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MIRORES: MIR/FIR Space Spectrometers for Lunar and Terrestrial Geological Prospecting

Abstract: MIRORES is a compact mid-infrared (MIR) to far-infrared (FIR) spectrometer designed for geological prospecting on the Moon and Earth. It covers the 6–20 μm range (optionally extending to $\sim 45 \mu\text{m}$) at $\sim 0.5 \mu\text{m}$ spectral resolution, enabling detection of mineral signatures (e.g., phosphates, oxides) not observable with visible/near-infrared sensors. A 256×320 focal plane array (with 16 narrowband channels of 20 rows each) and two additional detectors for apatite and ilmenite, paired with a lightweight optical system, delivers robust performance in both lunar and terrestrial applications. Field trials and integration plans demonstrate technical readiness and strategic alignment with space resource initiatives.

Keywords: Infrared Spectroscopy; Remote Sensing; Ore geology; Space Resources

Introduction

Advances in mid-infrared remote sensing are opening new frontiers for mineral exploration on planetary surfaces. The 6–45 μm wavelength range contains diagnostic vibrational bands of water ice and many minerals (oxides, sulfides, and phosphates) that are not detectable in the visible-to-short-wave infrared (VNIR/SWIR) spectrum used by most previous missions. For example, the lunar mineral apatite (a calcium phosphate) has a strong absorption band near 17–18 μm , and ilmenite (an iron-titanium oxide) shows a band around 19 μm . These signatures lie beyond the reach of instruments such as NASA's Moon Mineralogy Mapper (which operated at $< 3 \mu\text{m}$). They are only partially covered by the Lunar Reconnaissance Orbiter's Diviner radiometer, which has three of its four IR channels clustered near 8 μm [1].

As a result, critical resources such as phosphorus and rare-earth elements in apatite, and oxygen and helium-3 in ilmenite, remain challenging to prospect with traditional VNIR/SWIR sensors. MIRORES has been selected as the primary science payload for an upcoming lunar orbiter mission (the Lunar Mineralogy Mapper, under development by ESA) scheduled for launch in 2029. This mission will mark the first deployment of a far-infrared spectrometer around the Moon, and MIRORES will thus become a pathfinder for lunar resource mapping from space.

The MIRORES (Mid-/Far-Infrared ORE Spectrometer) instrument is conceived to fill this gap. Developed initially to detect sulfide ores on Mars in the 20–30 μm FIR range, MIRORES has been re-engineered to focus on the 6–20 μm MIR region (with extension to $\sim 45 \mu\text{m}$) that addresses high-priority lunar resources while maintaining compact size and feasibility. This shift leverages the fact that apatite and ilmenite can be identified within ~ 6 –20 μm , so extending beyond 20 μm is not essential for those goals. By narrowing the spectral scope, MIRORES achieves higher spectral resolution across the key 6–14 μm window, enabling unambiguous mineral identification against silicate backgrounds. Few spaceborne instruments have explored this MIR region for airless bodies, due in part to Earth's atmospheric opacity below $\sim 8 \mu\text{m}$ [1]. Notably, the Japanese Himawari-8 weather satellite's Advanced Himawari Imager (AHI) sensor recently demonstrated the value of 6–14 μm lunar observations [1], validating that mid-IR spectral data can reveal surface composition differences consistent with Diviner's findings [2, 3]. Likewise, NASA's SOFIA airborne telescope detected molecular water on the sunlit Moon at 6 μm [4], a feat impossible with ground-based observatories due to atmospheric absorption. These advances underscore the scientific and exploration potential of a dedicated MIR spectrometer.

MIRORES is designed to capitalize on this potential in both the lunar context and terrestrial applications. The instrument pairs a tailored spectral range with a high-sensitivity detector and miniaturized optics to serve dual roles: flying on lunar missions to map resource-bearing minerals, and operating on drones on Earth to survey mining targets. In the next sections, we detail MIRORES's dual use as a lunar instrument and for Earth applications. These two sections are followed by the engineering design, results from initial field tests, and the path toward deployment in the space resources economy.

