Detection Of Light Elements On The Moon Surface Using Combined Techniques

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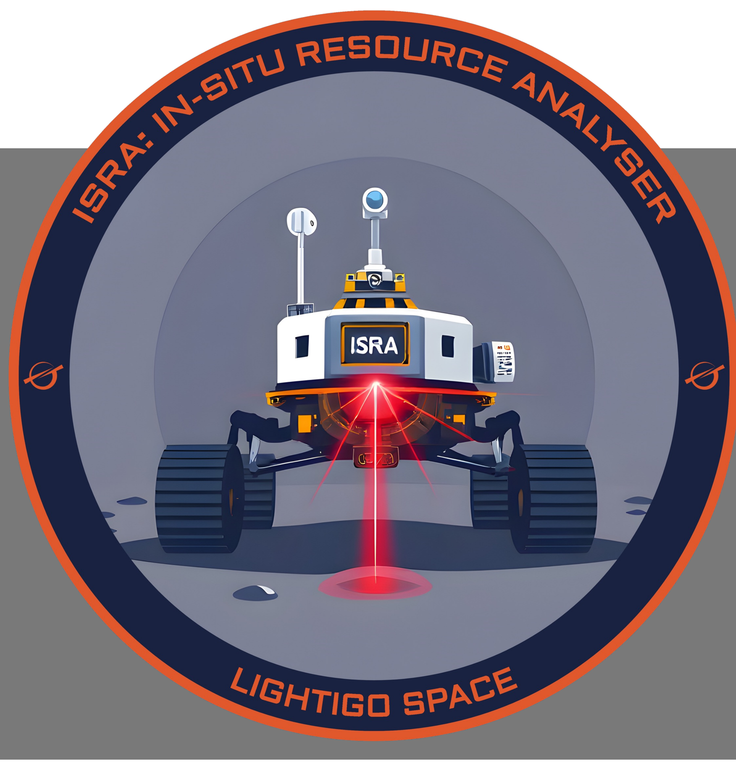


Abstract

As space exploration accelerates, driven by scientific ambition and commercial interest, establishing a sustainable human presence beyond Earth is becoming increasingly viable. A critical step in this process involves the development and study of technologies for In-Situ Resource Utilization (ISRU), which enables the use of local materials on the Moon, Mars, and asteroids. Among these technologies, Laser-Induced Breakdown Spectroscopy (LIBS) has proven valuable for elemental analysis, with successful deployment on both Martian and lunar missions.

Lightigo Space, is developing a compact LIBS-based payload - the In-Situ Resource Analyzer (ISRA) - for rapid geological surveys and resource prospecting on planetary surfaces. Unlike previous LIBS instruments flown to the Moon, ISRA is designed with the hypothesis that Helium isotopes, particularly Helium-3, could be detected in situ. Helium-3 is a highly valuable variable in the context of future fusion energy technologies. Although traces of these elements were found in lunar regolith samples returned by the Apollo missions, Helium-3 has never been detected directly on the Moon using in-situ instrumentation.

The detection poses a considerable challenge due to the element's extremely low abundance and lightweight nature. To address this, the team proposes integrating LIBS with mass spectrometry to improve sensitivity and specificity. Prior to space deployment, laboratory analysis will be conducted under Moon-simulated conditions. Upon successful detection, the next phase will involve building and qualifying the flight hardware.

Results

Leading space industries and companies prioritize Moon and Mars exploration, with scientific instrumen-tation playing a crucial role in the preparation phase. Advanced analytical tools will be essential for characterizing and utilizing planetary resources, paving the way for a sustainable lunar presence.

Detecting the full spectrum of elements on the Moon requires leveraging the strengths of different instruments and optimizing their combined use. The challenge of detecting light elements - such as **helium, hydrogen, oxygen, carbon, nitrogen, sodium, and potassium** - can be addressed through laser-ablation-based techniques, including **Laser-Induced Breakdown Spectroscopy (LIBS) and Laser Ablation Mass Spectrometry (LAMS)**.

Traditional LIBS analyzes laser-induced plasma radiation to detect individual elements, while LAMS takes advantage of the lunar vacuum to enable direct mass spectrometry, allowing for speciation and isotopic analysis (e.g., distinguishing helium isotopes).

Detection requirements: Scientific and commercial lunar exploration missions have differing requirements for element detection. Depending on the mission's objectives, it may sometimes be sufficient to detect the presence of an element and quantify its abundance. In other cases, distinguishing between isotopes is crucial.

