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The MicrOmega Investigation Onboard ExoMars

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Abstract

MicrOmega is a visible near-infrared hyperspectral microscope that is designed to characterize the texture and composition of martian samples presented to the instrument within the ExoMars rover's analytical laboratory drawer. The spectral range (0.5–3.65 μm) and the spectral sampling (20 cm^{-1} from 0.95 to 3.65 μm) of MicrOmega have been chosen to allow the identification of most constituent minerals, ices/frosts, and organics with astrobiological relevance within each $20 \times 20\ \mu m^2$ pixel over a $5 \times 5\ mm^2$ field of view. Such an unprecedented characterization will enable (1) identification of most major and minor phases, including the potential organics; (2) ascription of their mineralogical context, as a critical set of clues with which to decipher their formation process; and (3) location of specific grains or regions of interest in the samples, which will be further analyzed by Raman Laser Spectrometer and/or Mars Organic Molecule Analyzer. Key Words: Spectroscopy—Microscopy—Composition—Organics—Mineralogy. Astrobiology 17, 621–626.

1. Introduction and Science Objectives

As a follow-on of its Mars Express orbital mission, ESA is developing the ExoMars mission, with the overarching goal to search for and characterize potential life-hosting habitats and traces of past or present life (Vago *et al.*, 2017). This mission includes the characterization of the geological context and the environment at the time that living structures might have formed, from a macroscopic down to a microscopic scale. It also aims at identifying structures, minerals, and molecules and at recording the processes that have contributed to the formation and the post-formational alteration of the materials studied. This will be carried out, in part, by investigations that are implemented onboard a rover capable of acquiring samples to a depth of 2 m and subsequent analysis in a dedicated laboratory (analytical laboratory drawer—ALD) in which three instruments will operate sequentially: a visible near-infrared hyperspectral microscope (MicrOmega), a Raman spectrometer (Raman Laser Spectrometer—RLS; Rull *et al.*, 2017), and an Organic Analyzer (Mars Organic Molecule Analyzer—MOMA; Goesmann *et al.*, 2017). In this study, we describe the goals, functionalities, and performance capabilities of MicrOmega.

The prime objective of the MicrOmega investigation is to characterize, down to the microscopic scale, the structure and mineralogical/molecular composition of samples collected by the ExoMars rover drill. The samples will be distributed by the Sample Preparation and Distribution System (SPDS) and presented for analysis in a refillable container within the ExoMars ALD. A specific goal is to determine the nature and potential ''habitable'' properties of the soil and rocks investigated. These investigations will be performed in a truly nondestructive way to enable further analysis of the same samples with the RLS and MOMA to complement our characterization.

The MicrOmega science objectives can, thus, be summarized as follows:

1. Identification of rock-forming minerals to help determine the origin of the samples,
2. Identification of alteration products, including water-related minerals,
3. Characterization of potential organics,
4. Characterization of the morphology of the samples, all down to mineral grain scale.

The MicrOmega investigation is designed to contribute to determination of the climatic and geological evolution of Mars through the characterization of rocks and minerals at a microscopic scale. For each sample imaged, MicrOmega will simultaneously identify the following:

- The interrelation between the grains at a spatial sampling of 20 μm;
- The mineral composition: silicates, oxides, hydrated minerals, organics, and ices in each pixel (20 μm large);
- Within each mineral family (*e.g.*, phyllosilicates), the specific member (*e.g.*, nontronite, kaolinite, etc.) and/or compounds;
- The size and abundance distribution of the different minerals.

