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VNIR spectroscopy of Mars Analogues with the ExoMars-Ma_Miss instrument

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Abstract. The ExoMars 2018 mission will investigate the Martian surface environment with the aim of searching for eventual present or past signs of life, and to obtain a characterization of Martian soil and subsoil. The investigation of the near-surface environment and of the shallow subsurface with complementary techniques, will provide insights on the chemical and mineralogical composition, material grain size, the litotypes, the stratigraphy: these information will help us to understand the geologic processes that characterized the history of the Martian crust. The Ma_Miss (Mars Multispectral Imager for Subsurface Studies) instrument (Coradini et al. 2001) is a miniaturized visible and near-infrared spectrometer, integrated in the ExoMars Pasteur Rover Drill: it will acquire spectra of the borehole wall performed by the Drill, down to a depth up to two meters. Spectroscopic tests have been performed with the laboratory model (breadboard) on spectral targets and rock samples; furtherly, an activity of VNIR reflectance spectroscopy of Mars analogues has been begun with the breadboard to build a spectral library.

Key words. Mars: surface – Mars: subsurface – Mars: mineralogy – Mars: geology – Mars: terrestrial analogues – Reflectance Spectroscopy: VNIR

1. Introduction

The search for signs of past life on Mars is a goal of the present space exploration. The search for fossil life is strictly related to the search for geological processes driven by water; there are a lot of evidences and a few doubts that, at least in the early history of Mars, especially in the Noachian and early Hesperian periods (4.1 - 3.0 Gyr), liquid water could have lasted at the surface. Atmospheric conditions could have allowed liquid water to be stable on the surface for a long time, enough to produce lakes, valley networks, deposition and alteration of minerals (Carr & Head III (2010) and references therein), deposition of hydrated silicates and hydrothermalism (Marzo et al. 2010), production of carbonate-bearing rocks and layered deposits of hydrated sulfates (Murchie et al. 2009), precipitation of coarse grained crystalline hematite (Christensen et al. 2000) and perhaps to growth of the first great ocean

(Fairen et al. 2005). Biological activity could have occurred for example at the Meridiani Planum, where the presence of altered sedimentary rocks seem indicate the t races of an ancient aqueous environment (Squyres et al. 2004). Thus the study of the water and geochemical environment of the Martian surface and shallow subsurface could add more information to the current state of art of knowledge. Life-related processes can characterize the environment mainly in several ways: from a morphological point of view, bio-induced signatures can be evidenced by sedimentary mounds, fossilized bacterial mats or stromatolitic mounds. Chemical bio-signatures or organic molecules, if ever existed on Mars, could be well preserved in the subsurface; water ice in the Martian subsurface is suggested by several models (Mellon & Jakosky (1995) and references therein) and observations indicate its presence (for example Mars Odyssey - GRS data, Boynton et al. 2002). Organic molecules at the surface are soon destroyed by the high doses of UV radiation, by UV-induced photochemistry (through reactive oxidant species) and by ionizing radiation. Dust-borne particles carried by the wind and containing organics or biomolecules also are subject to strong UV and ionizing radiation. Studying the materials in the uppermost few meters of Martian subsoil will rise the possibility to discern life-related traces.

2. The experiment

2.1. The instrument

Ma_Miss is a miniaturized spectrometer that will acquire spectra in the VNIR range 0.4 - 2.2 μm. The instrument will be completely integrated within the Drilling system housed on the Pasteur Rover. The illumination source is a 5W halogen lamp; an optical fiber bundle carries the light from the source to the Optical Head in the Drill tip: the Optical Head focuses the light on the target with a spot of 1 millimeter, through a Sapphire Window, and then collects the light scattered by the target. The collected light, with a spatial resolution of 120-μm, is conveyed through a single optical fiber (Signal Fiber) to the spectrometer. All the subsystems, except for the spectrometer and the detector (and the electronics) are placed within the Drill tip. The Sapphire Window is on the tip side, as interface between the instrument and the hole walls, with a nominal distance of 0.65 mm; this element has the double advantage of high hardness and transparency. In the base configuration the instrument acquires spectra at a 50-cm depth; three extension rods will be used to increase the depth: a single signal fiber is integrated within each rod, whose length is 50 cm; the light signal is transmitted from the first rotating rod to the fixed part of the Drill by means of a Fiber Optical Rotary Joint (FORJ). Acquisition will be performed after the excavation basically in two configurations: a *column image* will be obtained acquiring spectra in adjacent positions during a vertical translation; a *ring image* will be constructed acquiring spectra in adjacent points at fixed depth, during a rotation.

