OVERVIEW AND DEVELOPMENT STATUS OF THE EXOMARS ROVER MOBILITY SUBSYSTEM

P.Poulakis [1], J.L.Vago[1], D.Loizeau[6], C.Vicente-Arevalo[5], A.Hutton[3], R.McCoubrey [4], J.Arnedo-Rodriguez[5], J.Smith[3], B.Boyes[3], S.Jessen[4], A.Otero-Rubio[5], S.Durrant[1], G.Gould[1], L.Joudrier[1], Y.Yushtein[1], C.Alary[1], E.Zekri[1], P.Baglioni[1], A.Cernusco[2], F.Maggioni[2], R.Yague[2], F.Ravera[2]

[1]European Space Agency / ESTEC, The Netherlands
[2] Thales Alenia Space Italy, Italy
[3] Airbus Defence & Space, UK
[4] MDA, Canada
[5] Thales Alenia Space España, Spain
[6] University of Lyon, France

ABSTRACT

The ExoMars 2018 rover mission will carry an ambitious payload to search for biosignatures that may provide clues to whether life ever started on Mars. It will be the first time that depth, the third dimension of Mars, will be explored using a sophisticated drill system that will allow access to the Martian subsurface down to 2m. In that context, the rover's mobility subsystem will be instrumental to reach locations with high scientific potential. Based on the 6-wheel triple-bogie concept, the Bogie Electro-Mechanical Assembly of ExoMars features eighteen actuators in total, and a sophisticated flexible metallic wheel design -all assembled into three highly optimised bogie structures. The Actuator Drive Electronics provide the motion control for the external mechanisms of the rover. They are designed on a "cold electronics" concept, based on which they will need to survive the Martian night temperatures without active thermal control. The development of the mobility subsystem also foresees an elaborate locomotion verification and characterization campaign, where extensive tests have been prescribed on identified Martian soil simulants. In parallel, ESA and Roscosmos are coordinating the landing site selection process within the international scientific community. Much work is being dedicated to obtaining information on the potential mobility risks of the candidate landing sites.

1. INTRODUCTION

Establishing whether life ever existed, or may still be active on Mars, is one of the outstanding scientific questions of our time. To address this question the European Space Agency has established the two-mission ExoMars programme which is carried out in cooperation with Roscosmos. The first mission foresees an orbiter module –the Trace Gas Orbiter (TGO)– plus the Schiaparelli Entry, Descent and Landing Demonstrator Module (EDM), both currently undergoing final testing and due to be launched in March 2016. The second mission, planned for launch in 2018, features a decent module, which will deliver a rover and a static lander platform to the surface on Mars.

If life ever arose on the red planet, it probably did when Mars was warmer and wetter, sometime within the first few billion years following planetary formation. Conditions then were similar to those on Earth when microbes gained a foothold on our young planet. The ExoMars rover will search for two types of life-related signatures: morphological and chemical. Morphological information related to biological processes may be preserved on the surface of rocks, while the effective chemical identification of biosignatures requires access to well preserved organic molecules. Such molecules would hold the record of early Martian life, if it ever existed, and could only be found in the subsurface due to the high ultraviolet (UV) and ionizing radiation doses that bombard the surface and shallow subsurface of the red planet. Studies have shown that a subsurface penetration in the range of 2 m is necessary to recover well-preserved organics from the very early history of Mars. To be able to embark on the search for life, the objective of the ExoMars rover development is to implement the following technologies:

A. Surface mobility –allowing the rover to reach scientifically interesting locations to investigate;
B. Access to the subsurface to acquire samples –required to maximise the physico-chemical integrity of the material to be studied;
C. Sample acquisition, preparation, distribution, and analysis with scientific instruments.

1.1. Exploration Strategy

The ExoMars rover will have a nominal lifetime of 218 sols (approximately 7 months). During this period, it needs to ensure a regional mobility of a few kilometres, relying on solar array electrical power.

