LUVMI-X: An Innovative Instrument Suit and Versatile Mobility Solution for Lunar Exploration

Jeremi Gancet[a], Diego Urbina[a], Simon Sheridan[b], Janos Biswas[c], Martin J. Losekamm[c], Anthony Evagora[d], Michael Deiml[e], David Vogt[f], Peter Wessel[g], Thibaud Chupin[a], Hemanth Kumar[a], Mathieu Deremetz[a], Guillaume Fau[a], Marc Kiggen[a], Maxence Debroise[a], Lutz Richter[e], Neil Murray[d], Susanne Schroeder[f], Joerg Neumann[g], Hannah Sargeant[b], Jae Schwanethal[b], Christian Gscheidle[c], Thomas Poeschl[c], Nektarios Chari [a], Marine Joulaud[h], Celia Kheng[h]

[a] *Space Applications Services, Leuvensesteenweg 325, 1932 Sint-Stevens-Woluwe, Belgium,* jeremi.gancet@spaceapplications.com

[b] *The Open University, MK7 6AA, Milton Keynes, UK,* simon.sheridan@open.ac.uk

[c] *Technical University of Munich, Boltzmannstraße 15, 85748 Garching, Germany* j.biswas@tum.de

[d] *Dynamic Imaging Analytics, Milton Keynes Business Centre, Foxhunter Drive, Linford Wood, MK14 6GD,* UK neil.murray@dynamicimaginganalytics.co.uk

[e] *OHB System AG, Manfred-Fuchs-Straße 1, 82234 Weßling, Germany,* michael.deiml@ohb.de

[f] *DLR Institute of Optical Sensor Systems, Rutherfordstrasse 2, 12489 Berlin, Germany,* Susanne.Schroeder@dlr.de

[g] *Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany,* p.wessels@lzh.de

[h] *CRPG-CNRS, 15 rue Notre-Dame des Pauvres 54500, Vandoeuvre-Les-Nancy, France,* marine.joulaud9@etu.univ-lorraine.fr

Abstract

LUVMI-X, as an evolution of the former LUVMI concept, is a low mass, mobile robotic payload designed to bring science instruments in areas of interest at the South Pole of the Moon within a range of several kilometres. Noticeably LUVMI-X incorporates three innovative low mass payload families:

- Mounted payloads for local remote sensing through "geochemical vision", based on standardized mounting interface
- Droppable payloads for long-duration environmental monitoring
- Launchable payloads to analyse areas not accessible to the mobile instrumentation.

All these three payloads categories can be accommodated on the LUVMI-X rover - a mobile platform based on, and extending the original LUVMI rover. Modular payload accommodation was a major driver for the LUVMI-X rover, with the aim of making it an appealing small to medium-size (~70 kg dry mass), versatile mobility platform that may serve as a competitive mobility solution baseline for recurrent lunar missions in the coming years.

The LUVMI-X payload suite aims to contribute to answering fundamental questions of planetary science by providing an integrated description of the physical and chemical properties of the top 20 cm of the lunar surface, in and around permanently shadowed regions (PSRs) at the lunar South Pole. PSRs may offer a repository for volatiles that have been thermally trapped following delivery to the Moon by cometary bombardment through the eons.

This paper presents the LUVMI-X instruments developed through the project, as well as the LUVMI-X rover platform hosting these instruments. Latest instruments and rover platform developments as well as preliminary tests results are reported in this paper.

Keywords: lunar exploration, rover, mobility, modular payloads, science instruments, volatiles, permanently shadowed regions

1. Introduction, Motivation and Notional Reference Mission

The 2018 ISECG Global Exploration Roadmap stated that future lunar exploration activities must be affordable and incorporate innovative approaches, meet exploration objectives as well as providing public benefits, be able to evolve and incorporate standard interfaces and support the preparation of human presence on the moon. This analysis was comforted by a Global Exploration Roadmap (GER) supplement in 2020. Aligning on this guidance, and leveraging former LUVMI project outcomes, LUVMI-Extended (LUVMI-X), in addition to mapping the lunar surface and subsurface for volatiles also aims to:

(1) Generate a deeper understanding of lunar resource potential by developing new instruments and new techniques to detect volatiles in new locations not accessible by the mobile instrumentation.

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

(3) Address sustainable presence on the lunar surface by making key measurements associated with in-situ resource utilisation (ISRU).

(4) Developing an architecture that makes the lunar surface accessible to key enabling technologies such as new instruments and new power generation techniques.

In our LUVMI-X notional reference mission, the vicinity of the Shackleton crater was selected as primary destination. In its initial configuration a LUVMI-X mission would span over 14 days, and would not be aimed to survive lunar night temperatures. Volatiles prospection and characterization is the primary scientific objective, however the LUVMI-X sensor suite offers a wider range of capabilities to carry out science – e.g. characterization of the radiation environment (LCNS instrument), rocks' chemicals (VOILA LIBS instrument), etc.

In this notional mission, excursions of a few hours in PSR are possible, and provisioned.

A full analysis of the traverse path was carried out, with criteria combining scientific objectives, geological characteristics, terrain topology and traversability (accounting for LUVMI-X mobility performances), and sun visibility optimization. A total traverse of 5km distance is foreseen as a baseline, with a majority of tasks achievable in the first 40% of the identified traverse path.

In the rest of paper, we introduce the LUVMI-X components, then we report on results and tests performed so far, as well as remaining testing and validation activities foreseen. We conclude the paper with next steps foreseen after project completion.

