Searching for Water Ice with the LUVMI-X Lunar Rover

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ABSTRACT

Our current knowledge about the abundance and the accessibility of water on the Moon is too limited to assess its economic potential or to rely on its availability for future manned exploration missions. We present LUVMI-X, a compact yet versatile rover that is equipped with complementary instrumentation to gather new data about the abundance of water at the lunar poles.

1 INTRODUCTION

Local resources will likely prove to be crucial for the establishment of a sustained human presence on the Moon. In-situ resource utilization (ISRU), especially the extraction of water and oxygen from the lunar regolith, promises to substantially decrease the amount of material that must be supplied to a permanently manned outpost from Earth. They may also be essential for the development of near-Earth space and form the basis for a cis-lunar economy [1]. Our current knowledge of the Moon's resource potential, however, is too incomplete to assess the technical feasibility and economic viability of ISRU and other resource-extraction efforts. In this contribution, we present LUVMI-X, a rover equipped with complementary instrumentation designed to search for water in the Moon's polar regions. We briefly summarize the mission's objectives before presenting the rover and its instrumentation.

2 WATER ON THE MOON

The Moon possesses abundant raw materials that promise to be of economic value for future activities in cis-lunar space. Perhaps most important for near-term lunar exploration missions are the suspected deposits of water ice at the lunar poles. Such deposits could be exploited to provide water and oxygen for astronauts and to produce hydrogen and oxygen for rocket fuel. Water may even play a role in shielding habitats and their inhabitants against cosmic and solar radiation [2,3].

Potentially exploitable reserves of water ice almost certainly exist in permanently shadowed regions at the poles [4-6], but only little data about the extent of these deposits is available. Based on data gathered by the Lunar Prospector [4] and LCROSS [6] missions, Crawford estimates that the uppermost meter of permanently shadowed regolith could hold as much as 2.9 billion tons of water [1]. If proven to exist, such vast deposits could support future polar missions and help to considerably reduce the mass of supplies and fuel that must be launched from Earth. The many scientifically interesting sites located far away from the poles, however, could not be easily supplied by these polar deposits [7]; the establishment of a base there would therefore be facilitated by other forms of water (ice) reserves. But even though the presence of water in non-polar regions that are not in permanent shadow seems to have been revealed by several missions [8,9], Anand et al. argue that the practical value of these deposits remains to be determined [10].

The data available today, collected almost exclusively by remote-sensing instruments aboard probes in lunar orbit, constitutes a strong but preliminary indication of the existence of water (ice) on the Moon. It is not yet clear, however, whether these potential reserves are sufficiently vast and accessible to allow economically attractive extraction operations, either for commercial purposes or to ensure that crews of government-led missions can depend on this water for their survival. Ambiguities in the measurements remain [11], and even the most direct evidence for

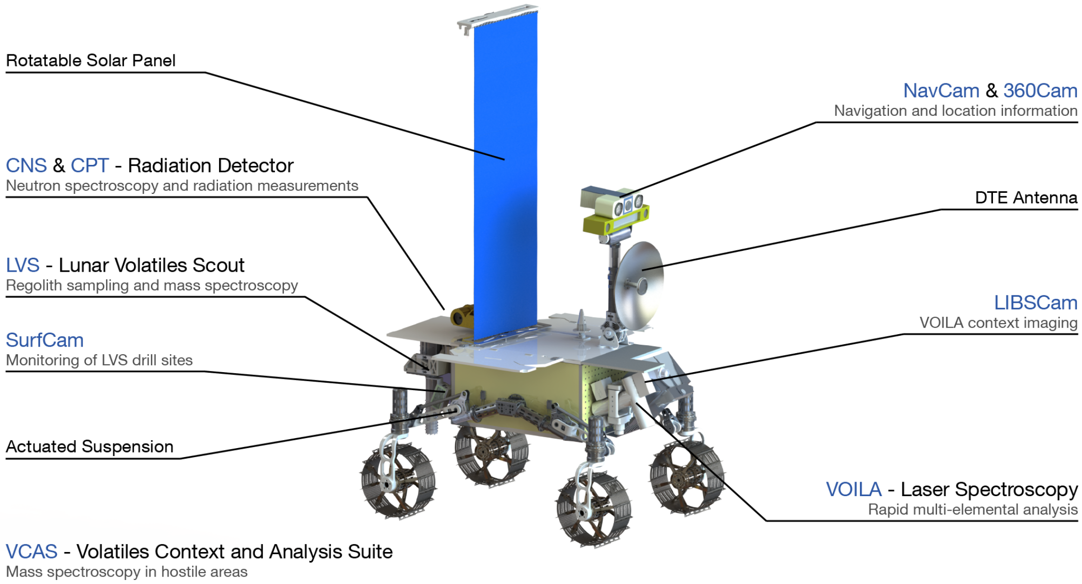

Figure 1: The LUVMI-X rover and its instrumentation.

the presence of water ice in a permanently shadowed crater by the LCROSS mission is strongly model-dependent and is statistically not significant [6]. It is therefore imperative that new missions be sent to the Moon to gather detailed data on the abundance of lunar water and to assess its economic potential. While there is still a lot that can be done from orbit, it is even more important that probes are sent to the surface to gather in-situ data. Ultimately, only ground data will be able to reveal how accessible water (ice) reserves on the Moon are.