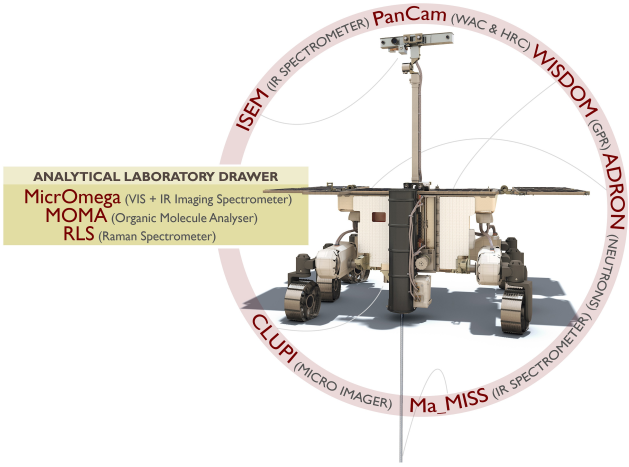


Figure 1. The ExoMars Rover instrument suite

The rover's Pasteur payload will produce self-consistent sets of measurements, capable to provide reliable evidence, for or against, the existence of a range of biosignatures at each search location. Pasteur contains: panoramic instruments (wide-angle and high-resolution cameras, an infrared spectrometer, a ground-penetrating radar, and a neutron detector); a subsurface drill capable of reaching a depth of 2 m to collect specimens; contact instruments for studying rocks and collected samples (a close-up imager and an infrared spectrometer in the drill head); a Sample Preparation and Distribution System (SPDS); and the analytical laboratory, the latter including a visual and infrared imaging spectrometer, a Raman spectrometer, and a Laser-Desorption, Thermal-Volatilisation, Derivatisation, Gas Chromatograph Mass Spectrometer (LD + Der-TV GCMS).

An important part of the mission will be devoted to identifying the most interesting surface targets and reaching them. The instruments on the mast, the agility of the mobility subsystem and the autonomous navigation performances will be key during this stage. Once the rover has reached an interesting outcrop, the goal will be to characterise it –is it the type of mineralogy we are interested in? What was the depositional setting? Next the scientists will try to understand how the outcrop "maps" into the subsurface. This is important to select a suitable place for drilling and collecting a sample for analysis. The rover will execute a complex, meander-shaped subsurface scanning pattern to determine the underground stratigraphy, its water content, and identify any potential buried obstacles. Thereafter drilling will be initiated, which is an expensive operation in terms of time and energy, as it requires several sols to drill down to 2m to collect a deep sample. To complete one experimental cycle the rover will then need to spend the next few sols stationary, investigating the mineralogy and chemical composition of the samples obtained.

1.2. European "Firsts"

The ExoMars mission will be the first European mission with surface mobility, and will pave the way for ESA, Roscosmos and European industry in the domain of planetary exploration. Following the very successful NASA/JPL missions on the surface of Mars, the ExoMars rover will have a mobile mass of 310 kg with an instrument payload of 26 kg (excluding payload servicing equipment such as the Drill and the SPDS). Besides its high payload-to-mass ratio, the ExoMars rover aims to be the first rover to scan and access the subsurface on Mars.

1.3. Industrial Consortium

A broad industrial consortium is developing the 2018 ExoMars mission. Airbus Defence & Space UK is the Rover Module Lead, namely the rover platform with all related equipment, including the mobility system. Through the partnership with Roscosmos, Lavochkin (LAV) is the industrial prime of the Entry, Descent and Landing system and the Surface Platform. Finally, the overall 2018 mission prime contractor is Thales Alenia Space Italy (TAS-I), who in addition to the above modules, coordinates the development of the Carrier Module (CM), the rover Drill and SPDS, the Autonomous Mission Management software and the Rover Operations Control Centre (ROCC).

1.4. Paper Structure

The paper is structured as follows. Section 2 presents an overview of the mobility subsystem. Section 3 describes the Bogie Electro-Mechanical Assembly (BEMA) of the rover and Section 4 is devoted to the Actuator Drive Electronics (ADE). An overview of the ExoMars locomotion verification approach is provided in Section 5, while the subsequent section offers a rover mobility-related perspective of the on-going landing site selection process. The paper closes with a summary and conclusions.

2. OVERVIEW OF THE MOBILITY SUBSYSTEM

The capability to traverse different terrains on the surface of Mars is provided by the mobility subsystem of the rover. In a holistic sense, it is the synergistic operation of the locomotion subsystem (suspension, wheels, actuators), the low-level motion control electronics, and the Guidance, Navigation and Control (GNC) subsystem providing the necessary agility and autonomy that implement the rover's mobility. In this paper we examine the mobility subsystem from a "hardware" perspective:

- The suspension and locomotion elements;
- The motion control electronics;
- The locomotion performance verification activities;