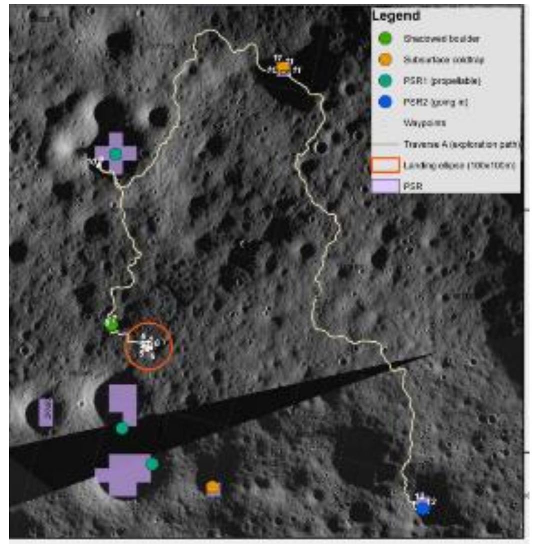

Figure 1: Reference traverse path based on multi-criteria GIS analysis

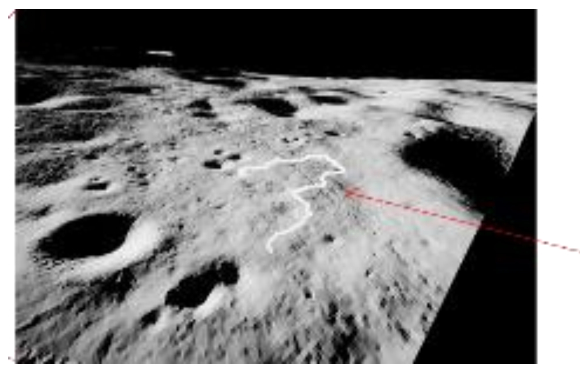

Figure 2: Sun visibility optimization through simulation

2. LUVMI-X components

2.1 Rover platform

The LUVMI-X Lunar rover platform is a mid-size rover designed to provide mobility to the LUVMI-X payload suit but also potentially to a variety of payloads thanks to its modular design. The rover is designed considering the conditions on the lunar (polar regions) surface as a core design driver.

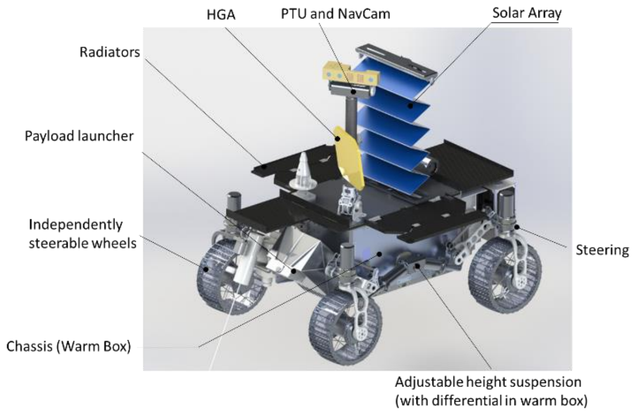

Figure 3: LUVMI-X rover rendering

The rover is comprised of a Chassis Assembly hosting equipment including internal avionics, suspension and wheel assemblies providing mobility, solar array and mast assemblies supporting driving, sampling and power functions. It features two payload bays (fore and aft) capable of hosting up to 24 U (12 U x 2) worth of scientific instruments, samples or other equipment accommodated on LUVMI-X rover's standardized payload bay, and either based on CubeSat-like volumes or using custom volumes. In the baseline configuration, the payload bays feature payload deployers able to launch or soft deploy and optionally retrieve a payload.

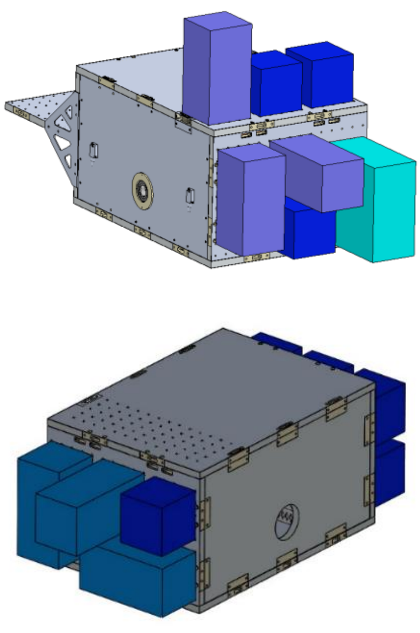

Figure 4: Modular payloads accommodation on the rover's chassis (front and back bays)

A 1-axis gimballed solar array provides optimised power to the rover and payloads in daylight conditions. A scalable battery provides power for peak power demand and short-term operations inside PSRs as well as (depending on the landing site) for short periods of hibernation. In the baseline configuration, the rover is optimised for operations at the Lunar poles, but the changes needed for use in equatorial locations have been identified.

In its baseline concept of operations, the rover is designed to be teleoperated from Earth, with the possibility of extending its navigation capabilities to semiautonomous operation. Interfaces and design changes for operation using a commercial lander as a relay are being studied. The rover can also be adapted to use orbital communications assets or be teleoperated by crew on the surface.

LUVMI-X baseline mission foresees PSR incursions, Short Night Survival, Fixed, Deployable and Launchable Payloads, and DTE communications, and high mobility through passive suspension, however the rover is to support other configurations in which less or different capabilities are supported, with associated mass changes.

The current rover architecture inherits the studies performed in the LUVMI project [14], in which many of the high-level architecture trades have been made and an early breadboard was prepared. In LUVMI-X a preliminary definition for a flight system has been completed, and an advanced breadboard is being implemented featuring modular accommodation formultiple instruments.

Mass: The mass of the full FM configuration excluding payloads is ~70 kg (includes unit and system margins). This configuration can achieve:

- PSR incursions
- Short (few hours) night survival
- Deploy payloads
- Launch payloads
- Extreme terrain mobility
- Direct to Earth communications

While a minimalistic modular configuration can be achieved within ~55 kg, for missions in proximity of a lander, with less energy and long-range mobility constraints. The volume of the LUVMI-X rover is

- Stowed volume: 1000 x 800 x 460 (Lmm x Wmm x Hmm)
- Deployed volume: 1000 x 800 x 1300 (Lmm x Wmm x Hmm)

The rover platform employs passive heat dissipation via radiators pointing to deep-space and active heating based on polymide heaters at the equipment.