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Table 1. Major Absorption Bands of Minerals and Organics That Could Be Identified by MicrOmega

Wavelength range	*Band width*	*Minerals*	*Assignment*
0.95–2.30 μm	>50 nm	Iron (ferrous and ferric) oxides; pyroxenes; olivines, Fe-bearing plagioclases	Electronic processes (Crystal Feature Absorption)
1.3–3.65 μm	10–50 nm	Phyllosilicates; Hydroxides; Amphiboles, Hydrated aluminosilica, and glass; AmpZeolites; Carbonates; Sulfates; Chlorides; Nitrates; Phosphates; Perchlorates	Combination and overtones of fundamental O-H, X-OH ($X = Al^{3+}$, Fe^{3+}, Fe^{2+}, Mg^{2+}, Si), C-O, Si-O, N-O, P-O
2.7–3.65 μm	10–50 nm	Adsorbed/confined water, Hydroxyl	Fundamental and overtones of OH & H_2O
		Organics and their assignments	
2.80–3.0 μm	>40 nm	First overtone of carbonyl C═O	
2.94–3.12 μm	>50 nm	N-H and NH_2 group (stretch and first overtone of N-H bend)	
~3.0 μm	>20 nm	Alkyne≡C–H stretch	
3.27–3.29 μm	>20 nm	Aromatic CH stretch	
3.38–3.39; 3.41–3.42 μm	>20 nm	Aliphatic CH_3; CH_2 asymmetric stretch	
~3.45 μm	>20 nm	CH_2 Fermi resonance	
3.38–3.50 μm	>20 nm	Aliphatic CH_3 asymmetric stretch	

Each mineral family requires, and thus records, a specific formation process: For example, phyllosilicates likely result from the aqueous alteration of magmatic rocks. The degree of leaching is imprinted in cation abundances, such as the Al/Mg ratio (with kaolinite, the Al pure endmember, the higher degree).

2. Instrument Description

The proposed concept and procedures were implemented with the intent to characterize the mineralogical/molecular composition of processed samples with an infrared hyperspectral microscopic imager. This imager has the capability to acquire, from each resolved pixel 20 μm in size over a 250×256 pixels field of view (FOV) (~5×5 mm^2), the spectrum in the near-infrared wavelength range (0.95–3.65 μm) as enabled by the use of an acousto-optical tuneable filter (AOTF) and its associated detector with a high spectral sampling of 20 cm^{-1} (2–14 nm) as well as a few images at wavelengths between 0.5 and 0.9 μm (illuminated with LEDs (light emitting diodes), at wavelengths 595, 643, 770, and 885 nm). The spectral range and sampling were selected to enable the identification of major diagnostic species, as summarized in Table 1, by using, in particular, measurements made by Hunt (1977), Clark *et al.* (1990), Bishop *et al.* (1995), Bishop *et al.* (1998), Bishop (2008), and Clark *et al.* (2009). The MicrOmega instrument onboard the MASCOT/Hayabusa 2 mission is based on the same concept (Bibring *et al.*, 2017).

2.1. Design overview

MicrOmega will characterize the texture and composition of samples at their grain scale through the acquisition of 3D (x, y, λ) hyperspectral microscopic image cubes. These image cubes will be built by sequentially illuminating the samples with monochromatic light of a different wavelength. The MicrOmega block diagram and the MicrOmega Engineering Qualification Model (EQM) unit before its being covered with the electronic boxes are illustrated in Figures 1 and 2, respectively.

This illuminating system is made of a bright white lamp and a dispersive system based on an AOTF. For a given frequency (RF [radio frequency]) of the acoustic signal, the AOTF output light beam has a specific wavelength. The sample, illuminated by this (monochromatic) light, is imaged onto a 2D HgCdTe detector array, cooled by a dedicated cryocooler. By stepwise scanning of the RF frequency, the sample is sequentially illuminated over the spectral domain, chosen to cover 0.95 μm up to 3.65 μm.

The samples will be distributed by a dedicated mechanism (SPDS) to a ''refillable container,'' inside the UCZ (Ultra Clean Zone), with a top surface (after proper ''flattening'' with a blade) accurately positioned at a known distance from the instrument. The samples will be imaged through a visible and near-infrared transparent window. A fraction of the FOV will be masked by a calibration target to obtain a radiometric reference in a small part of each monochromatic image.

Typical parameters, based on the MicrOmega EQM unit, are given in Table 2.