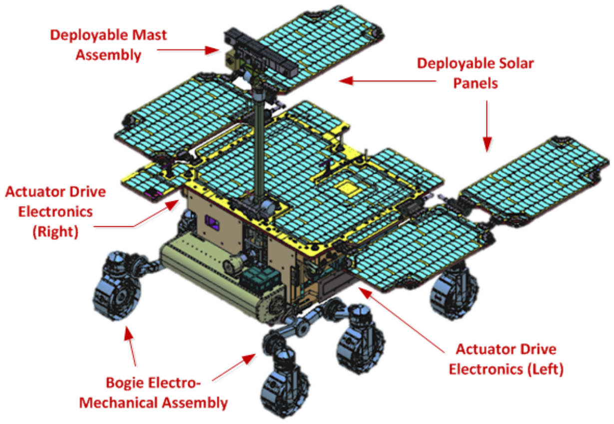


Figure 2. The ExoMars Rover

The key ESA requirements driving this development are the following:

- Have the capability to traverse four prescribed Martian soil simulants (ES1 to ES4).
- Be able to travel at least 0.5 km between sampling locations on ES4.
- Achieve a rover speed of at least 70 m/h on ES4 level terrain.
- Be able to accurately execute a meander-shaped pattern in support of the WISDOM ground penetrating radar measurements.
- Achieve specified uphill and cross-hill gradeabilities over all four soil simulants, with maximum 26° uphill gradeability on ES3.
- Surmount rocks of 0.25m height and overcome crevasses of 0.15m length.
- Guarantee a static stability on slopes up to 40° in all directions.

More details on the specified soil simulants are given in Section 5.2.

3. THE BOGIE ELECTRO-MECHANICAL ASSEMBLY (BEMA)

The BEMA is the suspension and locomotion element of the ExoMars rover. Under Airbus D&S responsibility, the BEMA is being developed by MDA Canada with maxon motor Switzerland as a subcontractor.

3.1. Kinematic Configuration

During the very early phases of the mission, ESA studied alternative novel kinematic configurations for the ExoMars rover [1], from which the triple-bogie concept emerged as a preferred solution due to its attractive balance between overall simplicity and locomotion performances. Since then it has seen several design evolutions aiming at improving performance metrics and meeting the mission's constraints [2].

The kinematic configuration of the BEMA is based on a triple-bogie concept with locomotion formula 6x6x6+6, i.e. 6-supporting wheels, 6-driven wheels, 6-steered

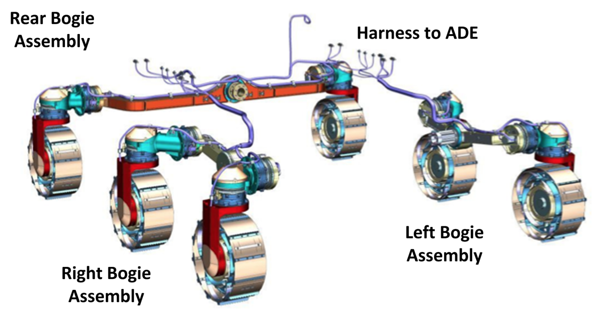


Figure 3. The BEMA triple-bogie configuration

wheels plus 6 deployment drives. It enables the rover to passively adapt to rough terrain, providing inherent platform stability without the need for a central differential.

The above locomotion formula offers the capability of performing drive and turn-on-spot manoeuvres. Due to the 6-wheel steering, the rover will be able to perform double-Ackermann and diagonal crabbing motions. The two latter manoeuvres will allow the GNC subsystem to implement more sophisticated trajectories and follow paths in a more agile and resource-efficient manner.

3.2. Design

The driving requirements for BEMA combine demand for high locomotion performance with limited use of resources:

- Sustain mobility loads derived from carrying 310 kg in Mars gravity while fulfilling the locomotion requirements of Section 2.
- Constrained mass (70 kg) and volume allocations.
- Worst-case cold start-up conditions as in [4] to maximise daily travel time.
- Planetary protection category: IVb.