The platform supports high data rate (spacewire) communication and low data rate communication (RS-422 and CAN) with payloads and equipment. The capacity for the downlink varies with type of the link. For DTE link, the data rate is 0.5 Mbps and for relay link the data rate is 3 Mbps.

The LUVMI-X DM rover is largely similar to the FM concept, with adaptations to undergo test campaigns under Earth gravity.

The DM rover Chassis consists of the primary structure hosting the rover equipment and avionics (within a “warm box”, aka. WEB) and providing support to the external payloads and locomotion mechanisms.

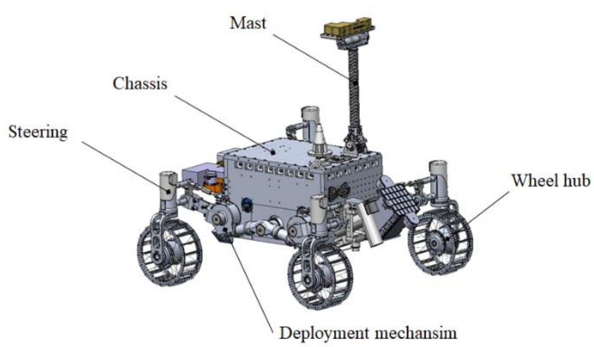

Figure 5: LUVMI-X rover ground demonstrator (CAD).

The rocker mechanism consists of a passive differential gearbox inside the rover chassis (see **Figure 6**) that connects the four suspension branches with the rover chassis and ensures optimal wheel contacts with the terrain by transferring forces.

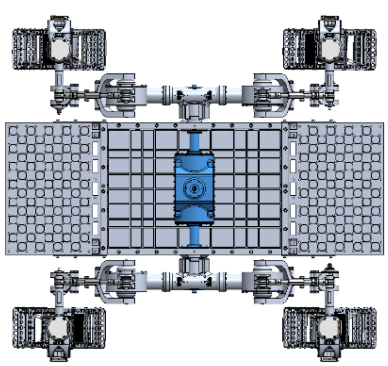

Figure 6: Rocker mechanism (in blue).

LUVMI-X rover’s adjustable suspension subsystem (**Figure 7**) provides accessibility of payloads to the lunar surface without the requirement for a robotic arm, while enhancing ground clearance from obstacles during traverses and performance while driving on slopes.

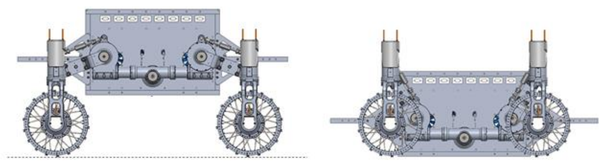

Figure 7: Adjustable suspension in raised and lowered configurations (0 to 25cm height)

Each wheel element is equipped with an independent steering mechanism (range of motion +/-175deg).

The wheels consist of a central hub interfaced with the steering assembly, embedding the motorization module and a peripheral structure connected to the central hub by means of spokes. The wheel features regular grousers offering high traction in sandy areas. (**Figure 8**).

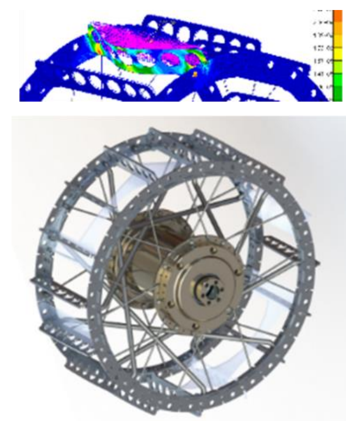

Figure 8: LUVMI-X rover wheel.

The mast assembly is composed of a Mast Pan-Tilt Unit (Mast PTU), Mast Fixed Antennae Plate and a Top Panel Interface Support. A CFRP mast supports the aforementioned components in the configuration shown in **Figure 9**. The PTU is fixed at the mast’s top end; it hosts two motor configurations that allow motion in panorama and tilt sense, braking of the mechanism and identification of the view angle. The plate on the top is used to mount navigation cameras, stereo bench or payloads that require specific pointing. The antenna plate, placed near the middle of the mast can be adjusted in position and orientation. Its primary goal is to carry the Low Noise Antenna while offering room for an additional 1U payload. The mast assembly is fixed on the rover’s main body via a rigid Top Panel Interface Support.

The tilt motor configuration of the PTU allows tilt angles in the range of ± 90° from the level position at an angular speed of 20 rpm for payload mass of 1 kg.

The pan motor allows movements of more than ± 360° at speeds of 19 rpm for 1 kg payload mass. Both motors can operate to a maximum payload mass of 3.4 kg at reduced angular speed of 8 rpm.

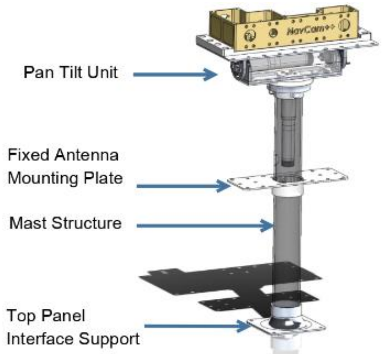

Figure 9: Overview of the Mast Assembly

2.2 Volatiles Sampler and Volatiles Analyser (VSVA++)

The VSVA++ is an integrated soil sampling instrument for the investigation of cold trapped volatiles in the shallow subsurface of the lunar polar areas (see Figure 12). It represents an evolution of the original LUVMI VSVA instrument [12] and features a more compact and robust design.

The bottom part, the Volatiles Sampler++ (VS++), is a hollow augered drill that can be inserted up to 15 cm into the ground. A central heating rod can heat the enclosed regolith column to more than 600°C to release volatiles. Pirani pressure sensors monitor the resulting pressure increase inside the drill shell and an orifice regulates the gas flow towards the Volatiles Analyser++ (VA++).

