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MicroLIBS Operations Concept of a miniaturized LIBS for planetary exploration

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Abstract

The MicroLIBS instrument for in situ elemental micro-mapping is being developed by CNES with IRAP (FR) and LANL (US) laboratories. It meets the need for lightweight, low-cost instruments that can be rapidly developed. The success of LIBS (laser-induced breakdown spectroscopy) laser experiments on the MSL and Mars2020 missions, with the ChemCam and SuperCam instruments respectively, led CNES and its partners to develop the MicroLIBS instrument for future Moon and Mars missions at low weight and low cost. MicroLIBS will have a similar performance to ChemCam and SuperCam, but with new capabilities of high scientific value.

With a weight of only 1.5kg, this miniaturized version on ChemCam/SuperCam (10kg) is designed to be mounted on a helicopter or a drone on Mars. It can also be installed on a tripod for use by astronauts on the lunar surface, or mounted on a small surface rover for near-real-time analysis of surrounding rocks. MicroLIBS can be used to remove dust, and simply positioned from a platform without the aid of a turret or robotic arm, it carries out its observations using LIBS in micro-scale scans on targets in its workspace.

MicroLIBS not only meets the needs of low-cost missions, but also and above all the microanalysis requirements identified in NASA's latest Decadal Survey. Sub-millimeter-scale analysis, or microanalysis, is crucial for future in situ missions to sort and select the most important samples worth bringing back to Earth. MicroLIBS will offer great geological diversity by analyzing multiple targets in each workspace. It enables complete in situ petrological analysis by performing micro-scans, akin to laboratory methods.

The paper will present the design and functions of the MicroLIBS instrument, and the concept of operations for Mars and Moon missions. A focus will be provided on the differences between operating the instrument on a rover or on a helicopter. Finally, this paper will provide the development status and how MicroLIBS fits within the CNES strategy to develop low cost instruments for Space Exploration.

Keywords: MicroLIBS, Mars, Moon, helicopter, rover, operations

Acronyms/Abbreviations

CLPS Commercial Lunar Payload Services
CNES Centre National d'Etudes Spatiales
DLR Deutsches Zentrum Für Luft- Und Raumfahrt
GEVS General Environmental Verification Standard
GSE Ground Support Equipment
GSFC Goddard Space Flight Control Center
IR InfraRed
IRAP Institut de Recherche an Astrophysique et Planétologie
I&T Integration & Test
JPL Jet Propulsion Laboratory
LANL Los Alamos National Laboratory
LED Light Emitting Diode
LIBS Laser Induced Breakdown Spectroscopy

MMX Mars Moon eXploration
MSL Mars Science Laboratory
OMP Observatoire Midi-Pyrénées
R&D Research And Development
RMI Remote Micro Imager
RTG Radioisotopic Thermoelectric Generator
SPA South-Pole Aitken
STM Structural and Thermal Model
SWIR ShortWave InfraRed
TRL Technology Readiness Level
TVAC Thermal and VACuum

1. Introduction

When the Mars Science Laboratory rover, Curiosity, landed on Mars on August 5th 2012, it carried on top of its remote sensing mast a breakthrough LIBS laser instrument called ChemCam. The LIBS (Laser Induced Breakdown Spectroscopy) vaporizes rocks and soils with a very high energy pulsed laser. This creates a plasma that emits light, which is analysed back in the instrument by a set of three spectrometers covering the 240-930nm spectral range (UV-VIS-VNIR). By comparing the spectra with a database of rocks analysis on Earth, one can obtain the elemental composition of the sample shot and identify the rock with the same composition (e.g. olivine, hematite, clay etc.). After more than one million laser shots on Mars, the ChemCam laser is still active and operating on a daily basis. Back in 2021, the Perseverance rover carried an evolved version of ChemCam called SuperCam, implementing an additional RAMAN spectrometer, an infrared spectrometer and a microphone. SuperCam has now exceeded 500,000 laser shots on Mars.