The BEMA features 18 actuators in total: 6 drive (DRV) – 6 steering (STR) – 6 deployment (DEP) actuators respectively. Following a trade-off between the benefits of customization and the drawbacks of programmatic complexity, a common core-actuator design approach was chosen, with a different final output gear stage ratio

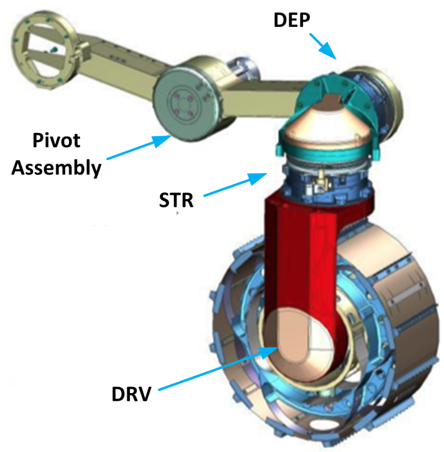


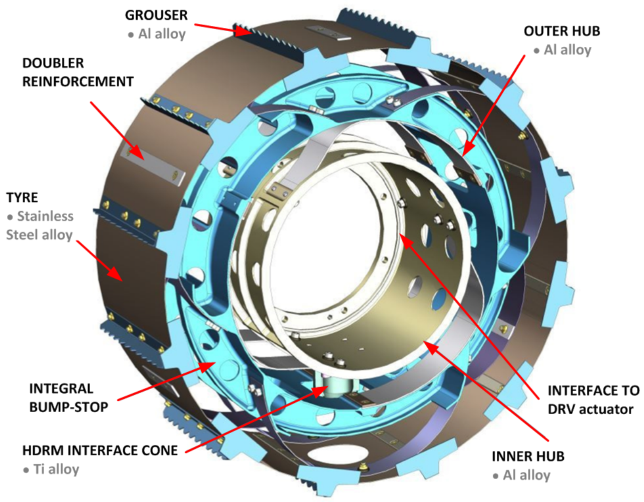
Figure 4. Right bogie beam with actuator locations

for DEP. Some BEMA design and performance characteristics can be found in [3] and [4].

In order to maximise stiffness and minimise mass, the bogie beam assemblies are thin-walled, riveted box structures made of Titanium alloy.

3.3. Wheels

Lander accommodation constraints have imposed the use of small wheels on the ExoMars rover. In order to reduce the traction performance disadvantages of this design choice, a flexible/deformable metallic wheel concept was adopted early on in the project. High wheel deformation increases the soil-contact patch and reduces ground pressure while offering substantial impact load absorption capability.



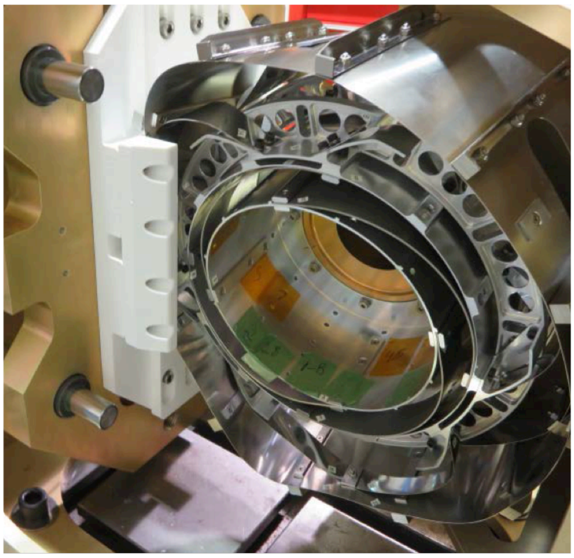


Figure 5. BEMA Wheel: design (top), during a blockage test at MDA premises (bottom)

Table 1. BEMA wheel parameters

Parameter	Value
Diameter / Width	285 mm / 120 mm
Energy absorption	13 J
Ground pressure*	~10kPa (average) / ~15kPa (max)
Radial stiffness	< 17 N/mm

* The Ground pressure calculation is based on the Effective Ground Pressure convention defined by JPL in [5] adapted to be applicable on flexible wheels.

MDA has further developed the early ExoMars flexible wheel concept in order to meet the demanding ground pressure and impact load requirements. Besides the mechanical analyses, the design team has opted to follow an exhaustive iterative testing approach to balance out the numerous design parameters and meet the performance/lifetime requirements, whilst respecting the imposed constraints.

Even though the wheel design is not yet finalized (MDA is currently performing tests on the Engineering Model (EM) wheels), Table 1 lists the current wheel parameters. It is acknowledged that the ground pressure specified for the ExoMars rover significantly exceeds the design guideline followed by JPL on the Mars Science Laboratory (MSL) –see [5]. This high ground pressure is the result of multiple constraints imposed on the BEMA/wheel design.