3 THE LUVMI-X MISSION

The objective of the LUVMI-X mission we present in this contribution is to address the shortage of in-situ data and to help resolve the remaining ambiguities referenced in the previous section. Its primary objective is to measure the concentration and distribution of volatiles in regions with different illumination at the lunar poles. The principal target of these measurements is the identification of water deposits, both in the form of ice and in chemically bound states, but the abundances of other volatiles identified by LCROSS and found in Apollo samples—such as hydroxyl, hydrogen sulfide, ammonia, ethylene, and carbon dioxide [6]—shall be determined as well.

As a secondary objective, LUVMI-X shall investigate the regolith's mineralogical composition in regions for which no reliable in-situ or sample data exists yet, with a focus on the polar regions. Another secondary objective is the characterization of the Moon's surface radiation environment in preparation for future manned exploration missions.

The mission is based on a compact rover platform that our consortium currently develops. This platform can be repurposed for a range of different mission scenarios. For LUVMI-X, the rover is equipped with a suite of new instruments that provide complementary data about the abundances of water and other volatiles. To further complement these three primary instruments, the rover will have the capability to place remotely operated sensor packages in partially illuminated and permanently shadowed areas. It is also equipped with several state-of-the-art light-field camera systems, which provide information about the surface properties of the regolith, the rover location, and for hazard identification.

3.1 The Rover

The LUVMI-X rover (see Figure 1) is capable of traversing a survey track of at least 5 km during a 14-day mission. It is equipped with four independently steerable wheels in a rocker-bogie configuration with an internal differential. An actuated suspension can bring chassis-mounted instruments into contact with the lunar surface and allows the vehicle to traverse obstacles up to 30 cm in height and to climb slopes with inclinations of up to 30 degrees. It also lets the rover assume a very compact stowage configuration (85 cm long, 77 cm wide, and 35 cm high), making it compatible with many (commercial) landers currently under development. The mass of the rover is 30 kg; a further 25 kg of payloads can be added in forward- and backward-facing positions.

The rover is optimized for operations in the Moon's polar regions. It is equipped with a vertically mounted, rotatable solar panel that works best at high latitudes and generates up to 140 W of power, about half of which is available for payloads. The thermal control system is likewise optimized for low illumination angles and hence features upward-facing radiators. The rover can operate without illumination for about six hours at a time and survive short lunar nights of less than 24 hours in hibernation mode. The mission's nominal surface lifetime is 14 days, during which it will mostly operate in areas of full illumination. Short-term excursions into partially illuminated and permanently shadowed regions will be performed at regular intervals to facilitate sampling in such areas. Operations will be conducted in supervised autonomy as much as possible, with the option to directly tele-operate the rover should operational and environmental conditions require it. Nominally, communication with the rover will be over a direct-to-Earth link, though relaying signals through a lander or satellite is possible should these options be available at the time of the mission.

4 INSTRUMENTATION

We present the three primary instruments LUVMI-X carries that can reveal the presence of water and hydrogen. These instruments are currently still under development, so we are not yet able to state performance or sensitivity parameters. We also briefly describe the sensor packages that can be placed on the lunar surface and be operated remotely.

4.1 In-Situ Volatiles Characterization

The Lunar Volatiles Scout (LVS) is a simple and lightweight instrument that enables LUVMI-X to release volatiles from the lunar regolith and analyze them [12]. It consists of the Volatiles Sampler (VS), a combined sample drill and gas-extraction oven that can be inserted into the regolith to release volatiles, and the Volatiles Analyzer (VA), a miniature ion-trap mass spectrometer for the elemental analysis of the released gases. The VS consists of a hollow auger drill shell that encloses a sample volume. A resistive heater, located at the center of the sample volume, can heat the surrounding regolith to about 500 °C. Such temperatures are sufficient to release loosely bound volatiles like water and the design is comparable to that of the OVEN payload of the now cancelled Resource Prospector mission. Pirani sensors measure the gas pressure inside the sample volume to provide some indication of the abundance of volatiles. The released gases are analyzed by the VA, a miniature ion-trap mass spectrometer (ITMS) derived from the Ptolemy instrument that provided the first in-situ measurements of volatiles on the surface of the comet 67P/Churyumov-Gerasimenko during the Rosetta mission [13,14]. It is mounted directly on top of the VS and is connected to the sample volume via a small orifice for pressure control. Even though it is a rather simple device, it can detect a wide range of ion species (m/z of 10 to 200) with a parts-per-million sensitivity across the detection range. This sensitivity allows the LVS to detect all volatiles species that have previously been detected in the LCROSS ejecta plume [6]. Due to the inherent sensitivity limitations of an ITMS at low masses, it will however be challenging to determine the relative concentrations of smaller molecules such as water, hydroxyl, and ammonia. We currently study the feasibility of using a miniature magnetic-sector mass spectrometer to measure hydrogen and its isotopes.