2.2. Laboratory model: the BreadBoard

The laboratory model (breadboard) of the instrument is now operating in the Laboratory of Spectroscopy at the Institute for Space Astrophysics and Planetology (INAF-IAPS). The breadboard is constituted by all main subsystems of the instrument tip, except for the spectrometer and detector: it consists of the Illumination System (a 5W lamp and an optical fibers bundle), the Optical Head, the Sapphire Window and the Signal Link (that is the single output optical fiber) that carries the light to the detector system. The laboratory model setup contains the breadboard coupled with a commercial spectrometer (FieldSpec Pro©; see Fig. 2). The FieldSpec acquires in the range 0.35 - 2.5 μm with three separated detectors corresponding to VIS, NIR and SWIR spectral ranges. It has as input an optical fiber bundle. Interfacing this bundle with the Ma_Miss single output signal fiber, because of the different spatial resolutions, required three separate acquisitions for the three different spectral ranges (0.35-1.0 μm, 1.0-1.8 μm, and 1.8-2.5 μm). The sample is placed on a sampleholder, which can be moved along three directions by

Fig. 1. A picture of the ExoMars Pasteur Rover with the Drilling system: the drill will perform excavations in the Martian subsoil, down to a depth of up to 2 meters
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a XYZ stage with micrometric screws: so, it is possible to move the rock or powder sample step by step and perform surface manual scans.

2.3. Preliminary tests: spectral targets

First spectroscopy tests have been performed on LabSphere© standard spectral targets; spectra have been acquired on four targets: they are dysprosium oxide (WCS-D0), erbium oxide (WCS-E0), holmium oxide (WCS-H0) and a fourth spectral target (MC standard reflectance factor); several spectra have been acquired in different positions on each target, and then an average measure has been determined. All these wavelength standard calibrators have continuum reflectance values in the range 80%-99% (a LabSphere 99%-spectralon has been used as reference target), and are

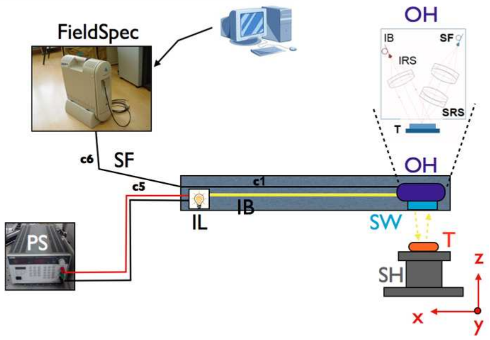

Fig. 2. Schematic view of the breadboard: the Illumination Bundle (IB) carries the light from the light source (IL) to the Optical Head (OH); the OH focuses the light, through the Sapphire Window (SW) on the target (T), and recollects the scattered light. The Signal Fiber (SF) transmits the light to the spectrometer.

characterized by an elevate number of very narrow absorption bands in the visible and near infrared spectral range. Here we report as an example the spectrum of the dysprosium oxide (WCS-D0; Fig. 3): the measurement obtained with the Ma_Miss breadboard setup has been compared with data from manufacturer and with a measure performed with the facility SPIM (Ammannito et al. 2014). The positions of the spectral bands have been determined for the three spectra, and are listed in Table 1: the minimum, maximum and average spectral displacements between Ma_Miss and LabSphere data are $\Delta\lambda_{LabS-min} = 0$, $\Delta\lambda_{LabS-max} = 18nm$ and $\Delta\lambda_{LabS-mean} = 6.6nm$; comparing Ma_Miss with SPIM data we obtain $\Delta\lambda_{SPIM-min} = 0.7$, $\Delta\lambda_{SPIM-max} = 13$ and $\Delta\lambda_{SPIM-mean} = 5.3$; for both cases, the maximum value has been obtained for the absorption at $\lambda = 1280nm$. In the VIS range, at $\lambda = 950nm$, we have a band detection threshold of about $\Delta R/R \approx 0.2\%$; in the NIR range, the detection threshold is $\Delta R/R \approx 0.03\%$ at $\lambda = 1201nm$; in the IR range, the threshold is $\Delta R/R \approx 6.7\%$ at $\lambda = 2136nm$. Clearly, in this experimental configuration, the SN ratio in the IR range is rather low, and decreases with lower albedo targets.

Table 1. Spectral bands positions for Dysprosium Oxide - WCSD0. Wavelengths in nm.