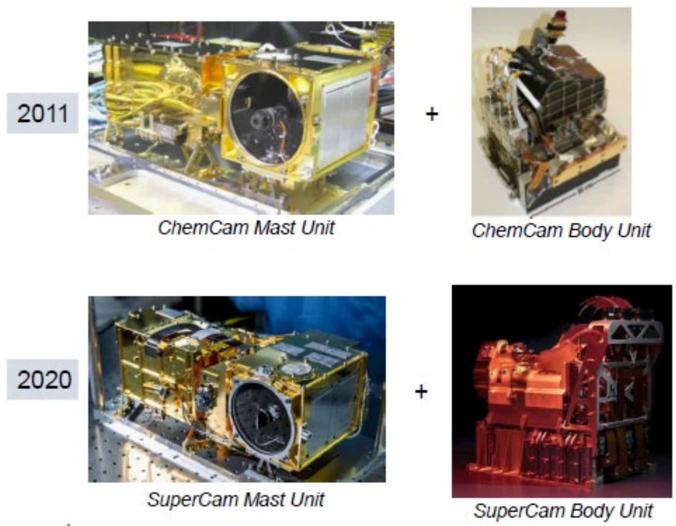

Figure 1The ChemCam and SuperCam instruments

The success of LIBS laser experiments on the MSL and Mars2020 missions (ChemCam and SuperCam instruments respectively) led CNES, the French Space Agency, and its partners to develop the MicroLIBS instrument for future lunar missions at low weight and low cost, with similar performance to ChemCam and SuperCam, but with new capabilities of high scientific value.

This paper will first introduce the MicroLIBS instrument and architecture, and its evolution with respect to ChemCam and SuperCam instruments: key differences, improvements, specific constraints, etc. The different versions of MicroLIBS will be presented and the key features of each of them will be discussed in the first part of this paper, namely a Mars version, a Moon version and an astronaut handheld version.

The operational concept of those instruments will then be presented, with the specifics and operational challenges for each of them. The inner details of the instrument operations will be covered as well as the more general context of a space mission, depending on the planetary body (Moon or Mars) and the platform on which the instrument will be mounted.

Finally, the paper will present the development schedule and the path forward for the years to come and opportunities that may become a reality for the MicroLIBS teams.

2. The MicroLIBS Instrument

CNES and its partners IRAP, LANL and DLR have started the development of a prototype version of MicroLIBS in 2022. The first phases of the development were focused on the design of the instrument and the technical challenges the team would face when the need to develop a flight version of the instrument would appear. The core idea of MicroLIBS consists in the miniaturization and technological update of the ChemCam and SuperCam instruments. Both instruments shall be mentioned here since not all components of SuperCam (which is an evolved version of ChemCam with an additional RAMAN spectrometer, an IR spectrometer and a microphone) will be implemented in MicroLIBS.

The objective of the miniaturization is to develop a low-cost, fastly built instrument, that could be mounted on a small 10kg rover on the Moon or on Mars, or on a (big) helicopter on Mars. Unlike ChemCam and SuperCam will be a single body instrument, and will not be split into an optical unit (on top of the mast) and a body unit (inside the rover). Both units will be mounted on top of each other inside a composite structure the size of a shoebox.

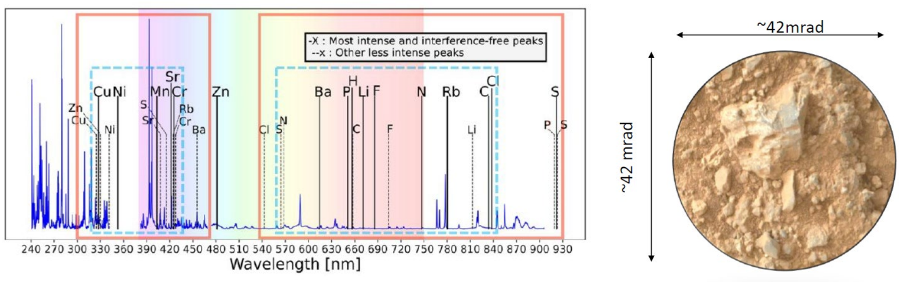

Figure 2 : Science products LIBS spectra and context images

On Mars a decade of experience with the ChemCam instrument onboard Curiosity, and now SuperCam onboard Perseverance, has proven the technique's reliability and capability to analyze rocks at a submillimeter scale for geological investigations. Miniaturization of LIBS systems has recently matured and now a set of handheld commercial devices ≤ 2 kg (battery and gas purge included) are available for geochemical analyses. Based on ChemCam and SuperCam subsystems heritage, we propose a new ≤ 1.5 kg instrument to perform LIBS analyses on Mars' surface with architecture closer to handheld devices.