2.2. Overview of key subsystems

2.2.1. Illumination unit. The monochromatic illumination system is based on an AOTF that operates as a

Table 2. Main Characteristics of the MicrOmega/ExoMars Instrument

Dimensions	*170×160×105 mm^3*
Mass	<2.4 kg
Spectral range	0.5–3.65 μm
Typical spectral sampling	20 cm^{-1} (2 nm at 1.0 μm, 25 nm at 3.6 μm)
FOV	5×5 mm^2
Spatial sampling	20 μm
Temperature for operations	(−40, +40°C)
Temperature for non-operations	(−50, +50°C)

FOV, field of view.

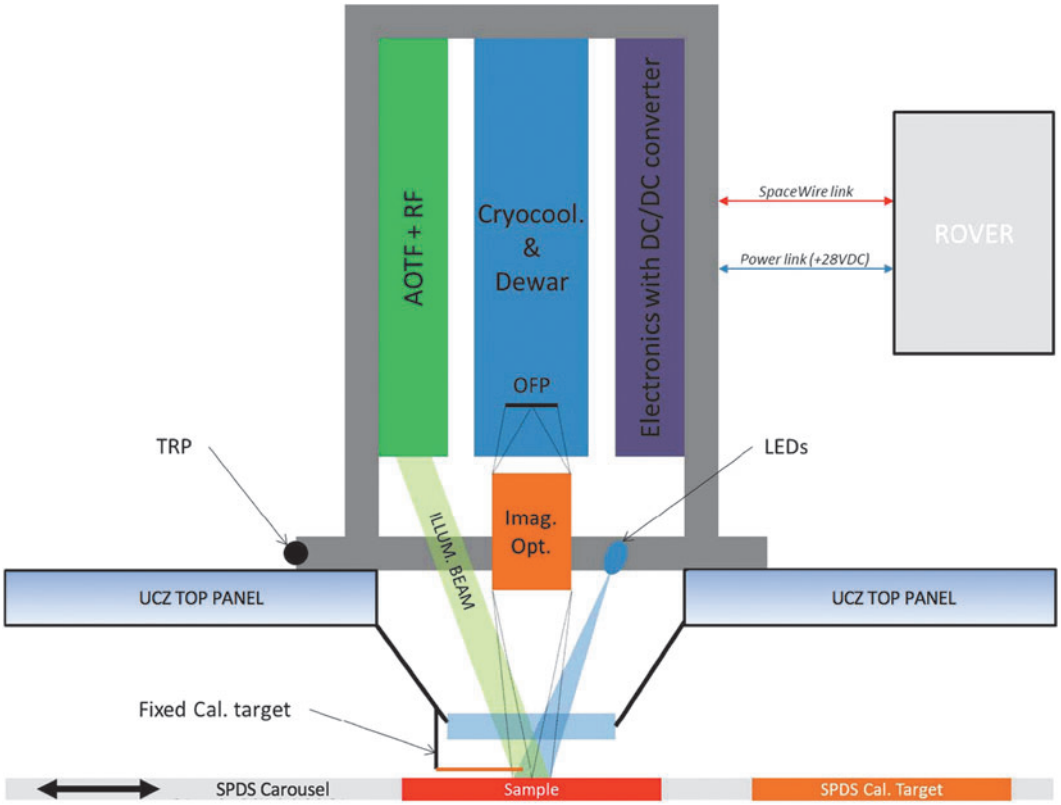

FIG. 1. Functional block diagram of MicrOmega. AOTF, acousto-optical tuneable filter; LEDs; OFP; RF; SPDS, Sample Preparation and Distribution System; TRP, Temperature Reference Point; UCZ, Ultra Clean Zone; VDC.