Lunar and Terrestrial Use Cases

The current impetus for MIRORES stems from objectives in lunar resource prospecting. Global space agencies have highlighted the need to locate and quantify in-situ resources on the Moon, water ice, oxygen-bearing minerals, metals, and other volatiles, as a foundation for a sustainable space economy in the Earth–Moon system (the so-called cislunar economy) [5]. In fact, the European Space Agency's Space Resources Strategy calls for "measurements at the Moon" by 2030 to establish the potential of lunar materials and inform their use in exploration architectures [6]. Among these materials, lunar apatite and ilmenite are particularly important. Apatite ($\text{Ca}_5(\text{PO}_4)_3\text{F/Cl/OH}$) not only contains phosphorus, which is critical for fertilizers, but can also host hydroxyl or water in its structure.

Furthermore, it tends to concentrate rare-earth elements. Ilmenite (FeTiO_3) is valued as a source of iron and titanium, and, importantly, it can yield oxygen and helium-3 via chemical processing, making it a key regolith constituent for future ISRU (in-situ resource utilization) oxygen and helium-3 production. In 2025, Interlune announced a first-of-its-kind agreement with the U.S. Department of Energy Isotope Program to purchase 3 L of lunar-derived helium-3 by 2029, and a parallel industrial contract under which Bluefors may buy up to 10,000 L of helium-3 annually between 2028 and 2037, indicating the emergence of an early commercial market for this isotope (interlune.space). Identifying rich deposits of these minerals on the Moon would directly support plans for crewed lunar bases and fuel

generation. However, traditional orbital imagers such as the Moon Mineralogy Mapper (M3), which operate in the 0.4–3 μm range, or even thermal mappers like Diviner (~7.5–23 μm) have limited capability to pinpoint apatite or ilmenite. These minerals' distinctive vibrational bands either lie outside the range measured so far or fall into coarse, overlapping channels [1]. Therefore, a specialized spectrometer, such as MIRORES, is needed to map these resources with confidence.

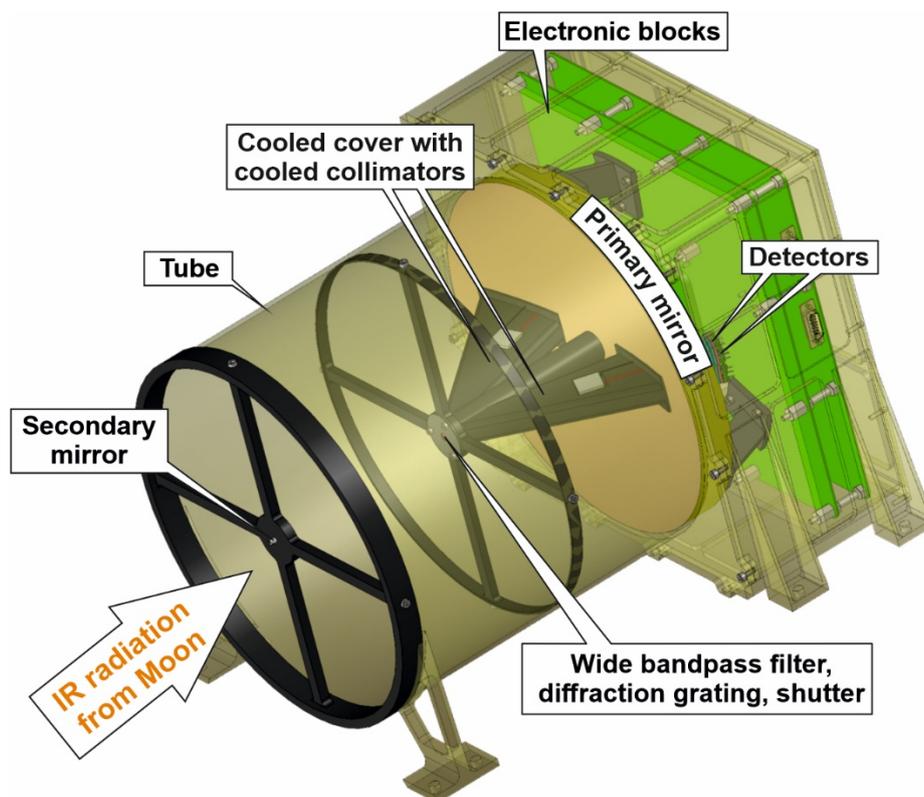
Although MIRORES originated as a lunar-focused project, it was conceived with Earth applications in mind as well. The spectrometer's wavelength coverage overlaps an atmospheric window (~8–14 μm) that is exceptionally useful for geological remote sensing on Earth [7]. In this thermal infrared region, emitted radiance from rocks carries mineral-specific signatures that can complement reflected-light (VNIR/SWIR) spectroscopy [8]. For instance, quartz-rich rocks, carbonates, clay minerals, and sulfates each exhibit unique reststrahlen bands or Christiansen features in the 8–14 μm range. Reststrahlen bands arise from strong fundamental vibrational absorptions (e.g., in Si–O or C–O bonds). Christiansen features correspond to local emissivity minima near wavelengths at which the real part of the material's refractive index approaches that of the surrounding medium [7,8]. These characteristics enable lithologic mapping that is difficult to achieve at shorter wavelengths [1]. Airborne and satellite sensors (e.g., NASA's ASTER and HyTES instruments) have exploited this window to map Earth's surface mineralogy, taking advantage of high transmission in the 8–12 μm interval [7]. However, absorption by atmospheric water vapor severely hinders observations in the 6–8 μm spectral region from the ground or orbit [1]. Here, a MIRORES unit, deployed on a low-flying drone or on site, could directly measure the 6–20 μm spectra of rocks with minimal atmospheric interference. Using drones opens up opportunities for mineral exploration in remote regions: a UAV-mounted MIRORES could scan for phosphate ore bodies (apatite-rich) or titaniferous sands (ilmenite-rich), both of which are of growing economic interest. The International Energy Agency projects a threefold to sevenfold increase in rare-earth element demand by 2040 due to clean energy technologies [9], and a parallel surge in demand for battery and photovoltaic minerals [9]. Developing portable MIR spectrometers for rapid reconnaissance of such critical minerals can help meet this demand. In essence, the same spectral tool that surveys lunar highlands for resources could survey arid terrain on Earth for new mineral deposits. A direct technology transfer from space exploration to terrestrial industry is therefore made. Future missions to the Moon are also viewed as both a testbed for sustainable exploration and a driver of economic benefits on Earth through knowledge of the Moon's resources [5]. MIRORES fits into this vision by providing a tangible, dual-use capability: a spectrometer that will serve lunar missions and subsequently the mining and geoscience sectors on Earth.