LabSphere	SPIM	Ma_Miss	$\Delta\lambda_{LabS}$	$\Delta\lambda_{SPIM}$
-	-	744	-	-
748	750.3	751	3	0.7
-	-	797	-	-
810	805.3	807	3	1.7
895	890.6	895	0	4.4
-	-	912	-	-
-	-	934	-	-
-	-	950	-	-
-	-	975	-	-
-	-	987	-	-
1093	1078	-	-	-
1125	1116	-	-	-
1190	-	1201	11	-
1235	1229	1232	3	3
1262	1267	1280	18	13
1310	1286	1299	11	13
-	-	1387	-	-
1620	-	-	-	-
1636	-	-	-	-
1687	1684	1683	4	1
1755	-	-	-	-
-	-	2136	-	-

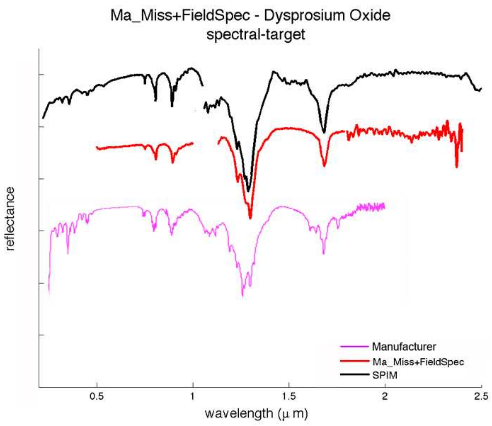

Fig. 3. Spectra of the LabSphere© spectral target Dysprosium Oxide (WCS-D0). Red: Ma_Miss; black: SPIM; purple: manufacturer.

2.4. Preliminary tests: plutonic rocks

The first rocks analyzed with the Ma_Miss breadboard setup are two cumulitic intrusive rock slabs from the Stillwater Complex: an anorthosite sample (ST18) and a gabbronorite sample (ST12).

These samples were studied by Carli (2009) and Carli & Sgavetti (2011). The anorthosite sample has plagioclase (Pl) (94.1%, An_{79}), clinopyroxene (Cpx) (4.1%, $En_{42}Wo_{45}$) and few zoisite (1.8%); the gabbronorite sample is characterized by: Pl (60.6%, An_{81}), Cpx (17.3%, $En_{45}Wo_{44}$) and orthopyroxene (Opx) (22.1%, En_{78}). Spectra have been acquired in several positions above the rock surface for both samples; the high spatial resolution of Ma_Miss (100 μm) allows to recognize crystals of the different mineralogical phases present on the rock. Spectra of the two samples are reported in Fig. 4 and 5. In Fig. 4 the anorthosite spectra in positions B1, G1 are characterized by Fe^{2+} absorption in the 0.9 - 1.2 μm region, while in the spectra C1, C3 the absorption occurs at shorter wavelengths, near 0.8 μm, indicating possible presence of Fe^{3+}. All spectra show water absorption at 1.9 μm; the spectrum C3 is characterized by very strong OH^-/H_2O absorptions at 1.4 and 1.9 μm and an absorption near 2.3 μm that has been attributed to Fe-OH; absorptions close to 0.8 μm are due to Fe^{3+}, Mn^{3+} (Clark et al. 1990); this spectrum could be related to aqueous alteration of the plagioclase (indicating the presence of the clay mineral zoisite). The absorption at 1.56 μm in the spectrum C1 is due to OH^-: this absorption is indeed often shifted at longer wavelengths in minerals like zoisite (Clark et al. 1990). The spectra of gabbronorite (ST12; relative to several positions on its surface) are in Fig. 5: all spectra show a positive (red) slope; spectra F1, F3 are characterized by a broad Fe absorption in the 0.9 μm region, and another at about 2.0 μm; these two bands are typical of pyroxenes (Burns 1993). The spectrum D1 shows a weaker Fe^{2+} absorption near 1.0 μm; the spectrum C3 presents an absorption at shorter wavelengths, centered near 0.8 μm, likely due to Fe^{3+} transitions. Other spectra (A3, B1, E3, G1) are characterized both by a dark albedo and weak or absent absorption bands. Spectra of rock slabs typically show a negative (blue) slope, when analyzed with an instrument characterized by a low spatial resolution (e.g. the FieldSpec: the spatial resolution is about 6 mm). In the case of Ma_Miss, almost all spectra often show a red slope (Fig. 5): this could be due to the very high spatial resolution (100 μm), that can be comparable with the size of crystals.

