18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID # 119

MMX-Rover: A small Rover for big firsts

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Abstract

MMX (Martian Moons eXploration) is a JAXA mission which aims to study the two moons of Mars, Phobos and Deimos. In addition to extensive in-situ scientific observation, the MMX probe is equipped to bring samples back from Phobos to Earth, and to deploy the CNES/DLR rover IDEFIX, onto its surface. IDEFIX mission is to investigate the Phobos surface properties, to secure the landing of the MMX probe itself and for scientific purposes. Another mission objective is to test some technological concepts, such as the use of CubeSat technology in the context of space exploration, the way to move in low gravity, and auto-navigation. To fulfil its mission, IDEFIX brings four scientific instruments: miniRad (Radiometer), RAX (Raman spectrometer), a pair of (stereo) navigation cameras, and two wheel-cameras. IDEFIX will be operated by two remote control centers, one in France and one in Germany, in close cooperation with the JAXA MMX ground segment.

The MMX mission will be launched in autumn 2026, and the landing of IDEFIX is presently scheduled for end of 2028/beginning 2029, after a first Phobos observation campaign by MMX probe and the selection of a landing site. IDEFIX operations on Phobos surface shall last at least 100 days.

IDEFIX mission will be the occasion of several firsts:

- First landing on Phobos
- First French and German rover,
- First rover aiming at driving, and experimenting auto-navigation, on a low gravity body,
- First dynamic analyzes of regolith at low gravity, thanks to its interaction with the wheels.

This paper will introduce the MMX rover mission objectives, the rover design, overall system composition and mission profile, with the outlines and principal constraints of the three main mission phases (Cruise, Landing, and Phobos Exploration). It will provide as well an overview of the mission calendar and main milestones.

Keywords: MMX, Rover, Phobos

Acronyms/Abbreviations

CNES	= Center National d'Etudes Spatiales
COTS	= Commercial Off The Shelf
DLR	= Deutsches Zentrum für Luft- und Raumfahrt e.V.
FOCSE	= French Operation Center for Science and Exploration
ISL	= Inter Satellite Link
LSS	= Landing Site Selection
MECSS	= Mechanical, Electrical, Communication Support System
MiniRad	= miniaturized thermal mapper
MMX	= Martian-Moons-eXploration
MUSC	= Microgravity User Support Center
NavCam	= Navigation camera
JAXA	= Japan Aerospace Exploration Agency
Phod	= Phobos day
RAX	= Raman spectrometer
RCC	= Rover Control Center
RF	= Radio Frequency
Rolbox	= Radiofrequency orbiter data communication interface box
SA	= Solar Arrays
SAS	= Sun Acquisition Sensor
SDB	= System Data Base
SKA	= Rover attitude control system
SLUD	= Separation, Landing, Uprightening and deployment
TC	= TeleCommand
TM	= TeleMetry
WheelCam	= Wheel Camera

1. MMX mission introduction

The MMX (Martian Moons eXploration) mission, led by Japan, will take off in 2026 to study the two moons of Mars, Phobos and Deimos [1]. In addition to extended scientific observation, the probe is equipped to bring back samples from Phobos [2], and will place a Franco-German mobile robot, named IDEFIX, on its surface.

The Martian Moons eXploration mission addresses two scientific objectives:

- Determine the origin of the moons of Mars and the process of planet formation within the Solar System.
- Specify the evolution processes of the Martian system (Mars, Phobos and Deimos)

Small in size, Phobos and Deimos could be asteroids captured by the gravitational field of Mars after a slow drift out of the main asteroid belt. If this is the case, they would be real time capsules that could explain the appearance of water on the terrestrial planets of the Solar System. Alternatively, these moons could have originated from a giant impact with the young planet Mars. This would make Phobos and Deimos direct witnesses of this collision, composed of fragments of the impacting object and Mars. By studying these small bodies closely, and by bringing back samples, the mission will attempt to provide definitive answers for the origin of the moons.

The return to Earth of more than 10 grams of samples from Phobos will also be an important technological step. Both for the extraction technique, but also for the profile of the mission itself.

In this context, the MMX spacecraft will measure the radiation of the Martian environment throughout its mission: its impact is a major potential obstacle for future exploration.