Figure 3: MicroLIBS concept evolution

2.1 Mars version

The first iteration of MicroLIBS is based on NASA's Chopper mission concept developed by the Jet Propulsion Laboratory (JPL) and Ames Research Center. Chopper is a much bigger follow-on to NASA's Ingenuity Mars Helicopter, which arrived at the Red Planet in the belly of the Perseverance rover in February 2021, and managed to achieve 72 pathbreaking flights on Mars, for the very first time in history.

Chopper is an hexacopter with six rotors, each with six blades. Unlike Ingenuity which was too small, it could be used to carry science payloads as large as 5 kilograms on distances of up to 3 kilometers each Martian day (or sol). Scientists could use Chopper to study large swaths of terrain in detail, quickly – including areas where rovers cannot safely travel or land during the Entry Descent and Landing phase.

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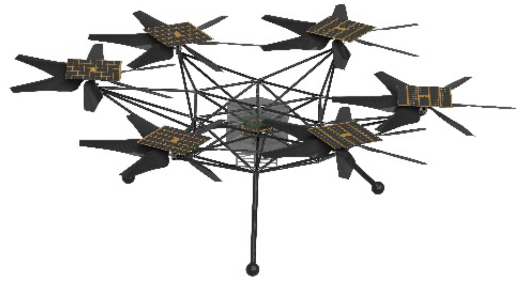

Figure 4 : Chopper hexacopter artist view (credit : NASA JPL, https://www.jpl.nasa.gov/images/pia26375-nasas-mars-chopper-concept-rendering/)

While Chopper remains in early conceptual and design stages, CNES took the opportunity of an R&D program to design an instrument that could fit such a mission and the pre-identified 5kg payload. The MicroLIBS team believes a miniaturized version of ChemCam/SuperCam can fit a 1.5kg mass instrument. The design phase ended in 2024 with a final design review being held in CNES premises in Toulouse, France.

MicroLIBS dimensions are 200x150x100mm, for an estimated mass of 1.5kg with margin. The maximum weight MicroLIBS does not want to exceed is 2kg, which current prototype design is consistent with. Those features are achieved by the synergy between several subsystems, designed by different entities: electronics (developed by LANL, Los Alamos National Laboratory, USA), spectrometers (LANL), imager (CNES), laser (Thalès, France), telescope (OMP, Observatoire Midi-Pyrénées, France) and a scanner. The choice has been made to develop 2 scanner subsystems in parallel by DLR, the German Space Agency in Berlin, and the french company ISP, since this is the only subsystem that was not part of ChemCam or SuperCam, and hence without hardware heritage. This 2-axis actuated scanning mirror will allow the analysis of multiple targets within an area below the platform. This mechanism will enable precise pointing of the 50 µm focused laser spot to perform closely-spaced grid observations on areas less than 1 cm².

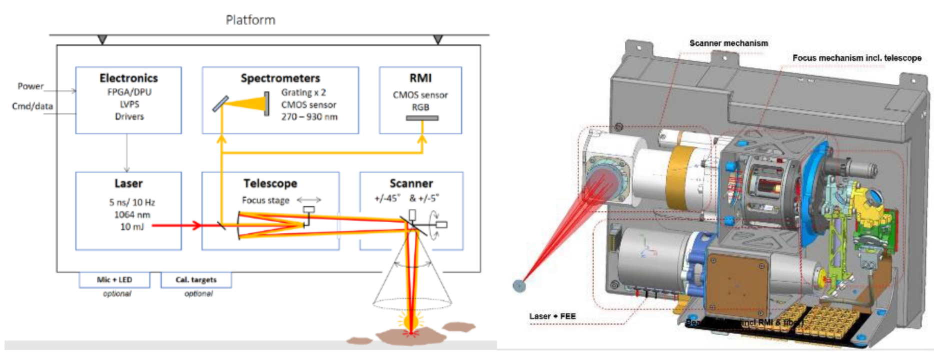

Figure 5 The MicroLIBS architecture and final design

The laser system is especially innovative with a mass of less than 150g and a LIBS energy of 10mJ. This is less than the previous instruments but MicroLIBS will operate at a distance of 20 to 50 cm, compared to 2 to 7m for ChemCam and SuperCam, enabling significant mass reduction compared to ChemCam and SuperCam designs.