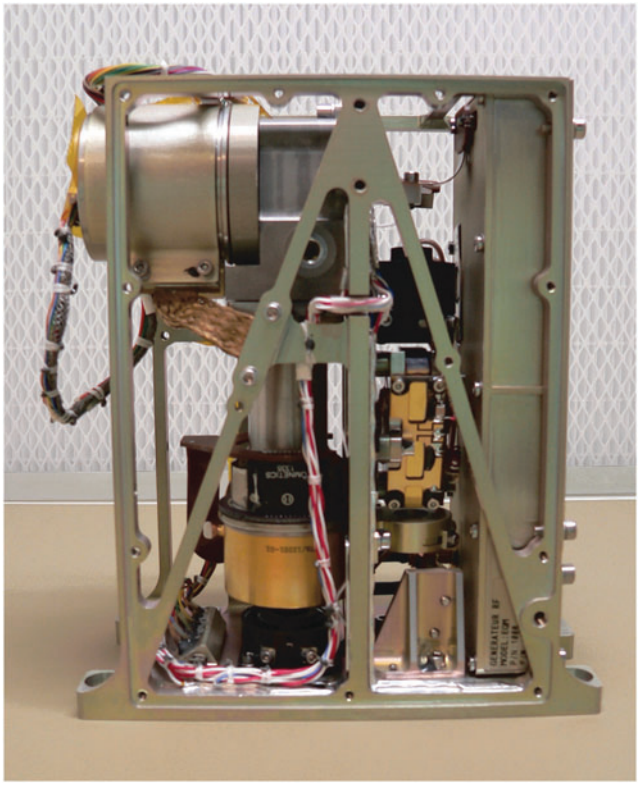

FIG. 2. The MicrOmega Engineering Qualification Model, before closing the structure with the panels in which the electronic boards are implemented.

monochromator. The broadband light source is a commercial, but qualified (at Institut d'Astrophysique Spatiale) long-life ($\sim$40,000 h), ultra-miniaturized filament lamp. The source illuminates the entrance of the TeO_2 AOTF crystal through an aspheric condenser. Two cross polarizers are used as a light trap (of the non-diffracted white beam). The AOTF has been designed and qualified to meet the spectral range requirement, from 0.95 to 3.65 μm, and the spectral width requirement ($\sim$20 cm^{-1}), through a two-transducer miniaturized system. When an ultrasonic wave is applied to the crystal, a monochromatic diffracted light beam exits the crystal in a fixed given direction. The wavelength of this output depends on the frequency of the ultrasonic wave generated by a Radio Frequency Synthesizer (RFS) in the 27–104 MHz range through piezoelectric $NbLiO_3$ transducers (Table 3). The relationship between the wavelength of the monochromatic light generated and the ultrasonic wave frequency applied to the crystal is bijective, and has been properly calibrated, as a function of temperature. The spectral width is $\sim$20 cm^{-1}; as a property of the AOTF, the spectral width of the output beam, when expressed in wavenumbers, is constant over the entire spectral range. It mostly depends on the size of the crystal. After exiting the AOTF, the light is directed to the UCZ Optical Window and the sample container, through an illumination system made of two sapphire plano-convex lenses and one gold-coated plan mirror. The scattered beam, with possible specific (and thus diagnostic) absorptions depending on its composition, is then imaged onto the 2D sensor.

Table 3. Main Characteristics of the MicrOmega Acousto-Optical Tuneable Filter

Material	TeO_2
Spectral range	0.95–3.65 μm
Acoustic frequency range	27–104 MHz
Bandpass, FWHM	20 cm^{-1}
Angular aperture	±3°
Diffraction angle	7°
Output polarization	In the diffraction plane
RFS power	~2 W

FWHM; RFS, Radio Frequency Synthesizer.

The scanning by steps of the RFS frequency provides the sequential illumination of the sample in all wavelengths between 0.95 and 3.65 μm, building a (x, y, λ) hyperspectral cube. Since it is electrically controlled, the AOTF operates as a monochromator without any moving part, which increases the robustness of the instrument and gives a high flexibility in the operations with the possibility of selecting any spectral sequence needed with any spectral pattern. The latter can be used to oversample spectral regions of interest (RoI) to increase both the signal-to-noise ratio (SNR) and the spectral accuracy, for diagnostic characterization as well as for optimizing the data budget for downlink, if limited to these RoI.