MMX is in the category of Martian probes weighing more than 3 tons at take-off, just like ExoMars, TGO, MSL / Curiosity and Mars2020 / Perseverance.

The MMX mission will spend 3 years in the Martian planetary system. It will first study Phobos, which is its main target, with progressive objectives. First, quasi-orbit observations of the largest of the two moons of Mars (11 km average radius) and the study of its surface using the onboard instruments. In parallel with this phase, the MMX scientific team will select two areas suitable for future MMX landings, with a view to collecting samples from Phobos by the probe, the heart of this mission. As part of the first dress rehearsal of this maneuver, during a descent to about 50 m above the surface, the small Franco-German IDEFIX rover of the mission will be released and begin its mission scheduled for 100 days (nominal duration) on Phobos.

The collection of samples on the ground, even if it benefits from Japanese feedback from the two Hayabusa missions on asteroids, will use a different technique. The MMX probe aims to land on the surface for several hours, on two different sites. Once landed it will use two different mechanisms to collect Phobos material: a core sampler, deployed by a robotic arm, will dig with a hollow tube about 2 cm below the surface, and a pneumatic sampler (made by NASA) will use pressurized gas to draw material from the surface into the sample container.

After completing the study of Phobos, the probe will head towards Mars' second moon, Deimos. The MMX probe will observe Deimos (6 km average radius) during a series of planned flybys to study precisely the composition of its surface and the origin of its formation. It will not land there and will remain at a safe distance until November 2030. The probe will then split into two, and the return module will ignite its engine to head towards the Earth. It will reach it in July 2031, and will release a capsule, specially equipped to cross the Earth's atmosphere. The latter will land in the desert in Australia, before being repatriated to Sagamihara (Japan) for the study of the first samples of the Martian system.

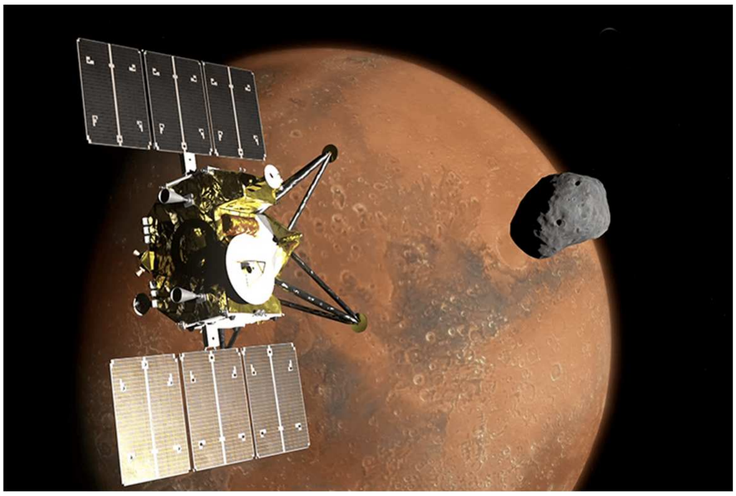

Fig.1: Artist's concept of the MMX mission © JAXA

2. Phobos presentation

Phobos is the larger and closest natural satellite of Mars, with a potato-like shape and an average radius of about 11 km. It is a dark body with no atmosphere, covered with craters and distinct geological features.

Phobos orbits Mars at an average semi-major axis of 9375 km, which is relatively close compared to the 3394 km of Mars radius. Its rotation is tidally locked, meaning it always shows the same face to Mars. Its orbital and spin period is remarkably short, about 7 hours and 39 minutes. The moon's rotation axis is nearly aligned with the Mars one.

Like other airless small bodies, Phobos experiences extreme temperature fluctuations, with surface temperatures ranging from -200 °C to 75 °C. It is an exceptionally dark body, similar to Carbon type (C or D type) asteroids.

Gravity at its surface is not homogeneous, due to heterogenetic mass distribution, that could cause local density variations. Also gravity is noticeably influenced by Mars' tides, meaning that the strength and direction change over a day. Current estimation of the gravity is that it could range from 0,003 m/s^2 near the equator to 0.007 m/s^2 at the poles. The size and the extremely weak gravity make operations around Phobos more similar to that around an asteroid rather than our Moon.

