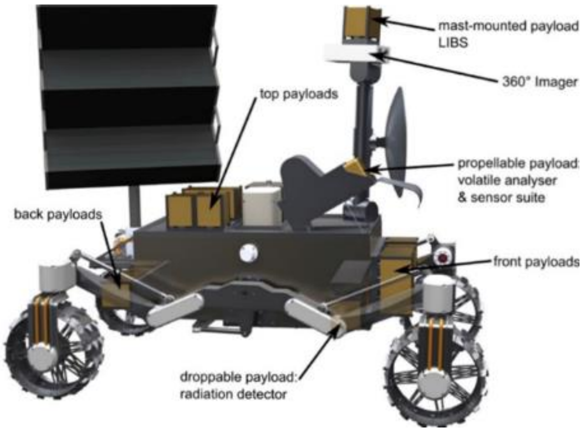

Figure 9. *LUVMI-X early concept*

6.1. Extending the LUVMI Instruments Suite

In modern astronomy and astrophysics, multi-messenger observations are becoming increasingly commonplace. Such investigations target the same object of interest with different observables ('messengers') to arrive at a more reliable conclusion. With LUVMI-X, we follow a similar approach and target lunar volatiles with four different instruments. A laser-induced breakdown spectroscopy (LIBS) instrument and a radiation detector both measure the (relative) abundances of hydrogen and other volatiles remotely and can thus be used to scout for areas of interest. They use two completely different observables (elemental emission lines vs. secondary radiation); measurements - one instrument can thus be used to validate those of the other. Only once an area of interest has been identified does one of the two in-situ instruments need to be used. An upgraded VS/VA instrument will analyse the (absolute) volatile abundances at different depths and refines the characterization performed by the remote-sensing instruments, for example by distinguishing water from other forms of chemically-bound hydrogen. The VA is also to be further miniaturized and packaged with a set of rugged environmental sensors to form a Volatiles and Context Analysis Suite (VCAS) that can be deployed to an area of interest not accessible to the rover and can measure at a specific time (e.g. during a terminator crossing). Combined, these four instruments are a powerful tool for comprehensively analysing the lunar regolith for its volatile content. The rover can thus be more effectively used as a scouting vehicle for volatiles than its predecessor.

6.1.1 Remote Rock and Regolith Analysis - LIBS

LIBS permits rapid in-situ multi-elemental analysis and is particularly sensitive to all kind of metals. Also, light elements such as hydrogen can be detected. The LIBS instrument can serve as a primary scientific tool for independent sample analysis but also as reconnaissance tool to quickly identify potentially interesting targets for further analysis with more laborious and time-consuming contact instruments or for guiding the selection of samples to be returned to Earth.

It can be optimized for volatile scouting such as water ice by focusing on the detection of hydrogen and oxygen elemental emission lines. It can also be used to infer the elemental composition of rocks and regolith. A LIBS measurement requires relatively little time and raster with several sampling positions allow to track changes in the regolith composition, for example to identify locations with increased content of an element of interest for follow-up analysis by the VS/VA.

In LUVMI-X, the LIBS will primarily provide information on volatiles abundance in the topmost layer of the lunar regolith. We are currently looking into three option to accommodate the system on the rover. (1) the instrument could be realized in a mast-mounted version, with high versatility to be applied in distances of up to 1.5 to 2 m from the optical unit. This, however, requires a focusing system to achieve the high irradiances necessary for ablation and plasma creation for suitable LIBS plasmas in vacuum. (2) A chassis mounted instrument, thus in closer proximity to the ground could be realized in a lighter and simpler configuration, with a working distance of ~0.5 m. To allow for some versatility, the LIBS instrument could be mounted on a pointing mechanism (pan or pan-tilt unit). (3) The simplest configuration would be similar to the LIBS instrument used on Chandrayaan-2 - with a laser focused to a fixed distance of 20 cm below the rover's body. Only one position can be sampled before the rover has to move again to present a new surface to the LIBS instrument.

The LIBS location will be consolidated by the PDR milestone, as a trade-off against the rover platform and other instruments' requirements.

6.1.2 Measuring Surface Radiation Environment

Analyses of the lunar radiation environment can help us understand the interactions of cosmic and solar radiation with the Moon's surface and its remnant magnetic fields. Radiation and its effects on the human body are also one of the major challenges that must be overcome if astronauts are to be sent into deep space on missions to the Moon, Mars, and other destinations.

The interplanetary radiation environment is dominated by charged-particle radiation of cosmic origin, the solar wind, and short bursts of energetic particles released by the Sun at irregular intervals [13]. Even though the Moon does not possess a significant atmosphere [14] or a global magnetic field [15], the radiation environment on its surface is substantially different from that in interplanetary space. Cosmic and solar radiation undergo a series of complex interactions with Earth's magnetosphere, the lunar plasma environment, remnant crustal magnetic fields, and the lunar surface [16]. Particles impinging on the regolith interact with it in a series of scattering, absorption, and nuclear-reaction processes that lead to the creation of secondary radiation.

The fluxes and spectra of this secondary radiation can be used to infer information about the composition and volatile content of the regolith. Most importantly, the measurement of neutrons at different energies allows to determine the (relative) abundance of hydrogen in the regolith and help to locate deposits of water (ice). Orbital neutron measurements have helped to consolidate the current picture of a Moon that has significant water-ice deposits, especially in the polar regions and permanently shadowed areas [5][9]. Abundancy maps based on these measurements, however, have low resolutions due to the inherent inability of most neutron spectrometers to measure the directionality of neutrons. A surface measurement could deliver much more precise data. Secondary neutrons and protons can also be used to determine the abundances of other elements, such as iron, titanium, and magnesium [17][18][19].