2.2.2. Detection unit. The sensor is the space-qualified Neptune SMW (Short and Mid Waves) made of an HgCdTe detection array, hybridized on a CMOS (Complementary Metal Oxide Semi-conductor) Capacity TransImpedance Amplifier readout circuit, provided by Sofradir. The array has a size of 500×256 px^2 and a 30 μm pixel pitch; for this mission, only the central area of 250×256 px^2 is used. The HgCdTe spectral sensitivity has been tuned to cover the 0.9–3.7 μm spectral range. It operates at 110K nominally, with a resulting dark current of 10 fA/px. The well depth is ~2.2 10^6 e^-/px. The detector is encapsulated in a hermetic Dewar, within which it is mounted on the cold finger of a dedicated Ricor K508S cryocooler (with a temperature closed loop control system). Within the Dewar, a baffle, cooled by being coupled to the cryocooler, is placed in front of the detector, to limit the thermal fluxes entering the detector to those coming from the sample.

2.2.3. Electronics

2.2.3.1 Hardware. Electronic functions are implemented on three boards with separated functions: (1) a DC/DC converter of the primary unregulated 28V, into four regulated power lines, at 4.4V, 6V, 12V, and 15V; (2) a MicrOmega Electronic Unit provides a simple power interface between the ExoMars OBC (On Board Computer), the SpaceWire/data interface (nominal and redundant link), and the control of all electrical subsystems; it also manages some simple data processing and a stand-alone test mode; and (3) the RFS generates a radio frequency signal in the 27–104 MHz range, which controls the AOTF transducers. The 20 kHz frequency step enables scanning of the light wavelength within the 0.95–3.65 μm range (10526–2738 cm^{-1}), with 2 cm^{-1} steps. The use of two transducers for the AOTF enables optimization of the impedance match over the whole RF frequency range; the voltage standing wave ratio, which characterizes the power transmission to the AOTF, remains below 1.15.

2.2.3.2. Software. To ensure optimization at system (ExoMars) level, the MicrOmega instrument has a very limited data handling and operational autonomy and relies on the ExoMars OBC to sequence its operations and process the data before transmission to Earth. The 3D hyperspectral data (x, y, λ) are obtained by sequentially acquiring 2D images (x, y) at different wavelengths (λ). The basic interface level is the request to MicrOmega by the OBC to acquire one image and transmit it back to the OBC. After reception of the image, the next one is requested. The number of images and the specification of all the parameters associated with each image (*e.g.*, integration time, summing, and RF frequency) are set by the OBC, based on a ground command defining the sequence of observations.

The 3D data cubes (x, y, λ) are compressed onboard before transmission to the ground. A number of compression modes and algorithms have been elaborated at IAS. They will be used to immediately downlink ''critical'' data sets for operation purposes, to prepare sets of scientific ''critical'' data sets to be downloaded for scientific analyses, and to identify and locate RoI, within the samples, based on specific criteria (*e.g.*, organics and/or water-rich phases), to enable the system to present them by a proper rotation of the carousel precisely below another ALD instrument for complementary analysis (Pilorget and Bibring, 2014).

2.2.4. Flight calibration target. An extended calibration plan will be performed on ground, before integrating MicrOmega within the ExoMars ALD. However, to correct potential variations in the instrument response (arising during any of the following mission phases: the launch campaign, the cruise phase, the Entry, Descent, and Landing, and the roving), two calibration targets have been implemented: one within MicrOmega, as described in Figure 1, and one on the carousel, with an inclined grid, enabling control of the eventual defocusing and the image quality.

3. Operations

In addition to a few tests during cruise, MicrOmega should be turned ON each time a sample is delivered to the refillable container, as well as for an imaging of the carousel calibration target and imaging of the MOMA dedicated oven, if needed.

Each operation will start by cooling down the detector package, followed by a set of monochromatic images (up to 320 spectral images), on specific commanding.

It is of interest to note that a baffle, thermally coupled to the detector array, is designed to block all thermal fluxes that would be emitted by the instrument; MicrOmega is, thus, essentially insensitive to the temperature of its environment, except for that of the sample itself. As a consequence, MicrOmega can operate at any day/night temperature, provided that the sample is maintained, within the UCZ, at low temperature (<0°C is the design goal).

Building of a fully space/spectral resolved 3D hyperspectral image cube of a given 5×5 mm^2 sample, with 320 spectral channels, requires typically 25 mn, including the initialization and cooling of the detector assembly, and the transfer to the rover system mass memory. Two contiguous image cubes might be acquired to image the entire refillable container, if necessary.