Phobos has already been observed by numerous Mars-orbiting spacecraft, including Viking 1, as well as by flyby missions like Rosetta. Extensive observation campaigns were conducted by Mars Global Surveyor (NASA), Mars Express (ESA), and Mars Reconnaissance Orbiter (NASA), but none of these observations has unlocked the secret of its origin.

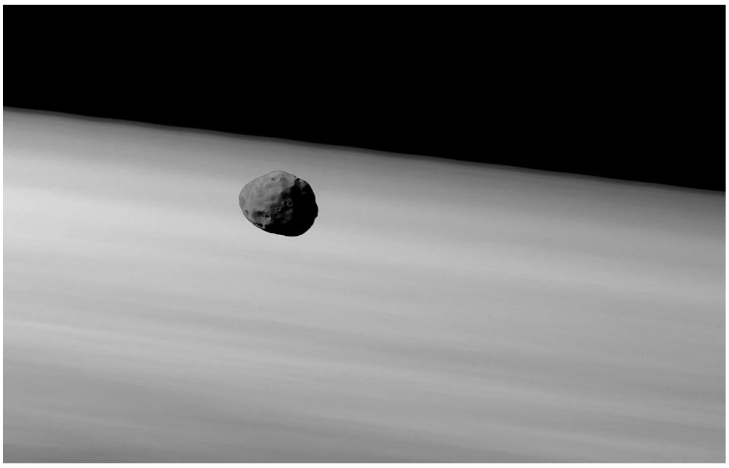

Fig. 2: Phobos above the Mars atmosphere © ESA/DLR/FU Berlin, G. Neukum, CC BY-SA 3.0 IGO

Fig. 3: Phobos, as imaged by Mars Reconnaissance Orbiter (Caltech-JPL, Arizona U. & NASA)

3. MMX Rover presentation

The IDEFIX rover, carried aboard the MMX probe, serves as a scout, a demonstrator, and an explorer, each role aligning with the mission’s three primary objectives [3]:

- Scout: Upon making contact with the surface of Phobos, IDEFIX will gather crucial data on the nature of the soil like its softness, adhesiveness, and potential electrostatic hazard. These insights will be helpful for JAXA, to prepare the landing of the exploration module of the MMX probe.

- Demonstrator: IDEFIX will prove that wheeled locomotion is feasible on a low-gravity celestial body [4]. By testing both traction and maneuverability, the mission will enhance our understanding of mobility on small bodies such as asteroids or Jovian moons. Additionally, it will serve as a testbed for autonomous navigation concepts, paving the way for future robotic explorers.

- Explorer: IDEFIX will explore Phobos in-situ, conducting observations and measurements at multiple locations [5,6]. IDEFIX aims to travel several dozen meters, analyzing materials at Phobos' surface, thermal variations, and even capturing the motion of regolith grains at a microscopic resolution of less than 100µm. This pioneering endeavor will mark the first-ever exploration of its kind, offering unprecedented data on the regolith and geological structure of small celestial bodies.

Fig. 4: IDEFIX Rover

4. Rover project organization

The IDEFIX Rover project is a collaborative project between DLR (German Aerospace Center) and CNES (French space agency), who equally share the project management, systems engineering, and operations.

The division of work for hardware design, development, and procurement, was as follows: DLR was mainly involved in the provision of the mechanical systems of the Rover (such as the structure, separation and locomotion systems), and in the supply of two scientific instruments. CNES was mainly involved in the provision of the avionic systems (such as on board computer, power control and distribution unit, battery, solar arrays, RF and thermal systems), in the development of the flight software and in the supply of the cameras. CNES was also in charge of the main AIT (Assembly, Integration and Test) of the Rover. A more detailed breakdown of the different parts of the rover with the respective sharing of responsibilities is presented in the next chapter.

CNES and DLR will also be both in charge of the Rover operations, therefore, two operation centers have been deployed: one at CNES- FOCSE in Toulouse, France, and one at DLR-MUSC in Cologne, Germany. The two control centers will be redundant, except for Flight Dynamics matters which will be mainly managed at CNES, and both will be able to coordinate and operate all the Rover functions. Only one control center at a time will be in charge of controlling the Rover, so the two control centers will hand over alternately the control [16].