4. THE ACTUATOR DRIVE ELECTRONICS (ADE)

The ADE is the actuation "heart" of the ExoMars rover. Its task is to actuate and thermally control/monitor all the external mechanisms of the Rover Vehicle (see Figure 2), namely:

- The Solar Array Assembly (SAA).
- The Deployable Mast Assembly (DMA, which includes the cameras Pan & Tilt mechanisms).
- The BEMA.
- All the Hold-Down and Release Mechanisms (HDRM).

The ADE development contract has been awarded to Thales Alenia Space España (TAS-E) with MDA Canada as a subcontractor.

4.1. Design

Given its assigned functionality, the ADE is considered a fundamental subsystem for the rover. Due to system-level constraints, the ADE could not be accommodated within the rover's thermally controlled compartment, and it has been split in two units located on each side of the main body structure. Consequently one of the key design requirements is for the electronics to survive the harsh Martian nights without active thermal control. A distributed control architecture over CAN-bus was specified, which offers system-level benefits as well: a) higher accommodation flexibility, b) reduced harness to the equipment and through the thermally controlled compartment.

The most significant "control load" for the ADE comes from operating the BEMA. In order to optimise driving capability it was deemed necessary for the driving and steering actuators to be operated simultaneously, which will effectively increase the rover's safety and distance-per-sol it can achieve. Long traverses are the operational cases that drive the worst hot-case for the ADE thermal design where –due to internal dissipation- analysis has shown local hot spots of up to 85°C on the boards.

Table 2 provides some key specifications that drive the ADE design, while Figure 6 depicts the ADE electrical architecture.

Table 2. Key ADE specifications

Parameter	Specification
Accommodation	External (left & right)
Mass	4 kg (for each unit)
Communication	over CAN bus with the OBC
Thermal excursion	-120°C to -45°C (non-op) -45°C to +85°C (operational)
BEMA actuation	12 motors simultaneously (DRV&STR or DRV&DEP)
Redundancy	Redundant boards for most functions

4.2. "Cold" Electronics

Motion control electronics having the capability to survive low temperatures is a very attractive concept for planetary exploration rovers. Multi-joint actuation requires a high number of power electronics circuits, hence being able to dispense with thermal conditioning opens up many possibilities, e.g. distributed architecture, downsizing of the thermally controlled compartment, reduced harness to name a few. Both NASA and ESA have performed studies on "cold" electronics in the past (see [6], [7]).

A system level design decision was made to have the ADE as non-thermally conditioned units and to accommodate them externally to the rover body structure. The decision was based on the fact that placing the ADE inside the temperature controlled Service Module (SVM) of the rover would have required an unaffordable oversizing of numerous subsystems. Based on the specified thermal environment and the identified operational scenarios of the units, the derived enveloping thermal design case for the ADE is the following. The units will be facing a thermal excursion ranging from -120ºC to -45ºC until switch-on (non-op), and temperatures between -45ºC and 85ºC at board level during operation.

A meticulous plan has been put in place by TAS-E together with experts from the whole customer chain, to evaluate the survivability of Electrical, Electronic and

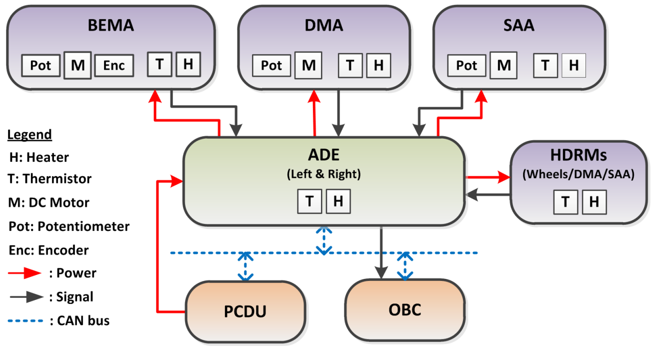


Figure 6. ADE electrical architecture

Electromechanical (EEE) components, as well as for the verification of assembly materials and processes.

The selection of EEE parts for ADE has relied on a dedicated risk analysis at part level, based on internal construction, materials and available test data in low temperature conditions. As a result, 120 different types of EEE parts among passive and active components –including complex integrated circuits- have been selected as suitable for use in the ADE design. Based on the risk categorization and on a reduction-by-similarity exercise, 40 of these component types were chosen to be submitted to a low temperature evaluation test campaign.

In parallel, a Surface Mount Technology (SMT) low-temperature verification plan has been defined for the component assembly processes. Several test vehicles have been designed incorporating up to 65 different types of packages and more than 100 different assembly processes. The environmental tests defined comprise a dedicated test to simulate the sterilization process needed by the planetary protection requirements of the mission, mechanical vibration and extended thermal cycling.