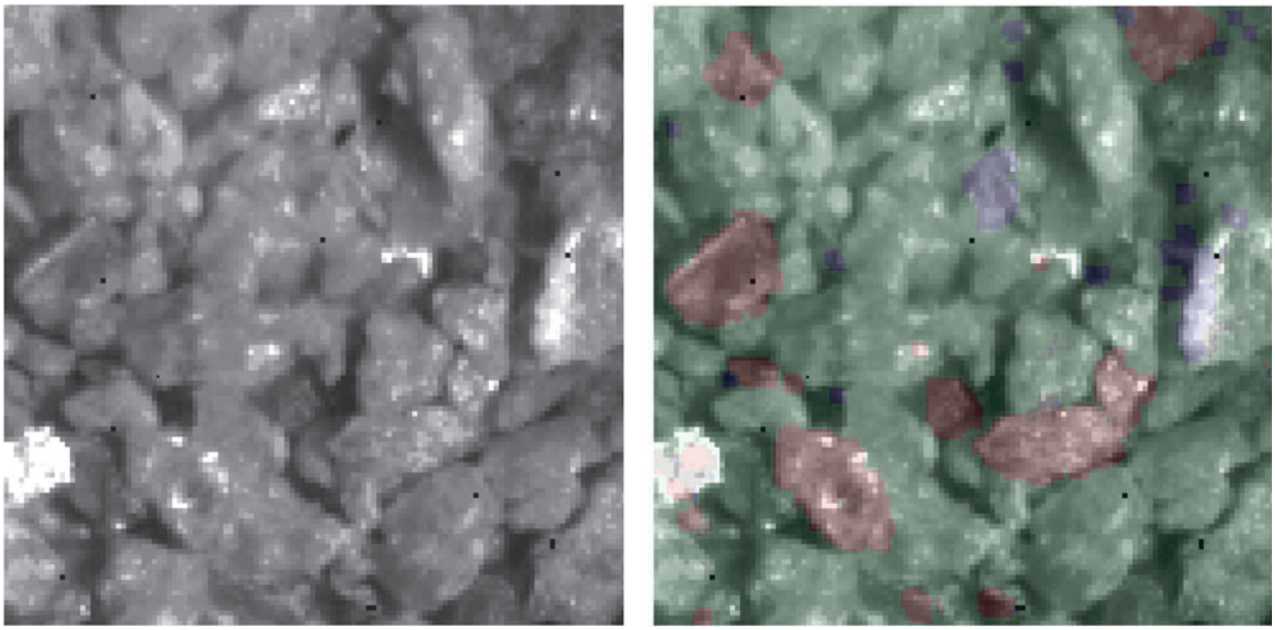

FIG. 3. Monochromatic image (left) of a sample mixing nontronite, gypsum, and calcite grains. On the right, false color image of the same sample, with grains of composition identified through their diagnostic spectral features, see Figure 4, located: nontronite (green, identified through the 1.4, 1.9, and 2.29 μm absorption), gypsum (red, identified through the 1.4, 1.7, and 1.9 μm absorption), and calcite (blue, identified through the 3.4–3.5 μm absorption).

Running the onboard algorithms, to compress the data set and/or identify RoI, requires a few minutes. RoI can be generated to be located, without requiring the ground teams in the loop, under RLS and/or MOMA spots for further analyses.

4. Performances

The MicrOmega EQM model (qualification unit) was assembled, tested, and calibrated at IAS. It was used to both qualify the design and validate MicrOmega compliance with its required performances.

In terms of SNR, the demonstrated performance exceeds the goal of being able to identify features down to a percent level in absorbance. In terms of sensitivity, it should be emphasized that, given the fact that spectra are acquired in each pixel, 20 μm large, the SNR quoted earlier applies at this high-resolution scale; if a given species of key importance, say a specific organic-rich grain, is only present at a level of 10^{-4} at a macroscopic scale, it will show up in at least a few pixels within the 250×256 pixels FOV and will be easily detected by MicrOmega. Actually, the region of interest algorithm (see 2.2.3.2 above) will both detect and locate, in an automated fashion, such constituents to enable their optimized spectral analysis.