MicroLIBS also includes a remote micro-imager to provide dust-free micro-textures with elemental grid overlaid. µLIBS laser can operate at 10 Hz and lower energy, making a typical 10x10 grid observation under an estimated 20 min duration or a 30x30 grid under 1 hour. These 100 to nearly 1000 grid points will help detect minor phases down to 1% and 0.1% of the rock and map their distribution. An LED illumination system is also foreseen to accommodate the potentially shadowy environment below the platform.

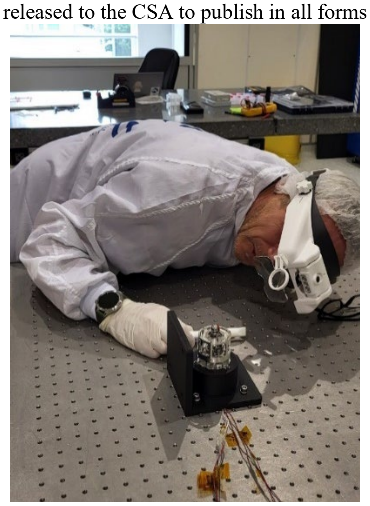

Figure 6 : Ongoing I&T of the MicroLIBS prototype

A microphone, directly inherited from SuperCam (ChemCam did not have a microphone), will provide the capability to record the sounds emitted by the rocks when they are zapped by the LIBS laser and plasma is being emitted. MicroLIBS analyses through its spectrometers the light emitted by the plasma, providing elemental composition of the rocks analysed. The microphone will provide information about the rock hardness by comparing it with a reference database of libs experiments on Earth. The MicroLIBS team is also working of a version of the microphone module that will be able to measure winds and the directions of the wind gusts that may be detected. This information is a key factor of success for a platform like Chopper, since a helicopter is very dependent on the wind conditions, which are often quite predictable on Mars from one sol to another.

Figure 7 : Artist view of MicroLIBS mounted on a Mars hexacopter

2.2 Moon version

MicroLIBS was originally designed for a helicopter mission to Mars. Missions to Mars are rarer and the chances of being selected as part of a scientific payload are much lower than for missions to the Moon, since many of them are currently in the bidding phase for scientific instruments. The "low-coast" approach of the MicroLIBS development is obviously more compatible with a small lunar rover mission, for instance in the frame of NASA's CLPS program, than with a Mars helicopter mission.

A Moon mission has different constraints than a Mars mission, and the thermal environment is a lot colder during the night on the Moon, which lasts 14 Earth days. Most current missions, rovers or landers, are not designed to survive the lunar night, hence only planning for a 14 days' mission.

No helicopter can fly on the Moon due to the lack of atmosphere, so that MicroLIBS would have to be mounted below the deck or on the side of a small rover. Even though some flexibility and adaptability exists, the currently designed shooting range of MicroLIBS's laser is 20 to 50cm, making it difficult to have it mounted on top of a rover mast, more than 1m away from the surface. For that reason the MicroLIBS team is working on a Moon version of MicroLIBS with a longer range for LIBS observations, 1m to 4m, with a self pointing system similar to a periscope. Also 2 additional spectrometers would be added to increase the resolution because the light emitted by the LIBS plasmas on the Moon is weaker than on Mars, where LIBS plasma creation is ideal with a 7mbar CO2 atmosphere.

It also makes sense on the Moon to add a SWIR Multispectral camera with 9 spectral bands implemented, as well as an illumination system due to the shadowy regions of the lunar South Pole and SPA Basin region. Overall the instrument mass would consequently increase to about 5kg, but the weight constraints for a Moon rover are way less restrictive than for a Mars helicopter. Another subsystem that would have an impact on the mass is the structure, that can be modified from a composite structure on Mars (and its heat dissipation issue) to a more usual titanium structure on the Moon.

The operational concept would nevertheless be very similar to the Mars version, with grid rasters of 900 points (30x30) being shot on a 1cm2 area just like on Mars.

