LASER-INDUCED BREAKDOWN SPECTROSCOPY FOR THE SUPPORT OF IN-SITU RESOURCE UTILIZATION (ISRU) ON THE MOON. D. S. Vogt[1], S. Schröder[1], N. Sandig[1,2], M. Gensch[1,2], H.-W. Hübers[1,3], B. Lomax[4], B. Gundlach[5], [1]DLR Institute of Optical Sensor Systems, Berlin, Germany, david.vogt@dlr.de, [2]Technical University of Berlin, Berlin, Germany, [3]Humboldt University of Berlin, Berlin, Germany, [4]ESA ESTEC, Noordwijk, The Netherlands, [5]Technical University of Braunschweig, Braunschweig, Germany.

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 on the lunar surface or to monitor and analyze the ongoing ISRU activities. Here, we demonstrate that payloads employing laser-induced breakdown spectroscopy (LIBS) are suitable for these activities. LIBS is capable of detecting hydrogen and oxygen in all possible configurations in the lunar regolith, can be used to analyze the composition of rocks and regolith, and allows for monitoring of ongoing ISRU processes. Compact LIBS payloads on lunar rovers, on ISRU facilities and as handheld instruments for human application on the Moon are therefore promising candidates for future lunar missions.

LIBS: LIBS uses a pulsed laser to ablate material from an investigated target, which forms a bright plasma plume that can be analyzed spectroscopically. Atomic and ionic emission lines in the spectrum offer information about the composition of the targeted surface. 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]. LIBS 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].

Scouting for ISRU resources with LIBS is as simple as taking measurements of the lunar surface along the traverse of the rover, where the quick measurements make it possible to investigate a large number of targets and to trace trends along the traverse. In addition to scouting purposes, LIBS spectrometers can also be mounted to ISRU payloads to monitor the ongoing

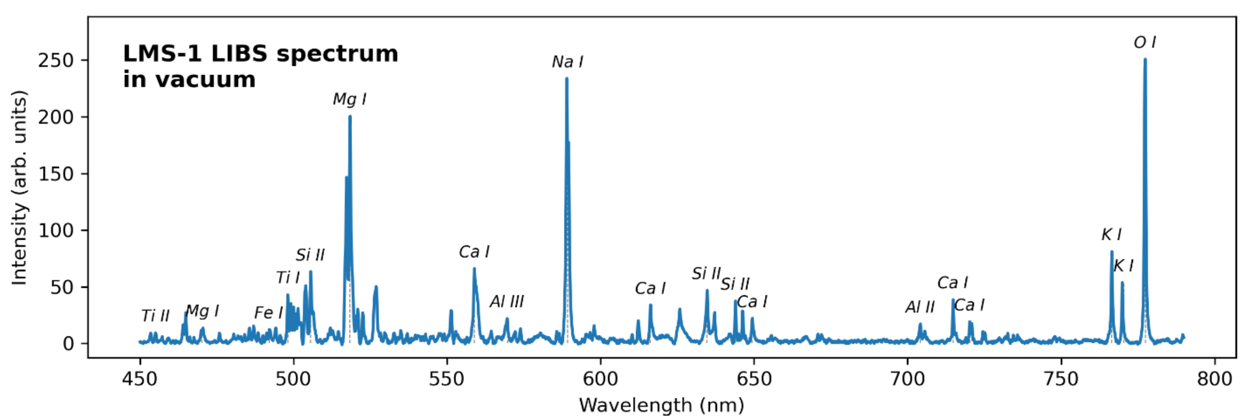

Figure 1: LIBS spectrum of Exolith LMS-1 simulant measured in vacuum conditions. All major rock-forming elements can be detected.

resource extraction processes directly. For example, oxygen production by ilmenite reduction or by electrolysis of lunar regolith can be monitored by measuring the decreasing oxygen signal in the LIBS spectra and the relative increase of the intensity of spectral lines from other elements as their relative abundance in the laser-induced plasma increases.

Setup: Experiments were made with the VOILA setup at DLR-OS that is designed to be a demonstration model for a lunar LIBS payload. The setup uses a vacuum chamber to reach pressures in the order of 1 mPa (10^{-5} mbar), so that the measurement conditions are sufficiently close to those on the lunar surface [4, 10]. A translation stage inside the vacuum chamber is used to adjust the position of the sample. Samples can be cooled with liquid nitrogen for LIBS measurements of frozen samples. The spectrometer system is mounted above the vacuum chamber with a fixed working distance of 400 mm and employs a pulsed laser developed by the Laser Zentrum Hannover e.V. and a fiber-coupled Avantes AvaSpec-Mini spectrometer. The laser operates at a wavelength of 1030 nm with a pulse energy of 17 mJ and a pulse duration of 7.8 ns. The spectrometer 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 via molten salt electrolysis, now with an oxygen concentration of less than 5 wt%. The decrease of the intensity of the O I triplet at 777.4 nm indicates the potential for the monitoring of oxygen production by analyzing the reduced raw material.

Conclusion: The preliminary results show that LIBS instruments are capable of supporting ISRU activities on the Moon. Two fields of application have been identified, where the first is the scouting for resources on the lunar surface and the second is the 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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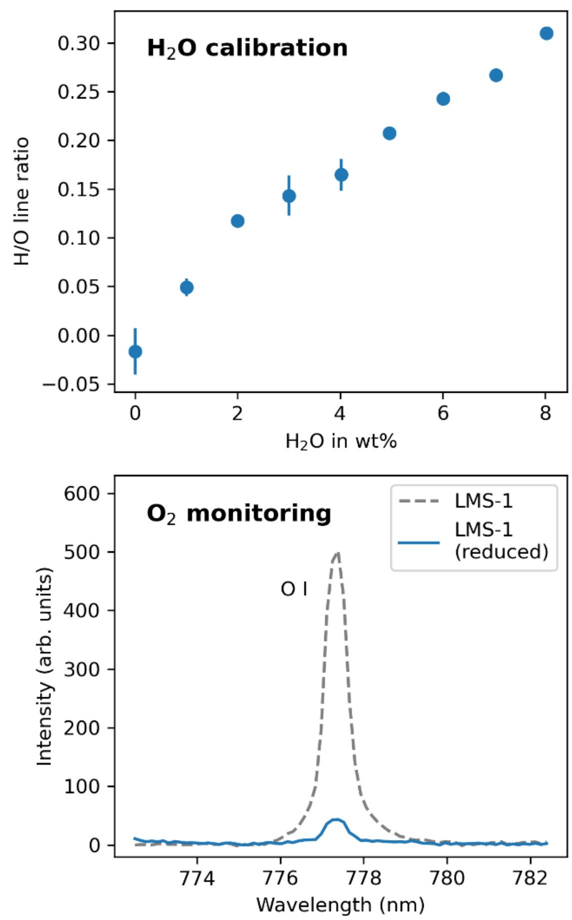

Figure 2: Top: The H/O line ratio in LIBS spectra of samples mixed from $CaSO_4{\cdot}2H_2O$ and Na_2SO_4. Bottom: O I triplet at 777.4 nm in LIBS spectra of the unaltered and of the reduced (<5 wt% O) LMS-1 simulant.