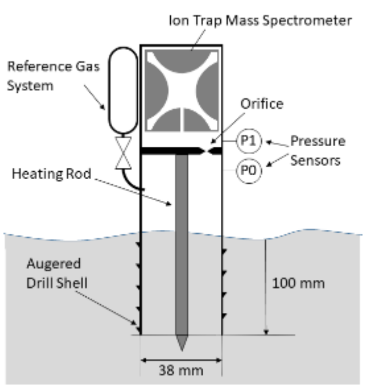

Figure 10: VAVS++ concept

The VA++ mass spectrometer is an Ion Trap Mass Spectrometer (ITMS), with the design deriving its heritage from the ITMS developed for the Ptolemy instrument that was used to perform in-situ measurements on the surface of 67P/Churyumov-Gerasimenko as part of the ESA Rosetta mission [13].

The VA++ ITMS is by design a rugged and miniature instrument that can identify a wide range of molecules and perform in-situ calibration using an on-board miniature gas calibration system. The VA++ ITMS consists of four discrete sub-systems these being:

- Control electronics
- Ionization source
- Mass separator
- Detector

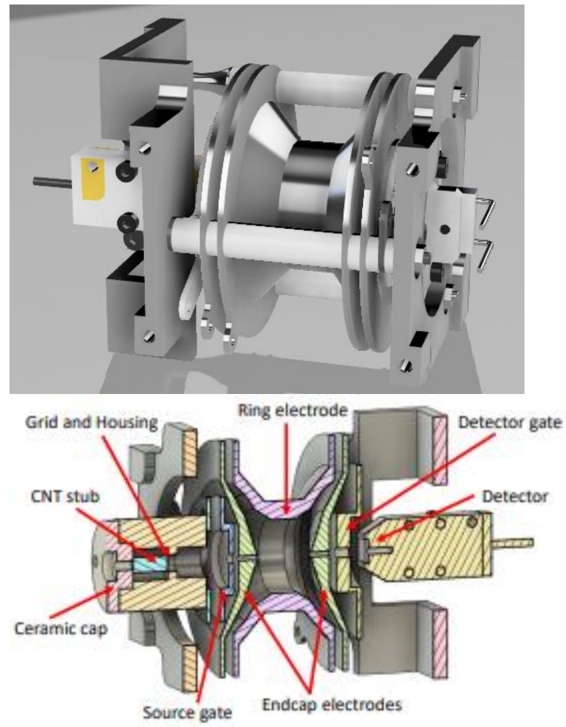

Figure 11 CAD model and schematic of the VA++ ITMS

The integrated instrument has a total mass of 4 kg (including backend electronics and margins), an average power consumption of 25 W and has been developed to a TRL of 5/6.

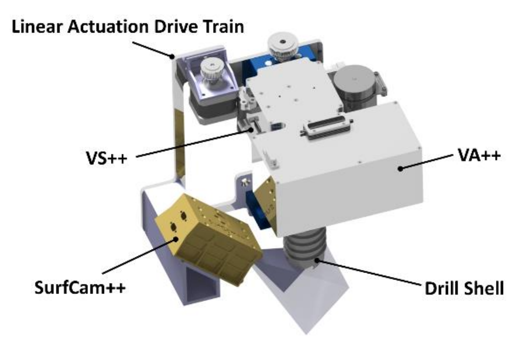

Figure 12: Render image of the VSVA++ instrument

The VSVA++ will be integrated on the LUVMI-X platform on a linear guide, which allows vertical movement and the drill site will be monitored by the SurfCam++.

2.3 Neutron Detector (LCNS)

The Lunar Cosmic-Ray and Neutron Spectrometer (LCNS) is designed to (1) measure the abundance of hydrogen in the soil beneath the rover to depths of about a meter and to (2) characterize the radiation environment on the surface of the Moon. To achieve this, the instrument comprises a neutron spectrometer, a charged-particle telescope, and several dosimeters sensitive to different aspects of the cosmic- and solar-radiation spectrum.

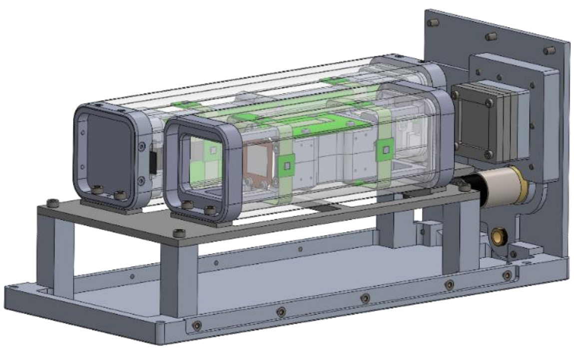

Figure 13: LCNS instrument

The neutron spectrometer can measure the (relative) fluxes of thermal, epithermal, and fast neutrons created in interactions of high-energy cosmic rays (mostly protons) with the lunar regolith. Hydrogen is a highly efficient neutron moderator and its presence—and thus that of water and hydroxyl—therefore leads to detectable changes in the energy spectrum of neutrons that diffuse upwards through the regolith to be detected by the LCNS. If combined with data from the LVS, these measurements will help to build a more complete picture of the vertical distribution of sub-surface water ice in the regions sampled by LUVMI-X. Data can also be compared to previous orbital measurements by Lunar Prospector [1] and the Lunar Reconnaissance Orbiter [2], as well as future measurements by LunaH-Map [3]. The charged-particle telescope can detect and identify charged cosmic-ray and solar-wind particles (i.e., protons and ions) with energies larger than 10 MeV (protons) and 50 MeV per nucleon (ions). It is therefore not only capable of providing a reference measurement of the flux of highly energetic particles that interact with the lunar regolith to produce neutrons, but it can also precisely characterize the radiation environment on the surface. The telescope's design was optimized such that it is most sensitive to particle energies that are highly relevant for a comprehensive radiobiological risk assessment of crew radiation exposure on the lunar surface. Data provided by the LCNS will therefore also contribute to optimizing shielding layouts and operational strategies for future exploration missions.