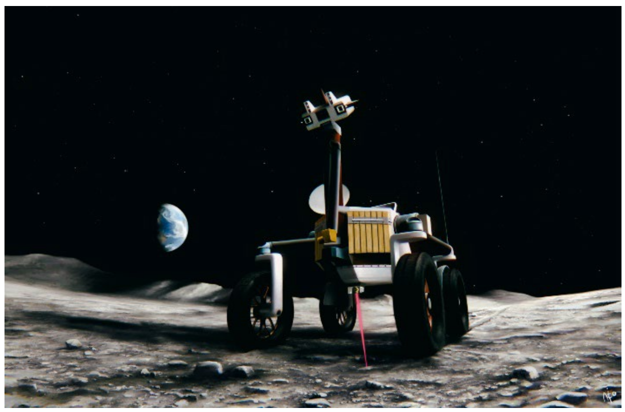

Figure 8 : MicroLIBS on a Moon rover concept

2.3 Astronaut version

The MicroLIBS team also has plans to develop a tripod for astronauts, allowing them to analyse in real time the surrounding rocks without the need for a high level geology training. MicroLIBS would be mounted on a tripod, a handle

Figure 9 : MicroLIBS Astronaut Tripod concept

The operational concept of a Moon tripod would differ from a MicroLIBS instrument mounted on a rover or a helicopter (on Mars). One can imagine an onboard LIBS spectra processing and display that an astronaut could read to decide if a rock is worth bringing back to Earth or not. Ground in the loop would not be necessary and MicroLIBS would be used as one of the handheld LIBS devices developed on Earth (similar to a "laser gun"), but with all the safety concerns of having astronauts around. Another concept is that the astronaut is only filling the task of installing the instrument on the Moon surface and then let the ground operate it remotely.

Ongoing development topics include energy procurement for the instrument, data transfer back to Earth, tripod stability, handle compatibility with future astronaut suits, etc.

In the frame of the current pre-development of the MicroLIBS prototype, the choice has been made to limit the development of the Moon and Astronaut versions of MicroLIBS to the design and operational concept study. To Moon hardware or prototype will be assembled. **CNES is confident that a functional Mars prototype that reaches TRL-6 is sufficient to prove the relevance of the concept and the technical maturity of the miniaturization process.**

3. The MicroLIBS operational concept

The MicroLIBS operations are based on Curiosity & Perseverance ChemCam/SuperCam operations. It is designed for non-real time operations, like most planetary science instruments. Its entire "day" of operations is programmed in advance, and an activity plan of activities is transmitted to the instrument at the beginning of an uplink cycle. This uplink cycle can be one sol or several sols on Mars, each sol lasting approximately 24h and 40min. The distance between Mars and the Earth can range from less than 60 million kms to 400 million kms, with an average distance of 225 million km. The signals sent to Mars (and received from Mars) take about 20min on average to travel the free space between the two planets, making it impossible to perform real time operations. Moreover, orbiters are used most of the time to communicate with rovers or landers on the surface of the red planet, adding an additional delay in radio communications.

On the Moon, a lunar day lasts 14 Earth days of daylight and 14 Earth days of night, so that an uplink cycle can be organized around a 28 days' uplink cycle for missions that don't require a lot of ground in the loop operations, like seismometers, temperature sensors or magnetometers for instance. Moon operations, much more than Mars operations, rely heavily on the landing site location. Landing near the equator on the near side of the Moon allows continuous and permanent communications, like for the NASA Apollo missions. Many current missions are willing to land on the far side of the Moon, and the scientific interest of the South-Pole Aitken Basin (or SPA) leads those missions toward the south latitudes. Operating on the far side of the Moon requires relay orbiters around the Moon that are mostly not available to this day, even though few are planned in the frame of upcoming Moon missions (NASA's CLPS program funded quite a few of them). A typical operational scheme is to plan a daily uplink cycle for the first 10 days of operation until the lunar night occurs, allowing the teams on the ground to perform payloads check out and commissioning. Then, provided the mission is designed to survive the lunar night and 14 consecutive days of temperatures below -200°C, routine operations can be resumed on a monthly cycle, scheduling 14 days of operations and 14 days of night "idle" state all at once. Most missions won't be able to operate during the lunar night, since maintaining a payload within thermal working conditions require a lot of energy that may not be available on the Moon. Current low cost missions rely on solar panels for the energy and do not embark an RTG.

The current prototype of the MicroLIBS instrument is designed for a Mars environment, and to be mounted on a flying spacecraft like NASA Chopper's hexacopter.