Commercial missions focused on regolith beneficiation primarily target the detection of hydrogen and oxygen. In contrast, scientific missions often require isotope differentiation, such as measuring the deuterium-to-protium ratio to understand the its origins. Certain commercial applications may also necessitate isotope identification - for example, in helium-3 detection, where merely confirming the presence of helium is insufficient.

Methodology

Methodology: Laser-Induced Breakdown Spectros-copy (LIBS) is widely recognized for its advantages across multiple industries and applications on Earth. It has also been successfully deployed in space, including on the surfaces of the Moon and Mars.

LIBS addresses the challenge of in-situ geological surveys of celestial bodies by providing detailed elemental composition analysis. It is particularly effective in detecting light elements [1]. As a remote sensing technique, LIBS enables elemental analysis with minimal sample preparation, making it an ideal choice for space exploration.

Laboratory studies have demonstrated the capability of LIBS to detect hydrogen isotopes. However, measurements conducted under vacuum conditions, simulating the lunar environment (Figure 1), indicate that while LIBS can detect elemental presence, it does not provide a detailed break-down of isotopic composition.

The primary factor reducing sensitivity and resolution is the vacuum environment and the way plasma expands within it. However, this effect can be leveraged by integrating mass spectrometry to enhance isotope recognition precision.

In low-pressure conditions, laser ablation produces rapidly expanding particles, allowing them to reach the detector at sufficient velocity for Orbitrap system analysis. Distinguishing helium-3 from helium-4 is particularly challenging due to their minimal mass difference, requiring highly sensitive techniques. Currently, Time-of-Flight Mass Spectrometry (TOF-MS) and Resonance Ionization Mass Spectrometry (RIMS) are being explored for light element detection. Both methods utilize an ionization source - such as laser ablation, which is also a fundamental component of LIBS instruments.

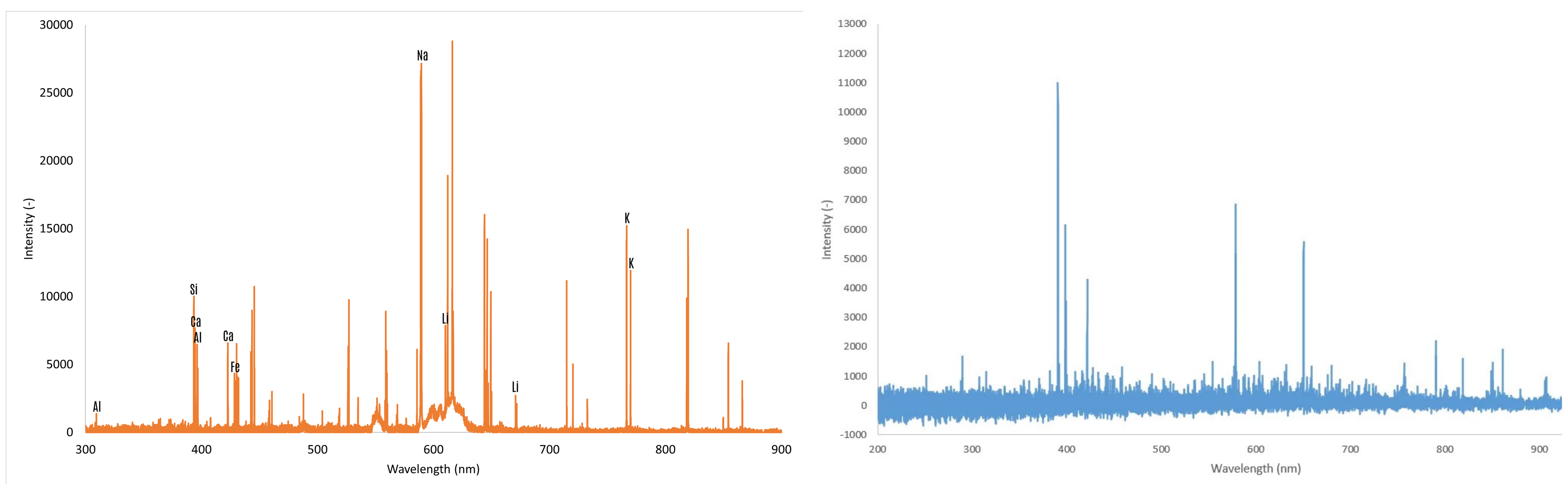
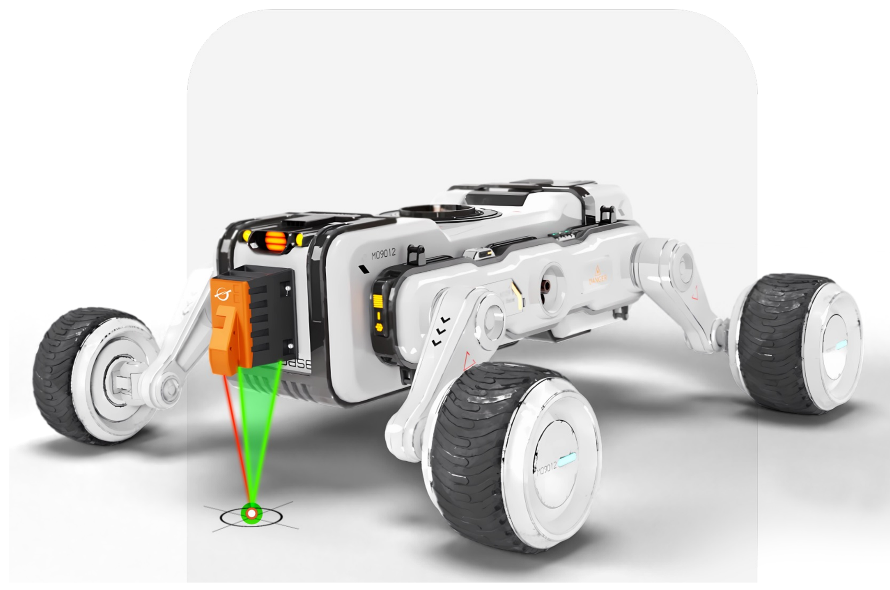