Both detectors are constructed from state-of-the-art yet commercially available materials and sensors that can operate in the environmental conditions on the lunar surface for prolonged periods of time without any impact on the instrument's performance. They are also designed in a modular manner, such that they can easily be scaled and adapted to changing mission requirements, for example by increasing the detector area to be more sensitive to small particle fluxes. The LCNS relies on heritage designs wherever possible to increase the reliability of the instrument.

2.4 LIBS (VOILA)

The VOILA instrument (Volatiles Identification by Laser Ablation) is an instrument that employs laser-induced breakdown spectroscopy (LIBS) to analyse the geochemical composition of the lunar surface. It uses a pulsed laser to ablate material from an investigated target, which forms a bright plasma plume. The plasma emission is analysed spectroscopically to gain an emission spectrum of atomic and ionic emission lines of the elements in the targeted surface. The technique only requires optical access to the target and allows for quick measurements within a few seconds, making it well-suited for analyses of multiple positions in proximity to the rover [5].

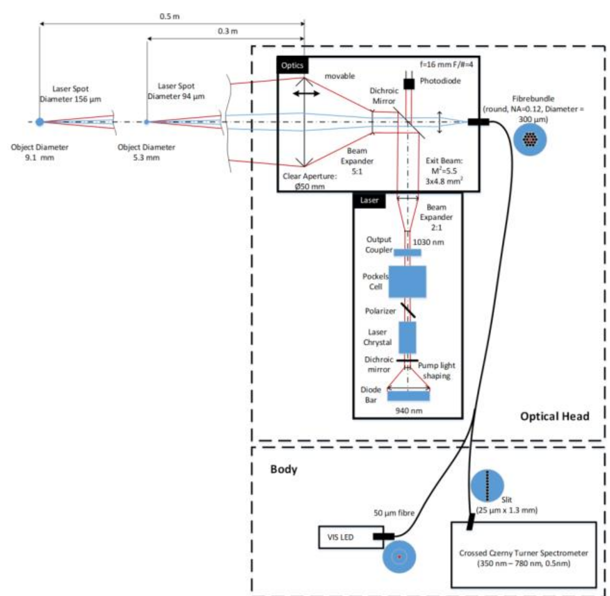

Figure 14: Optical architecture of the VOILA instrument, showing the separation into an optical head and a body unit. The optical head contains the laser and the focus optics, while the body unit

contains the spectrometer and an LED for target illumination

LIBS instruments have been of great interest for the in-situ exploration of planetary surfaces and are featured on all rovers currently operating on Mars (ChemCam on Curiosity, SuperCam on Perseverance, and MarSCoDe on Zhurong)[6][9][10][11][10]. The first LIBS instrument for the Moon was on board the lunar rover of the Chandrayaan-2 mission [11], but the lander failed to achieve a soft landing in 2019.

Figure 14 shows the optical architecture of the VOILA instrument. It consists of an optical head mounted to the front of the rover body containing the laser and focus mechanics and a unit inside the rover body, which contains the fiber-coupled spectrometer and the LED used for illumination of the target. The optical head can be rotated and achieves focusing distances from 30 cm to 50 cm to the ground in front of the rover. The spectrometer covers the wavelengths from 350 nm to 780 nm at a spectral resolution of less than 0.5 nm. This spectral range was chosen because the focus for VOILA was on the development of a LIBS instrument that is capable of detecting H for the detection of water ice as well as major elements in the lunar regolith. In the specified wavelength range, spectral lines of all major elements (Si, Ti, Al, Fe, Mg, Ca, Na, K, O) and H can be detected.

VOILA uses an actively Q-switched pulsed Yb:YAG laser developed by Laser Zentrum Hannover (LZH), which emits pulses at a wavelength of 1030 nm with a pulse energy of 17 mJ and a pulse width of 8 ns. At the working distances of 30 cm to 50 cm, the focusing optics produce a laser spot that is less than 190 µm in diameter, so that the peak irradiance of approximately >5 GW/cm² surpasses well the LIBS plasma threshold of 1 GW/cm². Consequently, a bright plasma is produced even in near-vacuum conditions and of unconsolidated materials such as the fine grained lunar regolith.

2.5 Imagers

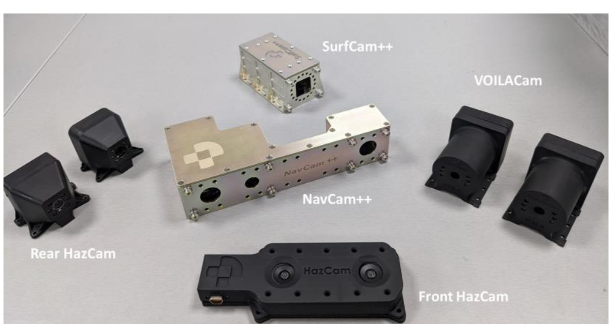

Figure 15: LUVMI-X imagers

SurfCam++ is a robust, small, low mass (250 g) camera designed to accommodate the 3Dplus SpaceWire camera module, providing 8-channel snapshot multispectral 3D image and video data of both rover drilling operations and interactions of the rover wheels with the regolith. This will aid in the understanding of the regolith geotechnical properties and aid in rover operations.

The current SurfCam++ provides a multispectral data cube of 450, 540, 600, 660, 725, 840, 940 and 970 nm consistent with other lunar exploration instruments. These can be readily changed for any application.

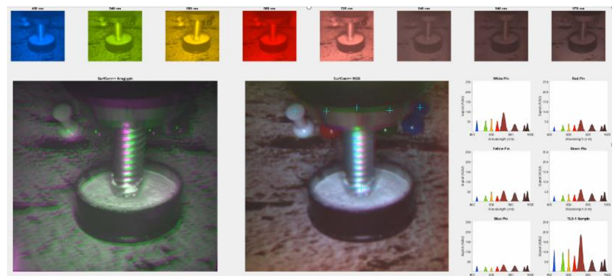

Figure 16: Multispectral imaging with the SurfCam++

The NavCam++ was also developed to accommodate a 3Dplus SpaceWire camera module and provides close range 8-channel snapshot multispectral 3D. It also features medium range 3D in form of a stereo bench and a long-range telescope for scouting potential sampling sites and route planning. The system will allow the build-up of panoramic DEMs through a pan and tilt mechanism and raster of the scene.