Spectral Engineering: Compact and Capable

Designing an imaging spectrometer for mid- to far-IR geological prospecting poses challenges in sensitivity, resolution, and size. MIRORES addresses these with a purpose-built detector matrix and optical layout that balance performance with compactness. At its core, there will be a two-dimensional 256 \times 320-pixel focal plane array (FPA), composed of two matrices, each 256 \times 160 pixels. These two mercury-cadmium-telluride (HgCdTe) matrices are cryogenically cooled and optimized for the 6–10 μm and 10–14 μm wavebands, respectively, offering high specific detectivity ($D^* \geq 10^{10}$ Jones). MIRORES leverages the 2D arrays by dividing them into spectral sub-arrays: the 160-pixel-high dimension in both matrices (320-pixel-high altogether) is conceptually segmented into 16 strips of 20 lines each, enabling the capture of 16 distinct wavelength bands. In practice, this multiplexing is achieved using discrete interference filters that spread different portions of the spectrum across designated detector rows. MIRORES's implementation dedicates ~20 detector rows per spectral channel

to ensure sufficient signal integration. Therefore, the instrument can simultaneously measure at least 16 narrow bands across a 6–14 μm range without moving parts, a significant advantage for mapping specific mineral fingerprints. The spectral resolution is $\sim 0.5 \mu\text{m}$. To resolve adjacent features such as the 17.5 μm vs. 19 μm bands, the design includes a diffraction grating that directs those wavelengths to pyroelectric detectors, bringing the total number of spectral channels to 18.

MIRORES uses a two-mirror Cassegrain telescope design that is folded into a small volume. In the original Mars-oriented design, the primary mirror diameter and focal length were chosen to achieve $\sim 10\text{--}20 \text{ m/pixel}$ ground resolution from orbit [10]. For the lunar mapping scenario, the requirements have been relaxed to a spatial sampling of $\sim 100 \text{ m/pixel}$ (since the focus is on identifying large-scale resource-rich areas). This relaxation allows a wider $\sim 10^\circ$ field of view without increasing the optics size (consistent with ESA constraints) or requiring significant changes to the telescope or cooling design. The primary mirror is 30 cm in diameter (sufficient to collect mid- to far-IR light over the FOV), and the entire instrument mass is under 10 kg (Fig. 1), fitting within a microsatellite form factor [11]. Half of the light from the telescope's secondary mirror passes through an aperture directly to the filter system, which partitions the spectrum into designated detector segments. An additional diffraction grating for the other half of the light diffracts the 17.5- and 19- μm wavelengths to the pyroelectric detectors for apatite and ilmenite. The same diffraction grating can also serve to diffract light to optional detectors for sulfides with spectral features between 24 and 39 μm [10, 11] and for water ice around 43 μm [12], for adopted versions of the MIRORES spectrometer for sulfide prospecting on Earth or water ice prospecting on the Moon. In any case, a longwave-pass filter will be used to cut off wavelengths below 6 μm and ensure temperature-invariant performance in the MIR/FIR.