At the time this paper is being written, both the EEE component evaluation and the SMT verification tests are ongoing. Visual inspection, electrical measurements and ultimately a Destructive Parts Analysis (DPA) will be the assessment methods of the former. Visual inspection, continuity tests and metallographic inspection using microsectioning will be applied to assess the outcome of the SMT verification.

4.3. CAN-bus

Another area where new ground is being broken is in the adoption of the CAN-bus as the main communication bus between critical rover subsystems. Indeed, the On-Board Computer (OBC), the Power Control and Distribution Electronics (PCDE), the UHF Transceiver and the ADE are all interconnected via CAN-bus.

Although the technology has being slowly gaining momentum within the space industry, it is still an exotic choice in conventional spacecraft internal communications. Due to the resource efficiency, CAN-bus is an enabling choice for the ExoMars rover, particularly in the case of ADE which implements a distributed motion control architecture –an established approach in contemporary terrestial robotic systems- with the two units being external and placed close to the BEMA.

In this architecture the high-level GNC algorithms run on the OBC (navigation, trajectory-following, rover kinematics) and the low-level motion control takes place within the ADE. The update of position/velocity setpoints from the GNC to the ADE has been set to 1 Hz.

A conventional multi-drop RS845 driver DS16F95QML is used, providing the electrical performance and data rate required in a very mass-efficient way. The adoption of the CANOpen protocol adds network management, device monitoring and a structured object dictionary. In this setup the OBC is the master node on the bus to allow for more deterministic control.

5. LOCOMOTION VERIFICATION APPROACH

The verification of the locomotion performance is considered a major milestone in the development of the ExoMars mobility subsystem. A dedicated activity has been initiated, the scope of which is to:

- Verify the locomotion performance requirements that have been set for the rover.
- Characterize the behaviour of the rover in a large number of locomotion scenarios and test conditions.

5.1. Locomotion Verification Model (LVM) and Test Facility

The LVM will be the rover test vehicle used for the verification and characterization activities. It will be composed of a BEMA Engineering Model (EM), two ADE EMs (left & right) and a connecting structure whose inertial parameters will be adjustable. The LVM will also comprise adequate instrumentation to measure mobility and impact loads. The driving requirement for the LVM is to be fully functionally and inertially representative of the ExoMars rover Flight Model (FM) under Mars gravity.

Table 3. Key LVM facility specifications

Parameter	**Specification**
Soil simulants	ES1 to ES4
Slopes	5°-26° (gradeability tests) 0°-45° (static stability tests)
Obstacle types	Hemispherical, Step/Crevasse, Pyramidal
Equipment	- Ground Truth system - Low/High frame rate cameras - Central, time-stamped data logging

The LVM test facility is specified to have all the available resources and equipment needed to carry out the extensive locomotion verification and characterization campaigns. Some key facility specifications are listed in Table 3.

5.2. Soil Simulants

Within the context of the ExoMars mission, ESA has dedicated a large amount of effort in the research and definition of Reference Soils for rover mobility. This work has involved planetary geologists, geotechnical experts and rover mobility experts. It culminated in the identification of four different types of Martian regoliths which are expected to be encountered by the rover. Furthermore, materials that emulate the mechanical properties of these regoliths during terrestrial mobility testing were identified.

Table 4 summarizes the identified regolith types and Figure 7 gives examples for their occurrence on Martian terrains. It should be noted that that Types 1-3 are considered the most challenging soil types for rover mobility while Type 4 is a more benign and easy-to-traverse soil. Finally, terrestrial soil recipes and their suppliers have been identified for the four soil simulants, and soil parameter characterization activities have been performed.

6. THE LANDING SITE SELECTION PROCESS AND CONSIDERATIONS ON MOBILITY

In agreement with the procedure established by ESA and Roscosmos for the evaluation of candidate landing sites, and considering the mission's search-for-life scientific objectives and landing site engineering constraints, the ExoMars 2018 Landing Site Selection Working Group (LSSWG) has recommended four candidate landing locations: Mawrth Vallis (22°N, 342°E), Oxia Planum (18.20°N, 335.45°E), Hypanis Vallis (11.9°N, 314°E), and Aram Dorsum (7.9°N, 348.8°E). The two former locations show ancient intense water alteration activity, while the two latter have large fluvial deposits accumulation [8].