A navigation technology demonstrator takes the form of a 360° stereo camera that is integrated into the antenna mast, so that the need for the mass and complexity of a pan and tilt mechanism is avoided, as well as the operational time saved in not needing to raster a camera to build up a local scene. The stereo capability allows for a snapshot LIDAR-like DEM to be created of the entire local area visible to the rover and a metrically calibrated range finding of specific features. Such a system could vastly reduce the number of cameras required on a rover reducing, power, mass and complexity.

Figure 17: snapshot 360 deg. 3D demonstrator

2.6 Deployable payloads

2.6.1. Propellable payloads

The Propellable Payload (PP) is a simplified version of the DP. The PP is a short-lived instrumented payload based on a 1U cubesat form factor that will allow volatile and environmental measurements to be conducted in locations that are usually inaccessible to mobile surface elements. The PP contains a series of sensors to allow the physical and environmental conditions to be measured in an inaccessible location. The demonstration unit PP (Figure 18) baseline instruments include a miniature mass spectrometer, an imager, temperature sensors, pressure sensors, an impact sensor and a dust impact sensor areas to perform measurements for a short duration.

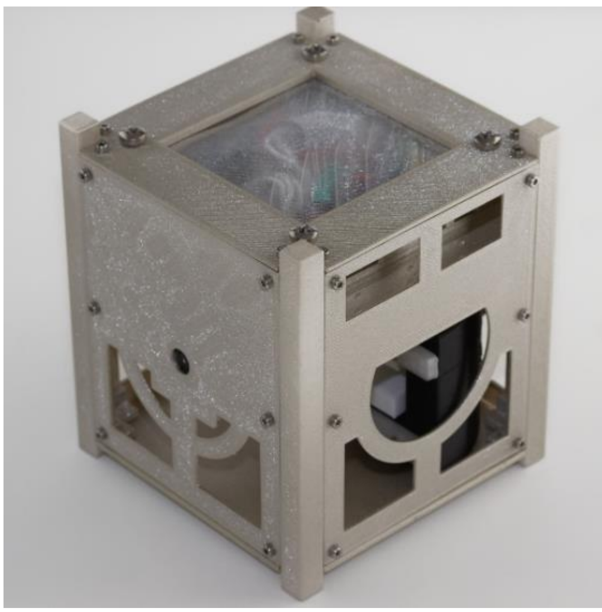

Figure 18: Demonstration PP unit

2.6.2 Droppable payloads

The Deployable Payload Platform (DPP) is a novel and innovative approach for lunar surface science. It is a standalone payload support platform that can sustain the Volatiles & Context Analysis Sensors (VCAS) payload for stationary long-term measurements and can therefore unburden the rover. It adheres to a 2U cubesat form factor (20cm x 10cm x 10cm), with 1U for the support module and 1U for the payload. The DPP is attached to the rover through the HOTDOCK Mini interface and will be deployed near a major PSR for exosphere measurements to detect volatiles released by meteorite impacts. The support module features a 96 Wh battery package, 10 solar cells that provide up to 5 W of solar power and an S-Band transceiver for direct-to-earth communication.

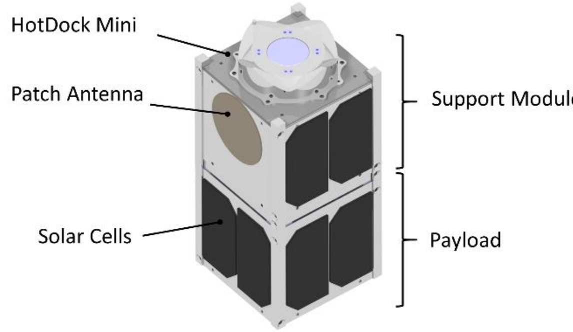

Figure 19: Deployable Payload Platform rendering

3. Preliminary Tests and Results

3.1 Rover platform

At the time of writing this paper, the rover platform is under assembly, integration and testing (AIT) in Space Applications Services' lab facilities.

Figure 20: LUVMI-X rover AIT in progress

Figure 21: LUVMI-X rover wheels early tests

Preliminary tests were carried out at locomotion sub-assembly level: wheels driving element, which motors are frameless hollow shaft based (assembled in house), and wheels steering elements in particular.

3.2 Neutron Detector (LCNS)

Testing the LCNS in a radiation environment that is (reasonably) similar to the one encountered on the lunar surface will not be possible, as no existing or planned facility can reproduce the complex cosmic-ray, solar-wind, and neutron spectra found there. The design of the LCNS therefore builds on a combination of simulations and representative tests at particle-accelerator facilities. Extensive simulations were performed using the Geant4 software framework that is widely used in high-energy and nuclear physics. These simulations showed that the current design of the neutron spectrometer should achieve a detection efficiency of 90% for thermal neutrons and of about 46% and 49% for epithermal and fast neutrons, respectively. At the same time, charged particles that could produce false signals in the spectrometer are rejected to 100%. For the charged-particle telescope, simulations showed that for energies between 10 MeV and 3 GeV per nucleon, protons can be correctly identified with more than 99.5% accuracy; for ions, the accuracy drops to about 96% for helium, 85% for carbon, and 80% for oxygen. The data-analysis algorithms used on the simulation data were, however, very simplistic; it is therefore reasonable to assume these values can be further improved.

Initial representative testing of the charged-particle telescope was performed at the Paul Scherrer Institute (PSI) in Switzerland in summer 2021. Using beams of protons and ions at different energies, a prototype detector was used to validate the reliability of the simulation setup and to cross-check its results. Additional testing with the veto detector used to reject charged particles in the neutron spectrometer was performed as well.