1. Scheme of the MIRORES Moon instrument (30 cm diameter). Redrawn from [12]

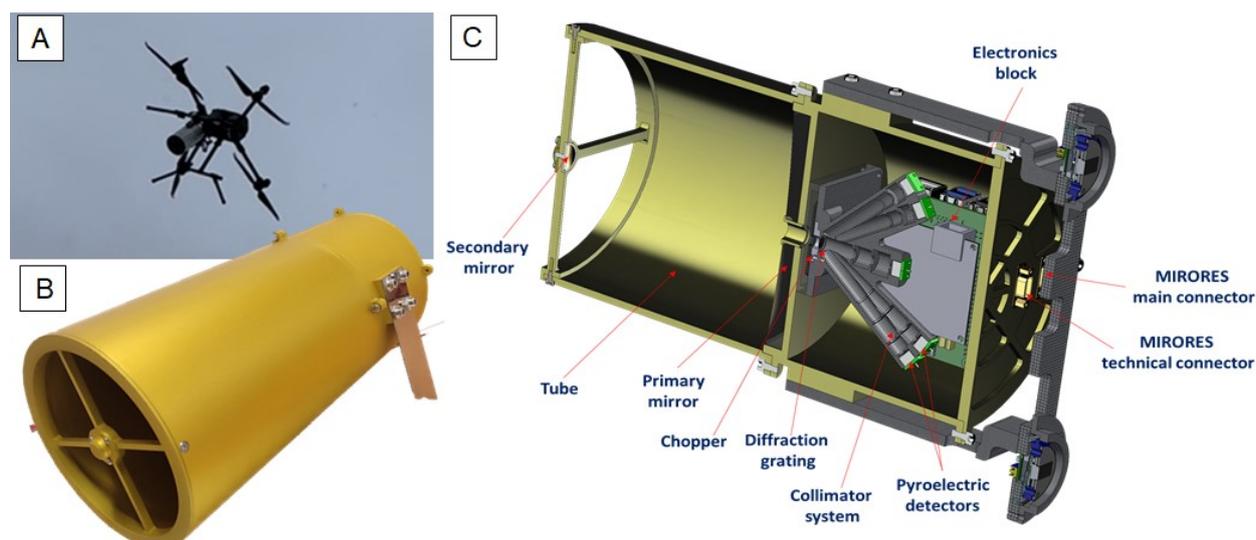
Thermal control is vital for a mid- to far-infrared instrument. A miniature cryocooler (e.g., TC2570) will cool MIRORES's space-based detectors to maintain the required low temperature for low noise. The optics will be thermally stabilized near 0 °C to prevent mechanical deformations. In contrast, the semiconductor detectors must be cooled to 50–100 K, and the space between the diffraction grating and the detectors is maintained at about 190 K. In the current design, modern cooled photonic detectors (HgCdTe) offer far superior sensitivity, so they have been adopted despite the need for cryogenic cooling. The electronics incorporate integrated amplifiers for each detector channel and a multi-channel readout to handle the 81,920 pixels (256×320) at video rates. Data can be processed on board to convert the raw signals into calibrated spectral radiance for each band. The spectral calibration uses reference observations and known blackbody sources; radiometric accuracy better than 5% is targeted, in line with mission requirements.