In the frame of such a mission, the MicroLIBS activities would start when the platform is landed and stable on the ground. It can be after a flight, provided enough energy remains available for payload operations, otherwise a full day on Mars can be dedicated to solar panel charging of the platform batteries for instruments operations and the upcoming flight.

Once landed, MicroLIBS will be able to analyse rocks and soils directly below the platform. Current design accommodates distances from 20cm to 50cm, but this optical design can be adjusted to the mission and platform. A 50cm distance is consistent with the reduced energy provided by the LIBS laser due to its miniaturization, where ChemCam and SuperCam could target rocks beyond 5 to 7m. Even though images will be acquired by the helicopter during landing, it is unlikely that those frames will be sufficient to select targets of scientific interest. Hence, MicroLIBS requires a stereo imaging of the MicroLIBS workspace, and the platform shall provide stereo imaging of the instrument workspace area before planning the instrument observations with a resolution better than 5mm for accurate distance estimate.

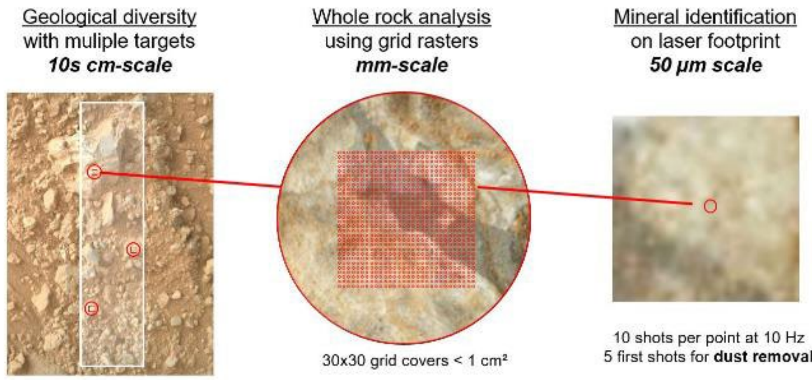

Figure 10 MicroLIBS 10cm to 50µm scale analysis

The choice has been made to not include a stereo imager to the instrument in order to stay within the 1.5kg accommodation. However stereo imaging benches have been developed at CNES in the frame of other missions (like the MMX mission Idefix rover designed and developed by CNES and DLR, the German Space Agency). A miniaturization of this stereo imaging system could be envisioned in case the platform does not have one, and the mass limit is extended beyond 1.5kg.

Mars helicopter operations hence start with a stereo imaging including the MicroLIBS workspace, and then a ground in the loop process once stereo images are sent on earth. Images are analysed by Scientists to validate the target selection (which requires operations delay). There is no plan to include automatic target selection based on AI techniques yet, even though such techniques are already being implemented and used on the Curiosity and Perseverance rovers.

The next day, the target's location is sent to the instrument and the MicroLIBS operations start autonomously, usually performing a raster of laser shots on the selected target. A raster that would match the scientific requirements of MicroLIBS would be a 30x30 grid of 10 shots at 10Hz on each of the 900 points of the grid. After operations, the 9000 LIBS spectra are sent to the platform, along with regular context images of the laser shots and microphone recordings if some have been commanded.

The requirement on the MicroLIBS instrument is to perform those 30x30 grid raster within 1 hour, including the displacement duration between each location. It is foreseen that only one target will be analysed during each sol of operations.

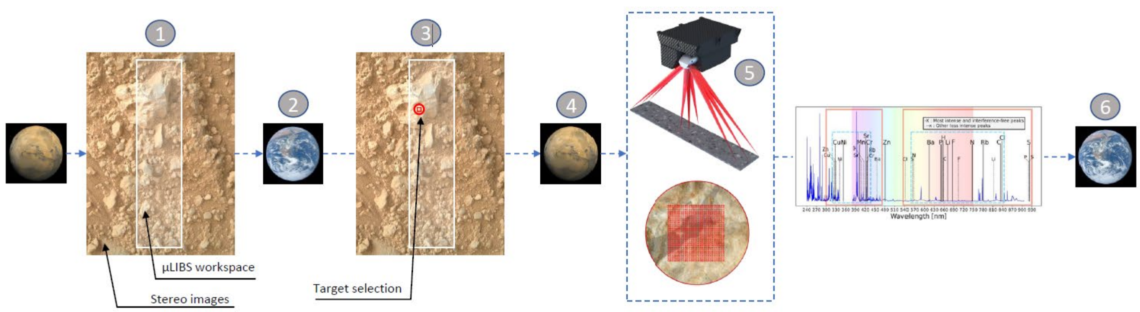

Figure 11MicroLIBS Ops Concept (credit B.Dubois, OMP)