The radiation detector we develop for LUVMI-X will be capable of detecting and identifying charged particles at cosmic-ray energies to characterize the lunar-surface radiation environment. It will also be able to measure the fluxes of thermal, epithermal, and fast neutrons to allow a determination of the abundances of hydrogen and other volatiles in the regolith.

6.1.3 A Multi-Eyed View of the Moon

Environmental qualification and the development of a Flight Model of SurfCam and NavCam will be undertaken under the LUVMI-X project. The imagers will undergo vibration, irradiation and thermal vacuum testing. The work will demonstrate that light-field technology is a robust candidate for use in the space environment.

Visual feedback of the environment will further be addressed by an advanced 360° imager mounted on the mast of the mobile platform. The imager will provide a radiation-hard and shock-proof solution for gathering geographical information on the surrounding area.

6.1.4 Miniaturized Sensor Suite - VCAS

The VCAS provides the supplementary information about the analysis site that is required to make full sense and use of the volatiles detection performed by the mass spectrometer allowing a 'geological context' to be ascertained. In addition to a VA, the VCAS may also include: (1) an imager that allows macro imagery of the local geology, rock formations, and illumination conditions; (2) sensors providing information on mechanical and thermal properties of the regolith (e.g. local temperature information); (3) dust sensors to study the near-surface exospheric particulate environment to understand the effects of rover operations on the lunar surface. The sensor suite will be integrated with processor and communications hardware that could be conceptually derived from the “ChipSat” concept [20] under development by Cornell University, USA.

6.2. Propellable and Droppable Payloads

There are several reasons why it may be desirable to operate a payload at a distance from the rover: (1) the rover platform may adversely affect the payloads e.g. through outgassing that increases the background in volatiles measurements by VS or through unwanted motion affecting celestial observations or passive seismic investigations; (2) some payloads may require long-term or multi-location deployments, or availability or resources (power needs, sun exposure, etc.) which constrain the rover operating timeline; (3) some locations of scientific interest may be inaccessible to the rover. For these reasons we are developing systems that can be detached and dropped (or ‘placed’) directly onto the lunar surface by the rover which then moves away to continue its operations; and ‘propellable’ systems that the rover can project to a distance of metres or tens of metres.

The **droppable** payloads can be placed on the lunar surface using the adjustable suspension of the rover, without requiring a dedicated robotic arm. These payloads will be designed to allow performing long-term science and grid-based wide-range measurements. The possibility of retrieving these payloads, besides offering the possibility to relocate them, shall also allow recovering the data measurements, offering a deeper understanding of the lunar environment. As an example, it may be interesting to pack and deploy radiation detection experiments as droppable payloads.

The **propellable** payloads (together with rover-mounted deployment system) enable LUVMI to study a site without needing to drive the rover through it. These innovative and highly integrated probes enable in-situ analysis of areas inaccessible or hazardous for the rover, such as pyroclastic vents (loose deposits), lava tube (rough topography with cavities) or PSRs (unlit). The possibility to implement the means to retract a propelled instrument back to the rover (based on a tether) is being considered. As an example, the VCAS is seen as a good candidate for deployment as a propellable payload.

6.3. LUVMI-X Exploitation

LUVMI-X introduces a number of innovations that lower the costs and technological barriers for new communities wishing to access the lunar surface. It will support surface payloads using the cost-effective CubeSat form-factor. It provides standardized interfaces for payload accommodation attaching/detaching enabling third-party researchers to provide additional payloads to LUVMI-X. architecture incorporating “plug and play” and standard interfaces also opens the door to easily test, verify and demonstrate new technologies on the lunar surface. We expect the LUVMI-X rover to be able to accommodate a total payload mass of ~25kg.

The LUVMI-X concept foresees three innovative low mass payload families in addition to the existing instrumentation developed in LUVMI:

1. Mounted payload for local remote sensing through “geochemical vision”;
2. Droppable (de-mountable / re-mountable) payload for long-duration environmental monitoring; these can be placed on the surface by lowering the active suspension system of LUVMI, without the need for a robotic arm;
3. Propellable payloads to analyse areas not accessible to a rover.

The concepts may address the following possible mission applications (one or a combination thereof):

Stand-alone Lunar Volatile Prospecting mission:
LUVMI-X is deployed on the lunar surface. It utilizes its instrument suite to investigate cold-trapped lunar volatiles in and around permanently shadowed areas near the lunar poles.

Third-party payload carrier:
The LUVMI-X rover is used as a commercial service that provides payload slots to institutional customers

Gateway - HERACLES precursor mission:
LUVMI-X is launched prior to HERACLES. Astronauts on Lunar Orbital Platform - Gateway teleoperate the rover on the lunar surface.

Pyroclastic vent investigation:
LUVMI-X approaches a pyroclastic vent (or another area inaccessible for rovers) and drops its propellable payload into the crevice.

ISRU Demonstrator precursor mission:
LUVMI-X is launched before the ISRU Demonstrator mission, providing ground truth to characterise the feedstock in the area surrounding the lander

7. CONCLUSION

LUVMI-X builds on LUVMI outcomes by adding new instruments and technologies to multiply the impact of the original concept. With the proposed innovation, we expect LUVMI-X to show the feasibility of developing a low to mid-size lunar rover platform with a comprehensive set of instruments for volatiles science. It is also our hope that the concept and project’s results may enable, in follow-up or parallel activities, to secure LUVMI-X as a full demonstration mission to the Moon.

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