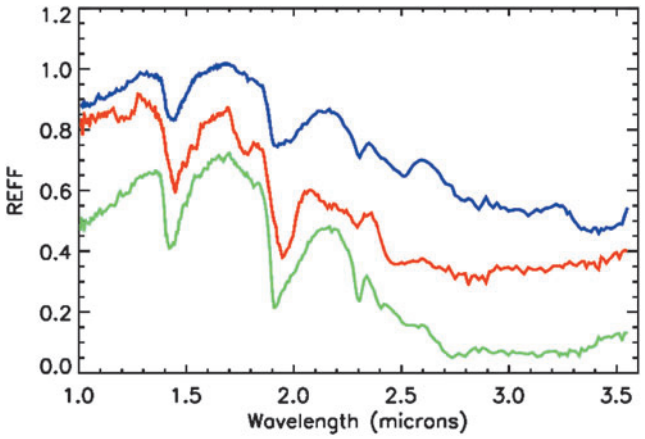

FIG. 4. Spectra, acquired at pixel ($40\times40\ \mu m^2$ for these tests) scale, of nontronite (green), gypsum (red), and calcite (blue), from which the mapping in Figure 3 was obtained (see text).

Different samples of interest have been tested with the MicrOmega EQM during the on-ground calibration. These tests have been performed under ambient pressure (~1 atm) and temperature (instrument temperature ~30°C, which constitutes a worst case) to ease operations. Although performed under such a warm environment, the results obtained during these tests are extremely satisfying due to the instrument design, specifically in reducing the effect of environmental conditions (with a thermal baffle, see Fig. 1). Spectral signatures obtained down the pixel scale ($40\times40\ \mu m^2$ for these tests) are of high quality and clearly enable identification of features down to only a few percent in absorption. As an example, results from tests performed with a powder sample mix of nontronite (phyllosilicate), gypsum (Ca sulfate), and calcite (Ca-carbonate) are presented in Figures 3 and 4.

5. Conclusion

As designed and tested, MicrOmega will be capable of acquiring 3D hyperspectral image cubes of each sample presented within the ExoMars ALD so as to characterize their structure and composition, down to their grain scale. These pioneering microscopic characterizations should constitute a major contribution to the assessment of the potential ancient habitability of Mars through the identification of phases that

might have hosted and harbored key ingredients of astrobiological relevance.

More specifically, if we assume that ExoMars, given its landing site, will explore terrains that preserve a record of processes that occurred during ancient times, when liquid water was likely stable at the surface, then ExoMars should be able to sample materials that are rich in aqueously altered phases, primarily phyllosilicates, of a distinct composition that reflect the specific conditions under which they formed. If life, within the Solar System, ever emerged elsewhere other than Earth, some of these samples might well represent its best-preserved record. MicrOmega would be able to identify samples such as these and search for potential carbon-rich phases that are coupled to, or even embedded in, them. MicrOmega's sensitivity has been demonstrated to be sufficient to detect such species, down to a micrometer scale, trapped within silicate layers constituting preservation sites—even if they happen to be present only in very few grains (at a sub-pixel scale) within the 250×256 pixels. The specific composition of the host minerals should indicate the Mars environment and context that favored the building of complex organic structures. This offers a unique possibility to decipher those processes by which life emerged on Mars, if, indeed, life did emerge on Mars, and thus constrain those processes that occurred on Earth.

Author Disclosure Statement

No competing financial interests exist.

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Abbreviations Used

ALD = analytical laboratory drawer
AOTF = acousto-optical tuneable filter
EQM = Engineering Qualification Model
FOV = field of view
MOMA = Mars Organic Molecule Analyzer
OBC = On Board Computer
RFS = Radio Frequency Synthesizer
RLS = Raman Laser Spectrometer
RoI = regions of interest
SNR = signal-to-noise ratio
SPDS = Sample Preparation and Distribution System
TRP = Temperature Reference Point
UCZ = Ultra Clean Zone