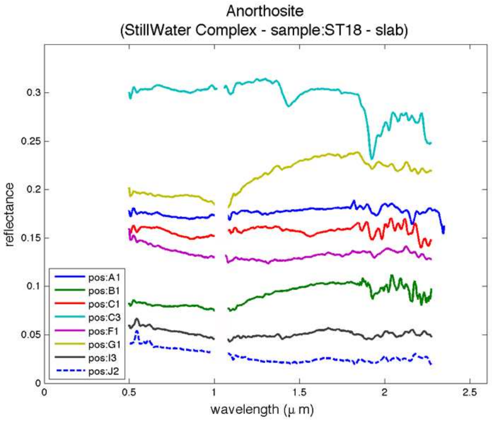

Fig. 4. Spectra of anorthosite (ST18). Ten zones (A-J) have been selected on the rock surface, three spectra have been acquired inside each zone. Spectra in position C1, C3 show absorptions which indicate aqueous alteration of plagioclase (clay mineral).

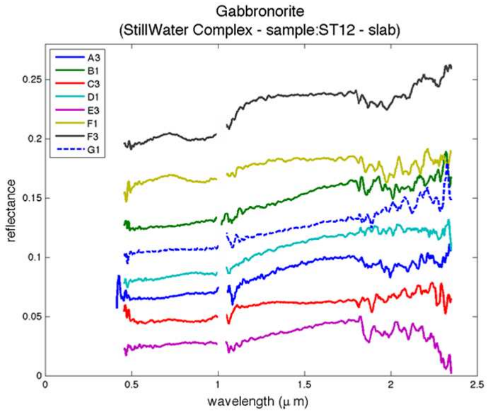

Fig. 5. Spectra of gabbronorite (ST12). Seven zones (A-G) have been selected on the rock surface, three spectra have been acquired inside each zone. Spectra in position F1, F3 reveal the presence of pyroxenes (Fe^{2+} absorptions at 1.0 and 2.0 μm). Spectra D1, E3 show Fe^{2+} absorption near 1.0 μm, while the spectrum in C3 shows an absorption near 0.85 μm likely related to Fe^{3+}.

3. VNIR Spectroscopy of Mars Analogues

Because of the particularity of the very high spatial resolution of Ma_Miss a spectral library of terrestrial and extraterrestrial Mars Analogues is needed, to support the ExoMars mission. We have begun a series of measurements on different rock and mineral types. Here we report spectra of two igneous rock samples and of a micritic limestone.

3.1. Volcanics: San Bartolo Lava (Stromboli)

This is a lava sample from Aeolian Islands, Stromboli Volcano (Italy); it is classified as High-potassium Calc-Alkaline (HKCA) por-

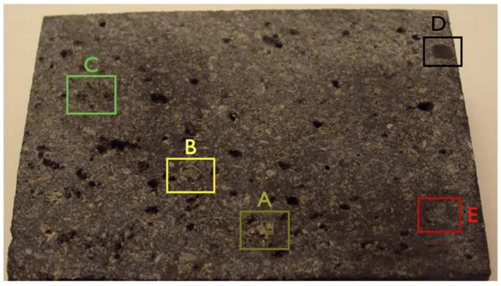

Fig. 6. Photo of the S.Bartolo Lava sample (slab). The five analyzed zones are indicated.

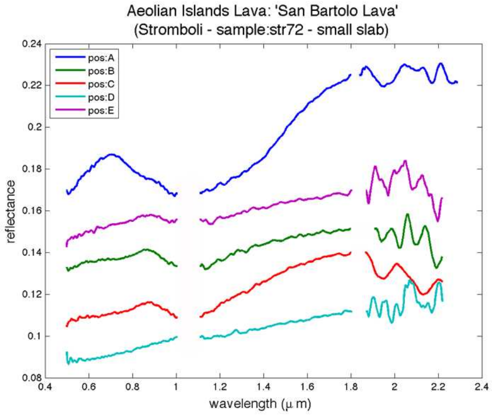

Fig. 7. S.Bartolo Lava spectra. Each spectrum corresponds to a single point within a zone. The spectrum A is olivine; the spectrum D (dark mineral in the D zone, Fig. 6) is an opaque mineral, probably iron-titanium magnetite. Spectra B, C, E show variable/different iron absorptions in silicates; the spectra B and C show Fe^{3+} absorption at 0.8 μm.

phyritic basalt, with mineralogy given by Pl as most abundant phase (An_{90-75}), Cpx of augitic composition (En_{57-52} and Wo_{40}), Mg-rich olivine (Ol) (Fo_{75-68}), Opx (hypersthene) and titano-magnetite as accessory phase (Laiolo & Cigolini 2006). A slab of S.Bartolo Lava has been analyzed (Fig. 6); thanks to the 100-μm spatial resolution it is possible to discriminate between different mineralogical phases visible on the rock surface. For example, spectra in position A (Fig. 7) is dominated by a wide absorption at 1.0 μm due to Fe^{2+} in M1 and M2 sites of olivine (Ol, Burns 1993) indicates the presence of olivine, while spectra in position D are typical of a dark opaque mineral (such as iron sulphide or iron-titanium oxide). Spectra in positions A, B, C, E all show Fe^{2+} absorptions near 1.0 μm; spectra B and C also show a weak absorption near 0.75 μm likely due to the presence of Fe^{3+}.