Figure 22: LCNS test facility

3.3 LIBS (VOILA)

In order to investigate the LIBS plasma and its spectrum in lunar ambient conditions, preliminary studies at low pressures were made with the LIBS laboratory setups at the German Aerospace Center's Institute of Optical Sensor Systems (DLR-OS). In these studies, the quality of the LIBS spectrum was investigated in dependence of several parameters such as the laser energy, the composition of the sample, and the granularity of the lunar regolith simulant. The optical design of the VOILA instrument was refined based on the results of these preliminary studies. Subsequently, a VOILA laboratory setup and demonstration model was conceptualized and realized at DLR-OS. The prototype laser for the demonstration model was developed by LZH and the breadboard optical head was developed by OHB using commercial off-the-shelf components. The laboratory setup is built around a vacuum chamber that is capable of reaching low pressures of less than 10^{-5} mbar to simulate the lunar conditions, since the LIBS plasma is strongly affected by the ambient pressure. The collected light is guided into a fiber-coupled spectrometer (Avantes AvaSpec-Mini) with a wavelength range of 340 nm to 910 nm and a spectral resolution of less than 0.4 nm. For the demonstration model, a fixed working distance of 400 mm is used.

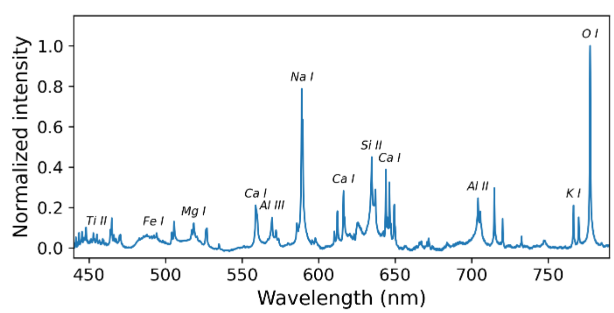

Figure 23: VOILA LIBS spectrum of lunar regolith simulant Exolith LHS-1, measured at a pressure of

less than 10^{-3} mbar. Spectral lines of various major elements are clearly observed.

The VOILA demonstration model was used to make measurements of different lunar regolith simulants and of minerals and rocks relevant to the lunar environment to investigate the performance of the instrument design. Figure 23 shows one of these spectra, in this case of lunar regolith simulant Exolith LMS-1 measured at a pressure of less than 10^{-3} mbar. Various strong spectral lines of Mg, Ca, Na, Si, Al, K, and O can be observed. The spectral lines of Fe and Ti are weaker. Their strongest lines are in the ultraviolet wavelength range, where the laboratory setup only has a reduced spectral efficiency in comparison to the VOILA flight model design.

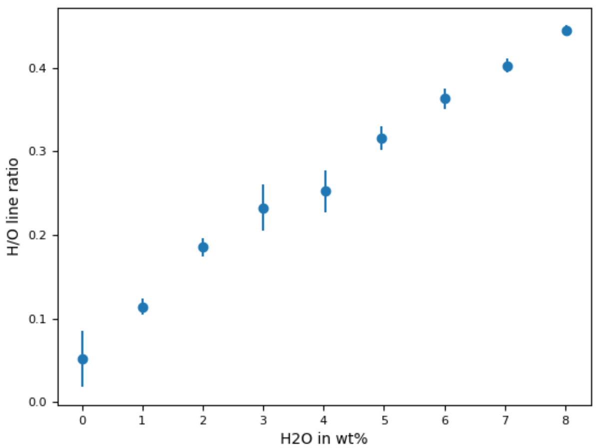

Figure 24: H/O line ratio for samples of lunar regolith simulant mixed with increasing amounts of hydrated gypsum. A linear correlation between the water content in the sample and the signal can be observed.

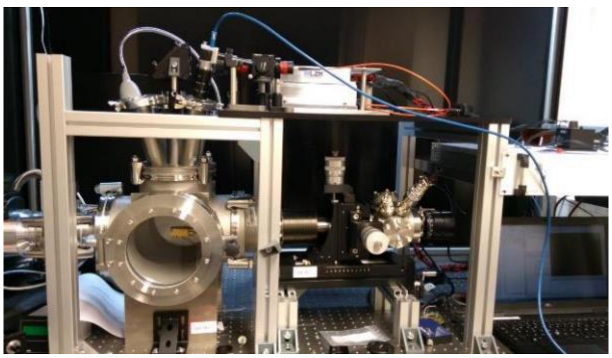

Figure 25: VOILA LIBS testing facility at DLR

In order to investigate the quantification capabilities of VOILA for water, samples of lunar regolith simulant mixed with hydrated gypsum in concentrations corresponding to 0% water to 8% water were measured. The resulting ratio of the H line at 656.3 nm and the O lines at 777.4 nm is shown in Figure 24. The linear trend that is observed here demonstrates that quantification of H in LIBS is possible and allows for the detection and quantification of water in the lunar environment. The lowest confirmed detection of water was achieved for 1% water by mass.

The results of the VOILA laboratory studies show that VOILA is capable of meeting its science requirements. All major elements can be detected and the intensity of the H line in the spectra can be used to calculate the water content in the regolith.

4. Additional plans for LUVMI-X Validation

4.1 Independent Instruments

4.1.1 Volatiles Sampler and Volatiles Analyser (VSVA++)

Figure 26: Image of the VSVA++ inside the LUVMI-X thermal vacuum test setup at TUM

A particular challenge in the development of the VSVA++ instrument is the creation of a representative testing environment for end-to-end testing. During the original LUVMI project, a thermal vacuum setup has been developed that allowed drilling and gas extraction to be performed at high vacuum and into a cryo-cooled regolith simulant container. For LUVMI-X, this test setup was upgraded by the introduction of a sample container revolver, essentially a carousel that allows the placement of six sample containers below the instrument. The containers can be both cryo-cooled to -196°C or heated to +100°C to recreate conditions found either in cold traps or well illuminated lunar regions. The setup will allow a dedicated test campaign with a focus on evaluating the risk of cross-contamination between samples, performance at very low volatiles contents (<100ppm) and the instrument performance in assessing relative volatiles concentrations. Figure 26 shows an image of the VSVA++ instrument suspended over the sample revolver in the vacuum chamber.