One of the constraints for operating the instrument, maybe more critical on Mars than on the Moon, is the time of day of the activities. Imaging will be performed directly below the platform, potentially affected by shadows. MicroLIBS relies on images taken at different focus to estimate the best position for the LIBS laser shots. A shadowy environment is hence likely to affect the autofocus performances. It is also important to operate at a time of day when the batteries are sufficiently recharged to provide the required energy.

4. MicroLIBS development path forward and perspectives

The goal of the ongoing development is to reach a TRL-6 status at the end of 2026 and phase A completion. 2025 will see the instrument I&T being completed and a functional prototype will be available at the end of this year. The end-to-end performance tests should validate the compliance of the MicroLIBS design with science requirements. The full instrument finite elements analysis (FEA) will be performed to ensure the MicroLIBS design supports the mission environments.

The year 2026 will be dedicated to the TRL upgrade of the instrument, with the use of an STM (Structural and Thermal Model) and the associated mechanical tests, consolidating the FEA analysis completed in 2025.

Initial tests and performance assessment have started and can be performed thanks to all kinds of GSEs before actual hardware can be used and the prototype is fully assembled: sGSE (software-GSE), eGSE (electrical-GSE), mGSE (mechanical-GSE). The optical system, called beam splitter, is the first one the be completed and integrated early 2025. The two scanner subsystems have been delivered and tested at CNES, and a decision will be taken early May 2025 to decide which scanner will be implemented on the current prototype. Note that if both re functional and compliant with the mission requirements, the other system could be implemented later on another prototype, like a lunar lander instrument.

The composite structure, the laser, the spectrometers and the electronics will be delivered, tested and integrated later this year in CNES premises in Toulouse.

Once I&T is completed in 2025, CNES has defined a TRL upgrade strategy to reach an overall TRL-6 status. This strategy is based on generic environments defined by NASA Goddard Space Flight Center, called General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects (see https://standards.nasa.gov/standard/GSFC/GSFC-STD-7000) . Hence since no mission has been formally defined for MicroLIBS yet, one shall estimate a realistic space environment to perform environment testing, especially the thermal environment, very different on the Mars surface and on the Moon surface. CNES plans to develop and use a structural and thermal model (STM) to perform environmental testing, since some subsystems on the prototype will not be able to undergo vibrations or TVAC tests, like the laser that will not be hermetic on the prototype (but will be for a flight model).

The procurement of QM subsystems is foreseen, especially for the laser and the scanner. This will come at a cost, but a lot of time and resources will be saved in case MicroLIBS has a flight opportunity in a near future with a potentially short development schedule. The team has selected the scanner and laser subsystems because they are a key factor of success of the instrument performances, and the scanner lacks a flight heritage from past missions.

With those elements aforementioned, MicroLIBS will be close to TRL6 in 2026, with a strong derisking strategy based on µLIBS tests and SuperCam/ChemCam heritage.

The MicroLIBS design can be adjusted to other missions or other platforms, like rovers for instance. Additional subsystems can also be implemented for an increased science return, like a SWIR camera or an infrared spectrometer, an enhanced microphone for wind measurements (for Mars only), etc.

After 2026, CNES will be looking for flight opportunities for MicroLIBS, and likely be working on a lunar version with a specific periscope pointing system for a rover mounting and a SWIR camera for increased science return.

6. Conclusions

MicroLIBS is set to make a breakthrough contribution to planetary exploration missions, with a low risk (heritage-based), low mass, and low cost with significant improvements in terms of accuracy and rapidity. It built up to the success of its predecessors ChemCam and SuperCam with a similar operational concept, while bringing to the table the capability to provide micro-scale elemental analyses of the surface of planetary bodies.

While 2025 and 2026 will be focused on the development and TRL upgrade of the prototype, the team remains on the lookout for future flight opportunities, on the Moon or on Mars.