The LVS drill shell has an inner diameter of 38 mm and a length of 150 mm, enclosing a sample mass of about 280 g. Driven by a brushed DC motor, the rotation of the shell ensures that the vertical force necessary for insertion into icy regolith remains below 15 N for depths of up to 10 cm. At this depth, water ice is believed to remain stable even in some non-permanently shadowed regions at the poles [15]. The entire system, including drill, heating element, and mass spectrometer, has a total mass of just 1.9 kg and a power consumption of 20 W. Even though its measurement capability is inferior to more sophisticated systems like PROSPECT, its low mass, volume, and power consumption make the LVS an ideal choice for mobile platforms. On LUVMI-X, it can investigate the lateral variability of lunar volatiles and can thus act as a precursor or complement to PROSPECT and other static instruments.

4.2 Rock and Regolith Analysis

The Volatiles Identification by Laser Analysis (VOILA) instrument uses laser-induced breakdown spectroscopy (LIBS) for the rapid multi-elemental analysis of regolith and rocks along the rover's track. The LIBS technique relies on ablating material from a sample by focusing a pulsed laser onto its surface, producing a micro-plasma of atoms, ions, and electrons [16]. The light emitted by the plasma is collected and its spectrum is analyzed to identify and quantify elements based on their characteristic emission lines. The instrument will provide spectral coverage from 350 nm to 790 nm and is optimized for the detection of hydrogen at 656.3 nm and oxygen at 777.4 nm. Its data will help to identify locations with high water and oxygen concentrations for the more time- and power-consuming sampling with the LVS. The instrument will also be able to detect rock-forming elements such as aluminum, silicon, and calcium and can thus determine the composition of the lunar regolith and rocks. A focusing mechanism guarantees repeatable measurement conditions on the lunar surface and a pointing mechanism allows to analyze targets within a lateral field of view of about 40 degrees in front of the rover. VOILA is more sophisticated than other LIBS instruments designed for lunar exploration [17] but is lighter and consumes less power than the more capable ChemCam and SuperCam instruments on the Mars Science Laboratory and the Mars 2020 rover, respectively [18,19].

4.3 Surface Radiation Environment

The Radiation Detector comprises a Compact Neutron Spectrometer (CNS) and a Charged Particle Telescope (CPT). The CNS' primary purpose is to aid the search for water and hydroxyl deposits by measuring the flux of epithermal neutrons. Neutrons are created by highly energetic cosmic rays that penetrate the lunar surface to depths of several meters. While diffusing upwards through the regolith, the neutrons scatter with its constituent nuclei and assume an energy spectrum that is characteristic for the composition of the regolith [20]. The presence of hydrogen (and thus water or hydroxyl) elicits a detectable change in this energy spectrum by lowering the relative flux of epithermal neutrons; Feldman et al. used this effect to estimate the amount of water ice present at the lunar poles using neutron-spectroscopy data from Lunar Prospector [4]. The CNS' sensitivity and energy ranges are optimized for the detection of hydrogen signatures, but the instrument will also be able to provide basic information about the regolith composition. The CPT can detect and characterize charged particles (protons and ions) of the solar wind and cosmic rays with energies larger than 10 MeV per nucleon. This allows the characterization of the radiation environment on the lunar surface, which is a crucial prerequisite for future manned exploration missions [21]. The lunar proton albedo may also contain information about the distribution of volatiles in the regolith [22]. Even though measurements of the radiation environment in lunar orbit have been performed in recent years (e.g. [23]), our knowledge of the surface environment, which is believed to be substantially different from the one in orbit [24], is still incomplete. The CPT will help to address this issue by providing particle-dependent energy spectra for charged particles with energies between ten and several hundred MeV per nucleon and by measuring the ionization dose of all radiation particles, including neutrons and gamma rays.

4.4 Miniaturized Remote Sensors

The Volatiles and Context Analysis Suite (VCAS) is a deployable instrument that will measure volatiles in locations that are difficult or too hostile for a rover or lander to access, for example on steep slopes or inside craters and lava tubes. The core of VCAS is a simplified and smaller version of the VA, optimized to fit into a CubeSat-like form factor. VCAS will also provide supplementary information about the analysis site, including images of the local geology, rock formations, and illumination, as well as measurements of the physical, mechanical, and thermal properties of the regolith. Several sensors will measure the local temperature and dust distribution to study the near-surface exospheric particulate environment. The VCAS sensor packages are self-sustaining and can be operated remotely.

5 CONCLUSION

The LUVMI-X rover is ideally suited to help gather much-needed data about the availability and accessibility of water (ice) on the Moon. Our intent is to develop an affordable and adaptable system that not only provides scientifically interesting data but also supports the development of lunar ice as a resource, which more than anything will require comprehensive in-situ measurements [25]. LUVMI-X therefore fits well into the diverse landscape of water-focused missions—such as the VIPER rover or the LunaH-Map, Lunar Trailblazer, Lunar IceCube, and Lunar Flashlight orbiters, to name but a few examples—currently under development in the US and Europe.

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