The ballistic entry of the ExoMars mission results in a relatively large landing dispersion area, defined as a series of 104km x 19km ellipses with azimuth angles spanning the 88° to 127° range. All sites present different geologic units and show variation in morphologies, rocks and loose material coverage within these units. Most of the surface in the proposed ellipses shows bright bedrock, which generally represents or contains the main scientific targets for the rover. This bedrock, however, is covered in places by overlying material of different origin: either ejecta blankets, or a dark capping unit that may have formed by lava flows and/or pyroclastic deposits and/or aeolian sediments. This overlying material is what is considered to be challenging for the rover mobility.

Table 4 – Identified Martian regoliths and terrestrial simulants

Regolith	Occurrence	Simulant
Type 1	Very fine-grained, porous and compressible material. Occurs locally in wind shadow areas and in terrain outside main wind fields.	ES-1: fine dust
Type 2	Slit to fine sand. Appears to be very common and is found in the troughs of ripples and dunes.	ES-2: very fine sand
Type 3	Comprise scree, polymodal surficial lag and local courser Aeolian accumulations. Can be encountered near bedrock.	ES-3: gravelly medium to coarse sand
Type 4	Crusty-cloddy soil, quite prevalent in overall flat and gently sloped terrain. It is characterized with higher cohesion, and bearing capacity and shear strength are not an issue.	ES-4: stiff, high-density gravelly sand

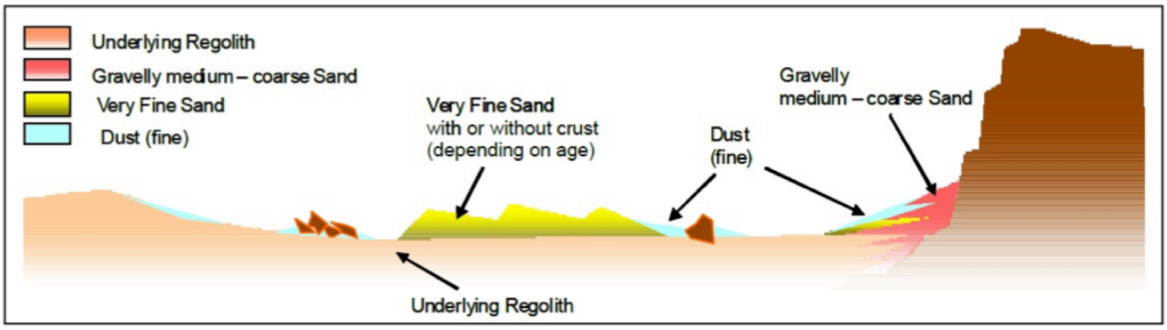


Figure 7. Visualization of Martian regolith occurrence (source: G.Kruse)

Terrain characterization at these sites can only be made with orbital data. In particular, HiRISE/MRO images [9], at ~30 cm/pixel, are progressively being acquired to fully cover the ellipses. From orbit, one can identify aeolian landforms like Transverse Aeolian Ridges (TARs) and bedrock, but when the surface is homogenous, it is impossible to determine how loose or indurated the terrain is, which poses a risk for rover operations. A suggested approach is to characterize the terrain on well-defined representative areas of available HiRISE images with the help of the THEMIS thermal imagery [10]. These results could then be extrapolated to other areas in the candidate landing sites to estimate –to the extent possible– the mobility risks and the existence of poorly consolidated soils.

6.1. Preliminary Assessment of Oxia Planum

The top part of Figure 9 depicts with dark rectangles the HiRISE image coverage for the Oxia Planum landing ellipse as of October 2014. The three areas analyzed for the presence of problematic soft terrains are denoted in the lower image by the coloured polygons, where the percentage area covered by TARs is indicated.

Figure 10 shows a section of a HiRISE image obtained within Zone #3 (red polygon in Figure 9). This area includes many instances of light toned, clay-rich outcrops constituting excellent science targets for the ExoMars rover. To be able to reach them, the rover would need to move across wind blown fine soil TARs, which can be seen almost everywhere in the image and can be recognized by their wavy crests.

It should be noted that TARs do not constitute definite risks for the rover’s mobility, only potential ones, and their presence should be taken under consideration.

