SUPPORTING LUNAR IN-SITU RESOURCE UTILIZATION (ISRU) WITH LASER-INDUCED BREAKDOWN SPECTROSCOPY.

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Introduction: In-situ resource utilization (ISRU) on the Moon is of great interest due to its relevance for achieving a sustained human presence on the Moon and for human space exploration in general. The two most important resources are water and oxygen, which are vital for life support on future Moon bases and for potential applications as propellants for spacecraft [1]. Large reservoirs of water ice in permanently shadowed regions (PSRs) at the lunar south pole could serve as a potential water source [2], though water could also be produced via electrolysis of hydroxyl groups in the lunar regolith without requiring access to PSRs [1]. Oxygen can be produced via ilmenite reduction or via electrolysis or pyrolysis of lunar regolith [1]. Other raw materials in the lunar rocks and regolith can also be used for metallurgic and chemical production processes.

Due to the importance of ISRU for future lunar exploration, scientific payloads for upcoming lunar missions should be capable of supporting these ISRU activities. This can be achieved by providing the capability to search for resources (prospecting) or to monitor and analyze the ongoing ISRU activities. Here, we demonstrate that laser-induced breakdown spectroscopy (LIBS) is suitable for these activities and we investigate potential payload concepts for different application scenarios.

LIBS: LIBS uses a pulsed laser to ablate material from an investigated target, which forms a bright plasma plume that can be analyzed spectroscopically to gain information about the composition of the targeted sample. LIBS is well-suited for quick analysis at stand-off distances, since it only requires optical access and measurements take only a few seconds [3]. It has been successfully employed on Mars by ChemCam on NASA's Mars Science Laboratory mission, by SuperCam on NASA's Mars 2020 mission, and by MarSCoDe on CNSA's Tianwen-1 mission [4, 5, 6]. The first LIBS instrument to be employed on the Moon was on board the Pragyan rover of India's Chandrayaan-2 mission [7], but the lander failed to achieve a soft landing in September 2019. Together with OHB System AG and Laser Zentrum Hannover e.V., the DLR Institute of Optical Sensor Systems (DLR-OS) has recently developed a conceptual design and laboratory breadboard model of a LIBS instrument called VOILA (Volatiles Identification by Laser Ablation) for a lightweight lunar rover [8].

Payload concepts: A variety of potential LIBS payload concepts are considered that are suitable for specific application scenarios. These include handheld devices as well as different concepts for LIBS payloads on lunar rovers in dependence of the intended use case.

Prospecting: Prospecting ISRU resources with LIBS is as simple as taking measurements of the lunar surface along the traverse of the rover. In order to provide a large range of potential targets, a mast-mounted concept can be considered, as it offers the largest working distance at the cost of requiring a higher mass and volume. Alternatively, a lighter LIBS payload on a rover arm provides less range, but more versatility. It can be used to specifically target the same samples as other payloads.

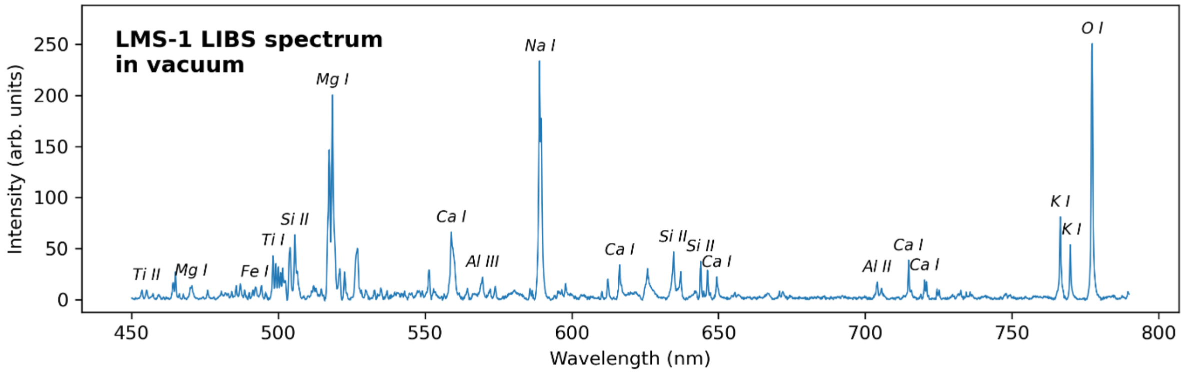

Figure 1: LIBS spectrum of Exolith LMS-1 simulant measured in vacuum conditions. All major rock-forming elements can be detected.