4.1.2 Neutron Detector (LCNS)

Additional testing with the LCNS prototype detectors will be required to fully verify that they provide the necessary performance to achieve the scientific goals of LUVMI-X. Most importantly, the neutron spectrometer must be tested at a neutron irradiation facility to validate its simulations setup, as has already been done for the charged-particle telescope. So far, this testing has been impeded by the availability of facilities. The charged-particle telescope also requires additional testing at higher particle energies than were available from the beamline used at PSI. This testing could be performed either at a different beamline at PSI or at CERN. The data-acquisition electronics used in the LCNS are in large part derived from those of the RadMap Telescope [4], a radiation monitor that will be deployed to the International Space Station (ISS) soon. On-orbit data from the ISS will be sufficiently representative to demonstrate that the electronics of the LCNS will perform as expected. In addition, thermal testing will be conducted to quantify the impact of thermal changes on the instrument performance.

4.1.3 LIBS (VOILA)

Based on the selection of optical elements in the design, a list of potentially temperature-critical components has been derived. These components, which include laser diode bars and metallized optics as well as glued and brazed optical and opto-mechanical assemblies, will be tested on component level individually at low temperatures down to -140°C to assess their qualification for the extreme temperatures found at the lunar polar regions.

Upcoming studies with the VOILA demonstration model in the DLR-OS laboratories will focus on the detection of water ice in specially prepared mixtures of lunar regolith simulant containing fine ice granules at known concentrations. The expansion of the spectral database of relevant geological samples measured with VOILA in simulated lunar conditions is an important secondary objective, since this will provide further insight into the expected results of the geochemical analysis of the lunar surface, which may be relevant to identify environments that are suitable for prospecting purposes.

4.2 Integrated System Validation

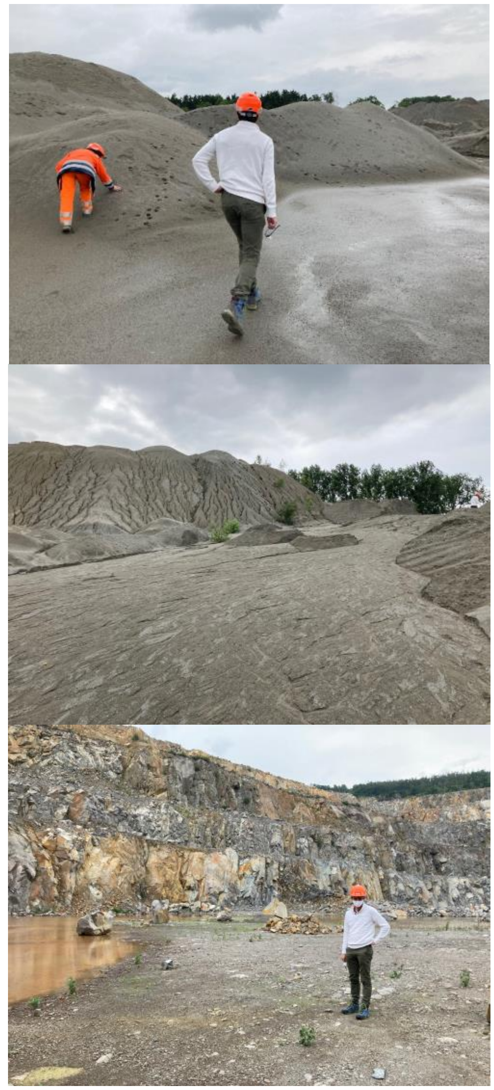

Figure 27: Quenast quarry - selected location for outdoor analogue trials

Due to their nature, most of the scientific instruments developed in LUVMI-X are not aimed at being used under atmospheric conditions, therefore making it useless to integrate the resulting TRL5-6 instruments models onboad the rover platform. Instead, mock-ups with representative form factor, dimensions, mechanical mounting interface, as well as power and data interfaces, are in the process of being integrated onboard the rover.

The overall integrated LUVMI-X system will be brought in outdoor analogue conditions, to validate key requirements with a focus on (1) concept of operation considerations and (2) locomotion / navigation considerations.

After carrying out trade-offs with multiple options (and accounting for Covid related travel restrictions), it was decided to carry out the outdoor trial campaign in the Quenast quarry in Belgium (Figure 27), in sandy areas offering large open sky spaces, and a variety of slopes. More rocky terrains are also available on site. The main campaign is scheduled to take place in the last week of October 2021.

5. Conclusion and Next Steps Towards Flight

After almost 3 years, LUVMI-X is approaching its conclusion with the delivery of a series of novel, high scientific value instruments developed and under tests, and a versatile mobility solution enhancing and extending the former LUVMI rover concept.

Most LUVMI-X scientific instruments reached a TRL of 5 to 6, therefore making them close to being usable in short terms missions. Several developments were carried out with heritage of previous missions and/or synergy with ongoing ESA mission preparation (e.g. the Ion-Trap Mass Spectrometer).

The rover platform reached TRL4 (FM baseline) in the scope of the project, and a notional maturation roadmap allows envisaging a flight by 2025-2026. The LUVMI-X rover is a versatile mobility solution for the Moon, with ability to accommodate different payloads configurations in a modular manner. A business plan was worked out to establish potential exploitation routes and commercial opportunities primarily in Europe and in the US. At an institutional level, ESA EL3 programme is an appealing perspective for LUVMI-X partners, both for the rover and instruments related outcomes.

Finally as a short term related activity, the LUVMI-X rover will participate in the ESA-ESRIC space resources challenge to take place in the Netherlands in November 2021.

Acknowledgements

The LUVMI-X project is co-funded by the European Commission through its Horizon 2020 programme under grant agreement #822018.

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