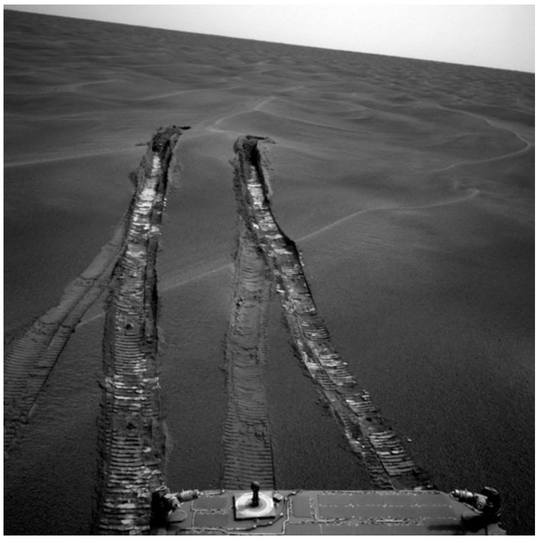


Figure 8. Opportunity driving away from Purgatory Dune TAR-field after being immobilized for 5 weeks (source: NASA/JPL)

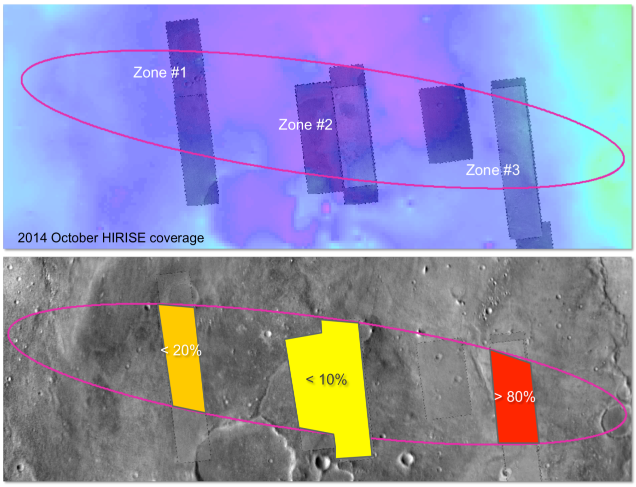


Figure 9. HiRISE coverage of Oxia Planum (top) and percentage of TARs detected (bottom)

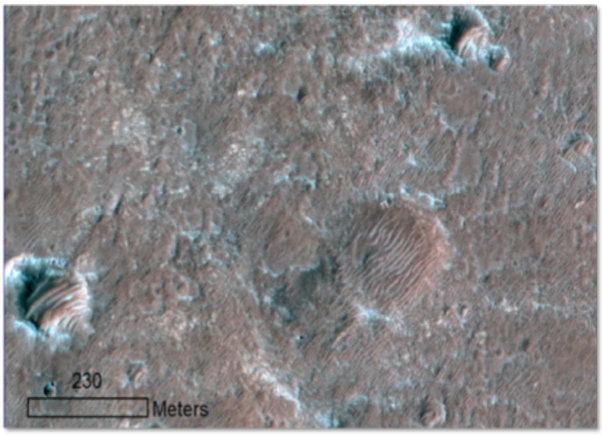


Figure 10. HiRISE coverage of Oxia Planum (top) and percentage of TARs detected (bottom)

7. CONCLUSIONS

The ExoMars mission is ambitious and inspiring in many ways and marks the first close collaboration between ESA and Roscosmos in planetary exploration. The rover to be delivered to the surface will carry a novel exobiology instrument suite, which will be the first to analyse samples from the subsurface of Mars.

The industrial consortium is breaking new ground to bring European technologies to the maturity level needed for the 2018 rover mission, among which achieving robust mobility capabilities –a fundamental technological objective in itself for ExoMars. All the elements of the mobility subsystem are based on innovative technologies in their domain. The BEMA is a highly optimised triple-bogie locomotion module, with a novel flexible-metallic wheel design and 18-actuators that offer sufficient agility for sophisticated manoeuvres and trajectory-following. The ADE actuates all the external mechanisms of the Rover Vehicle and includes an impressive set of features: simultaneous control of 12 BEMA actuators, distributed architecture over CAN-bus and survivability over a temperature range of 205°C (between -120°C and 85°C). A significant part of the ADE development effort is devoted to quality assurance activities towards the evaluation of EEE components and SMT processes.

An extensive test programme is put in place to verify and characterise the locomotion capabilities of the rover. Four well-specified soil simulants capture the span of regolith variation expected to be encountered on Mars. Finally, as the landing site selection process moves ahead, effort is going into the analysis of the candidate landing sites with respect to mobility risks.

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