Monitoring: LIBS instruments can be incorporated into ISRU payloads to monitor the ongoing resource extraction processes. This design uses a fixed position at a small working distance of several centimeters to provide a precise analysis of the change in the sample composition over time. An example is oxygen production by ilmenite reduction or by electrolysis of lunar regolith, which can be monitored by measuring the decreasing O signal in the LIBS spectra.

Human exploration: Handheld devices provide the most versatility for human exploration of the Moon. They can be used directly on the lunar surface to analyze geological samples before collecting them. For these devices, a large focus must be placed on ergonomics, an intuitive design and on capable software for on-the-fly spectral analysis. Handheld devices can be used for prospecting as well as for monitoring of ISRU processes, provided that the ISRU payloads offer external optical access for the LIBS handheld, for example by adding a window through which LIBS measurements can be made.

Experiments: Experiments to demonstrate the capability of LIBS for the support of lunar ISRU activities were made with the VOILA breadboard setup at DLR-OS, which is capable of simulating lunar conditions in a vacuum chamber [8]. The LIBS spectrometer has a working distance of 400 mm, uses a prototype laser (developed by Laser Zentrum Hannover e.V.) operating at a wavelength of 1030 nm with a pulse energy of 17 mJ and a pulse duration of 7.8 ns, and covers a wavelength range from 350 nm to 910 nm with a spectral resolution of about 0.4 nm.

Results: Fig. 1 shows a LIBS spectrum of lunar regolith simulant Exolith LMS-1 measured with the VOILA setup in vacuum. For the composition of LMS-1, all major rock-forming elements can be detected with a signal-to-noise ratio of at least 10 for at least one spectral line, offering a spectral fingerprint of the investigated sample that could enable identification of the target. Ilmenite ($FeTiO_3$) could be identified by a spectrum consisting mostly of Fe and Ti lines.

Hydrogen detection and quantification with LIBS was investigated with different samples, including mixtures of lunar regolith simulants and granular water ice, hydrogen-bearing minerals such as goethite (α-$Fe^{3+}O(OH)$) and limonite ($FeO(OH)\cdot nH_2O$), and salt mixtures with different water content. The H-alpha line at 656.3 nm is a strong signal that can be used to detect and quantify water in concentrations as low as 1 wt%, as can be seen in the calibration curve in Fig. 2 (top).

Fig. 2 (bottom) shows early results that demonstrate the monitoring of the oxygen production from lunar regolith with LIBS. The dashed line shows the LIBS spectrum of the original LMS-1 simulant, while the blue continuous line shows the LIBS spectrum of LMS-1 after reduction, now with an oxygen concentration of less than 5 wt%. The decrease of the O signal at 777.4 nm indicates the potential for the monitoring of oxygen production.

Conclusion and outlook: The preliminary results show that LIBS instruments are capable of supporting ISRU activities on the Moon. The most relevant fields of application are prospecting on the lunar surface and monitoring of ongoing ISRU processes. LIBS instruments could be realized as payloads for lunar exploration rovers, as instruments in stationary ISRU facilities, and as handheld devices for human exploration of the Moon.

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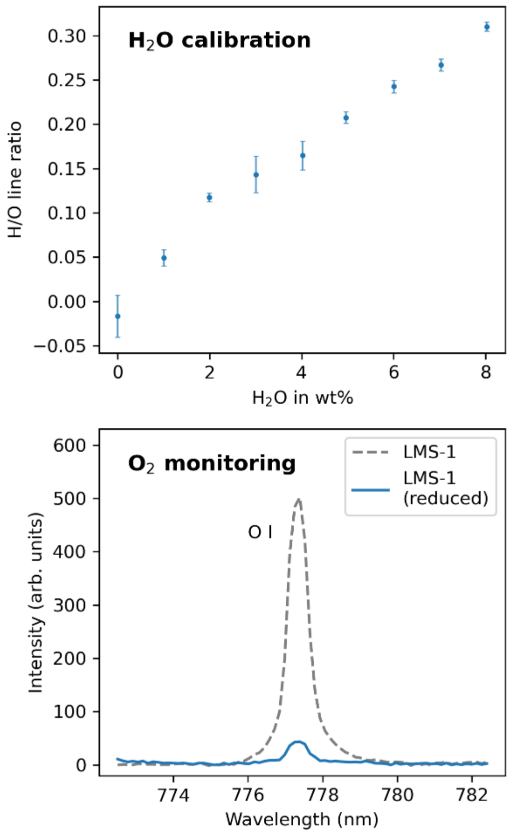

Figure 2: Top: The H/O line ratio in LIBS spectra of samples mixed from $CaSO_4\cdot 2H_2O$ and Na_2SO_4. Bottom: O I triplet at 777.4 nm in LIBS spectra of the unaltered and of the reduced (<5 wt% O) LMS-1 simulant.