Field Trials and Terrestrial Integration

To bridge the gap between design and deployment, MIRORES is undergoing stepwise testing under laboratory and field conditions. Initial validation has focused on its core function: distinguishing target mineral signatures in mixed scenes. In the laboratory, powdered mineral samples (e.g., apatite, ilmenite, pyrite) are analyzed with various IR spectrometers to generate reference spectra and simulate MIRORES's band responses. Simulations based on these measurements confirmed that ilmenite and pyrite bands can be detected even when these minerals constitute as little as ~10% of a powdered mixture with silicates, given MIRORES's spectral resolution and signal-to-noise [10, 11]. Such studies increase confidence that the instrument will detect ore minerals against a regolith background [10, 11]. Finally, a MIRORES prototype is used to acquire mid-far-infrared spectra of the same samples, confirming that the diagnostic bands identified in the simulations are observable with the instrument itself.

In parallel with static tests, the team has begun integrating MIRORES onto a drone (Fig. 2A). The low mass (<3 kg) and power consumption (10 W) of MIRORES make it feasible to fly on a medium-sized drone, such as a DJI Matrice 350, for surveys of tens of hectares. MIRORES can fly over rock outcrops and open-pit mines containing various ore minerals. An autonomous scanning mode is envisioned in which the drone sweeps the spectrometer's field of view over a grid, producing an absorption spectral map. Although atmospheric conditions influence mid- to far-infrared sensing from an airborne platform, flights at low altitude (50–100 m) in dry conditions can minimize absorption by water vapor. Furthermore, bands beyond ~12 μm (e.g., 17–20 μm) can be partially corrected using the drone's onboard atmospheric humidity sensors. MIRORES is also being adapted for stationary deployments (e.g., scanning ore on conveyor belts in mines) or even as a handheld mineral analyzer (Fig. 2B and 2C).

Results from ongoing tests are guiding final engineering tweaks. For example, if strong ground vibrations are found to affect the detector, additional damping mounts can be implemented. The following steps will involve increasing the prototype's autonomy and robustness. A fully self-contained unit (with onboard calibration sources and data processing) is in development for longer-term field deployment, potentially in mines or at exploration sites. By demonstrating operations outside the lab, the MIRORES team is lowering risk for eventual use in space and building credibility for use in terrestrial industries.



2. A) The MIRORES spectrometer adapted for drone mounting (13 cm aperture). **(B)** A 15 cm-diameter MIRORES unit designed for use over conveyor belts or as a handheld device. **(C)** Technical schematic of the same 15 cm unit for industrial/handheld use.

Tab. 1. Key parameters of the MIRORES spectrometer in the lunar and UAV configurations.

Parameter	Value	Configuration / notes
<i>Lunar configuration</i>		
Spectral range (nominal)	6–20 μm (MIR), with option to extend to $\sim 45 \mu\text{m}$	Continuous 6–14 μm on FPA; design optimised for MIR
Spectral resolution	$\sim 0.5 \mu\text{m}$	For the narrowband channels on the focal plane array
Number of spectral channels	≥ 16 narrow bands on FPA + 2 discrete bands (17.5, 19 μm)	16 interference-filter channels + pyroelectric apatite/ilmenite detectors
Detector array	256 \times 320 pixels (2 \times 256 \times 160 HgCdTe matrices)	Optimised for 6–10 μm and 10–14 μm ; $D^* \geq 10^{10}$ Jones
Telescope	2-mirror Cassegrain, 30 cm primary mirror	Folded layout; fits within a microsatellite form factor
Field of view	$\sim 10^\circ$	For relaxed spatial sampling in lunar-orbit configuration
Spatial sampling (lunar orbit)	$\sim 100 \text{ m/pixel}$	Designed for resource-scale lunar mapping
Instrument mass	$< 10 \text{ kg}$	Complete spaceborne instrument (excluding spacecraft bus)
Detector/optics temperatures	Detectors 50–100 K; grating–detector space $\sim 190 \text{ K}$; optics $\sim 0^\circ \text{C}$	Achieved with miniature cryocooler and thermal stabilisation
Radiometric performance	Radiometric accuracy better than 5 %	On-board calibration with reference/blackbody measurements
<i>UAV configuration</i>		
Mass	$< 3 \text{ kg}$	Drone-mounted MIRORES unit
Power consumption	$\sim 10 \text{ W}$	Compatible with medium-size UAVs (e.g. DJI Matrice 350)
Typical survey geometry	Flight altitude 50–100 m; coverage of tens of hectares	Low altitude to minimise atmospheric absorption