Fig.1: Comparisons of spectra under terrestrial and lunar conditions



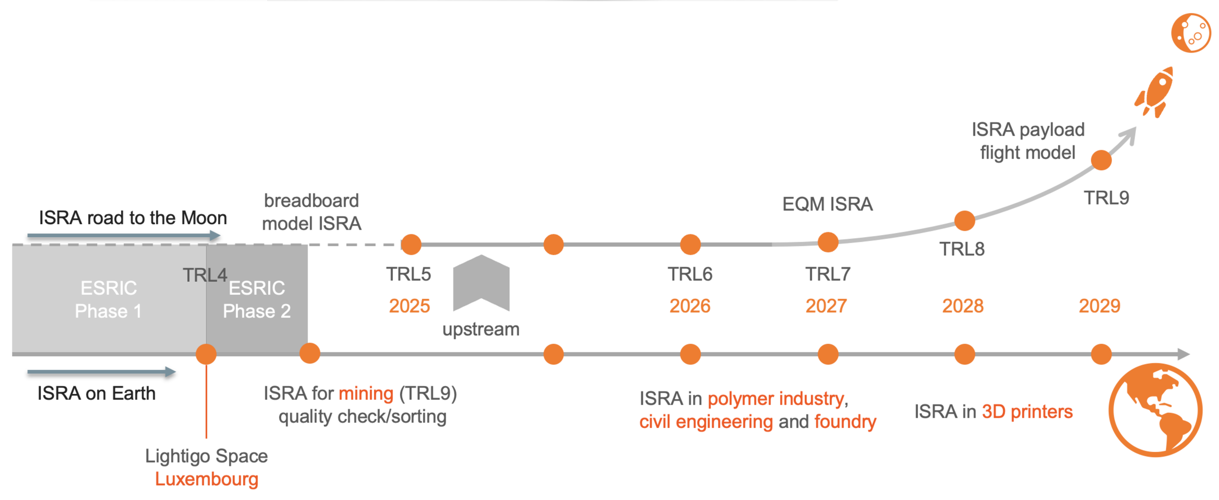


Fig.2: ISRA visualization and development timeline

Instrumentation set up

Selected Laser Parameters	
Pulse Energy	30 mJ
Pulse Duration	(10÷25) ns
Laser Wavelength	1064 nm
Selected Spectrometer Parameters	
Spectral Range	(270÷900) nm
Targeted ISRA Parameters	
Maximum Dimensions	(250×250×250) mm^3
Maximum Mass	<5 kg
Maximum Power Consumption	<5 W

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Conclusion

Introducing an instrument with a single laser source for ionization and dual outputs to expand the spectral range and enhance detection sensitivity for selected elements offers significant benefits for In-Situ Resource Utilization (ISRU) missions. Optimizing instrument performance to balance high data quality with cost efficiency focuses on reducing mass, power consumption, and development time. A comparison of commercial lunar exploration vehicles provides preliminary design requirements, enabling the development of a plug-and-play solution for commercial availability.

References

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