3.2. Intrusive rocks: the Martian Meteorite Chassigny

A powder sample of the Martian meteorite Chassigny has also been analyzed; the sample, classified as a dunite (igneous intrusive rock), consists almost entirely of olivine, with modal mineralogy: 91.6% relatively iron-rich olivine (Fo_{68}), 5.0% pyroxene, 1.7% feldspar, 1.4% chromite, 0.3% melt inclusions (Prinz et al. 1974). The spectrum of this sample is shown in Fig. 8, and it is compared with a measurement acquired with the FieldSpec (standard conditions: illumination at 30 deg; emission at 0 deg; light source: QTH lamp, 78W): the spectrum is characterized by the strong and broad Fe absorption at 1 μm indicating olivine.

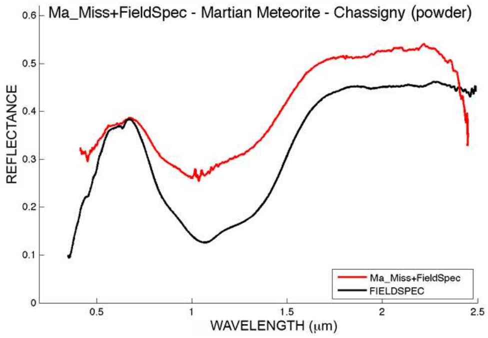

Fig. 8. Martian Meteorite Chassigny (powder). Red line: Ma_Miss; black line: FieldSpec setup. The rock, classified as dunite, is composed almost entirely of olivine. The strong absorption at 1.0 μm is due to Fe^{2+}. Because of the different experimental conditions (in particular the illumination power) the two spectra show different spectral contrast.

3.3. Sedimentary rocks: Red Micritic Limestone

A sample of red micritic limestone (Umbria) has been analyzed as analogue of ancient ma-

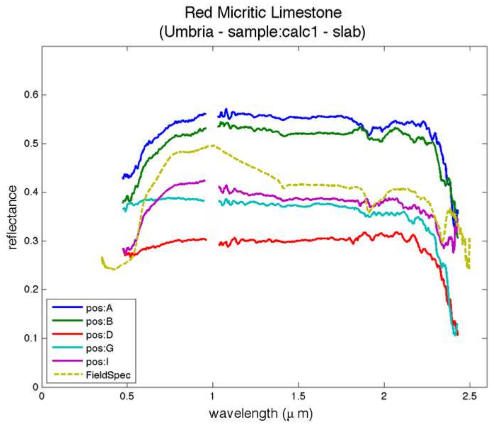

Fig. 9. Spectra of the Red Micritic Limestone (slab). Spectra D, G have been acquired within calcite veins. Spectra A, B, I have been acquired on different points above the slab surface: they show OH^-/H_2O absorptions at 1.4 and 1.9 μm; CO_3 absorptions at 2.3 μm; Fe^{3+} absorption at 0.85 μm.

rine environment: this rock, consisting of calcium carbonate, has originated by accumulation of very small sediments in a deep sea environment characterized by hot-tropical climate (Cretaceous/Paleocene limit).

The sample is characterized by a reddish homogeneous surface, fine grain size texture, with grey/white veins that filled fractures in the rock, mostly calcite. Spectra have been acquired in nine positions on the surface: spectra are in Fig. 9.

They show the OH^-/H_2O absorptions at 1.4 and 1.9 μm. Absorptions near 2.35 μm due to CO_3 are visible.

Spectra D and G have been acquired within the veins: the indicate calcite.

Spectra A, B, I and the one acquired with the FieldSpec all show a weak absorption at 0.85 μm, likely indicating the presence of some ferric iron; moreover they are characterized by a strong UV absorption.

4. Conclusions

The Ma_Miss miniaturized spectrometer will be integrated in the Drill of the ExoMars Pasteur Rover. It will acquire spectra of the borehole wall excavated by the Drill in the Martian subsoil, down to a depth of up to 2 meters, in the VNIR range 0.4-2.2 μm. Spectroscopic tests have been performed with the breadboard on spectral targets, and on cumulitic intrusive rock samples with good results. An activity of VNIR reflectance spectroscopy of terrestrial and extraterrestrial Mars Analogues has been begun, to build a spectral library in support of the ExoMars mission: such a spectral library is necessary considering the high spatial resolution of Ma_Miss.

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