Future Outlook and Strategic Vision

MIRORES is on a fast-track trajectory from concept to deployment thanks to its alignment with current exploration initiatives. The instrument has been selected as a baseline payload in a Phase A study for a prospective lunar mission, where its ~6–20 μm MIR capability fills a noted gap in the mission's science requirements. Under this ESA-sponsored Phase A of High-Resolution Lunar Mineralogy Mapper, the team is refining MIRORES's flight design to ensure that the field of view, spectral resolution, and other parameters meet the spacecraft's constraints. Over the next 1–2 years, the team aims to raise the space instrument's technology readiness level (TRL) from the current ~5 (component validation in the lab) to TRL 7–8 by building an engineering-qualified model and a flight model. These models would undergo thermal-vacuum testing, vibration testing, and radiometric calibration to simulate conditions on a lunar orbiter. The goal is to have MIRORES mission-ready by 2028 and launched by 2029.

In parallel, the strategic vision extends to commercial and scientific utilization on Earth. The push for a sustainable space economy has highlighted how technologies developed for exploration can spur terrestrial innovation [6]. MIRORES exemplifies this dual-use paradigm. As space agencies and companies invest in lunar prospecting, the same sensor can be offered to mining companies or geological surveyors on Earth as a rapid mineral-mapping tool. We foresee a service model in which MIRORES instruments are deployed (on drones or fixed platforms) to scan areas of interest identified from satellite imagery, providing high-fidelity mineralogical maps that guide drilling or extraction. Such an approach will reduce the cost and time of exploration campaigns by pinpointing ore-rich zones through remote sensing rather than extensive sampling. Early discussions with industry partners have focused on integrating MIRORES data into existing exploration workflows, for instance, using its hyperspectral thermal imagery alongside conventional airborne surveys. By keeping the instrument design modular, we can tailor it to different platforms: a vacuum-rated version for spacecraft, and an atmospheric version (with protective enclosure and cooling) for terrestrial use.

Importantly, MIRORES's emergence comes at a time when demand for critical minerals is surging. The International Energy Agency (IEA) reported in 2023 that global demand for rare-earth elements could grow 300–700% by 2040 under clean energy scenarios [9]. Elements such as phosphorus (for agriculture) and metals such as copper, nickel, and cobalt are also set to see exponential demand growth [9]. Meeting this demand sustainably will require not only mining new deposits on Earth but also, in the longer term, sourcing materials off-world. MIRORES contributes on both fronts: enabling more efficient discovery of Earth's remaining resources and characterizing extraterrestrial resources that could be a cornerstone for lunar exploration. The instrument thus aligns with a broad strategic vision shared by space agencies and industry, one in which resource mapping and utilization form a bridge between space exploration and Earth's economic needs [5].

In the space sector, MIRORES is positioned to contribute to upcoming missions focused on lunar geology, especially as either a primary or a secondary payload on small-satellite missions orbiting the Moon. Given its low mass and power, MIRORES could also be considered for missions to asteroids or Mars. In summary, MIRORES represents a new class of MIR/FIR spectrometers that marries technical innovation with strategic relevance to resource exploration. It advances scientific goals by filling the MIR/FIR observational gap and identifying minerals crucial to planetary science and in-situ resource utilization. At the same time, it answers a commercial call for improved mineral-sensing tools on Earth, at a moment when resource security is paramount. As humanity expands its reach to the Moon and beyond, instruments like MIRORES will be our "eyes" in wavelengths long-overlooked,

guiding us to the materials that will fuel both space exploration and sustainable development on Earth.

Conclusions

MIRORES is a compact mid- to far-infrared spectrometer designed to fill the 6–20 μm observational gap for resource-bearing minerals on the Moon while simultaneously supporting mineral exploration on Earth. This dual-use space technology exemplifies cross-sector innovation: techniques developed for lunar exploration can directly enhance terrestrial mineral exploration and resource management. From a national perspective, MIRORES presents a niche opportunity for Poland in the space sector, capitalizing on domestic expertise in designing optoelectronic systems that operate reliably under high radiation levels, at very low temperatures, and in the absence of atmospheric water vapor. By combining tailored spectral coverage, high-sensitivity cooled detectors, and a compact folded optical design, MIRORES enables the detection of key ore minerals such as apatite and ilmenite from lunar orbit, UAV platforms, and fixed industrial installations. The planned maturation of the spaceborne instrument for a lunar mission, together with ongoing field trials and terrestrial integrations, indicates that MIRORES can serve as a technological bridge between space-resource prospecting and more efficient, data-driven exploration workflows in the mining and geoscience sectors.

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