Beside CNES and DLR, who are in charge of the programmatic and technical aspects of the project, the following laboratories contribute to the scientific aspects of this mission:

- DLR Institute of Planetary Research, 12489, Berlin, Germany, Principal Investigator for the MiniRad instrument measurement
- DLR Institute of Optical Sensor Systems, Berlin, Germany, Principal Investigator for the RAX instrument measurement
- OCA (Observatoire de la Côte d'Azur), at Nice, France, which ensures the French scientific coordination of the Rover mission
- LAM (Laboratoire d'Astrophysique de Marseille), at Marseille, France, Principal Investigator for the NavCams images

- ISAE-Supaéro (Institut Supérieur de l'Aéronautique et de l'Espace, aeronautics and space high school) – at Toulouse, France, Principal Investigator for the WheelCams images and movies
- University of Tokyo, Tokyo, Japan
- Centro de Astrobiología, INTA-CSIC, 28850, Torrejón de Ardoz, Spain

5. MMX Rover design

The development of the IDEFIX rover was constrained by cost and a tight schedule. To deal with these constraints, the design of the rover had to be as simple as possible, and to follow the CubeSat development approach, which is based on the use of COTS components and of instruments with significant heritage. This strategy made the development of the Rover in five years possible, from a blank sheet to a product ready to fly, land, and drive.

As for any machine sent into space, the Rover is structured around several modules that provide specific functions, but it also requires specific equipment remaining on board the MMX probe. In summary we can distinguish the three main following elements: the IDEFIX rover itself, which is the unit that will land on Phobos' surface, the Rolbox, which is the data interface between the Rover and the Spacecraft, and the MECSS, which is the mechanical and electrical interface between the Rover and the MMX Spacecraft. These three elements are described in more detail in the next sections.

5.1 IDEFIX Rover

The IDEFIX rover is a quite small rover, its mass is about 25kg and its size in stowed configuration (Solar Arrays folded and legs retracted) is about 40 X 40 X 20 cm^3. It is composed of the following main parts:

5.1.1 IDEFIX instruments

The instruments, responsible for achieving scientific objectives of this mission, are:

- NavCam: The NavCams are a stereo-bench of two cameras [7]. They use the same detector as SuperCam on Mars 2020 with a 2048 × 2048 panchromatic resolution, with an RGB Bayer filter. They are used for autonomous navigation, to get images of the landscape [17], as well as to provide context information for other instruments like miniRad, or to provide images of the environment for safe locomotion. The field of view for 3D reconstruction is about 2 meters in front of the Rover.

- WheelCam: These two cameras capture images of different wheels from distinct angles They use the same detectors as of the NavCams, The WheelCams achieve a spatial resolution of approximately 35µm at the center of the scene, enabling detailed characterization of regolith particle properties and size distribution [8]. Their primary function is to observe regolith movement around the wheels as the rover drives, providing critical insights into grain and soil behaviour. This data helps mitigate risks for MMX and enhances our understanding of regolith dynamics in Phobos' low-gravity environment. Additionally, colored LEDs will illuminate the scene at night, allowing for the detection of potential space weathering effects by analysing the wheel trench (e.g., blue/red Phobos or other variations).

- MiniRAD [9]: boarded to conduct thermal analysis. miniRad, derived from the heritage of Mascot's MARA instrument (Grott et al. 2017), is a radiometer designed to measure radiative flux across a wide scene in front of the rover using six thermopile sensors, each equipped with individual filters. Its observations will be fully contextualized, as its field of view aligns with the stereo field of view of the NavCams. In addition to assessing thermal properties, miniRad can also provide constraints on the mineralogy of the examined sites.

- RAX (RAman Spectrometer for MMX) [10]: Its primary objective is to determine the surface mineralogy of Phobos. The surface directly beneath the rover is irradiated with green laser light at 532 nm and the Raman spectrum between 535 nm and 680 nm (90 – 4000 cm^{-1}) is detected, providing fingerprint data for mineral identification. The rover has first to be lowered to approximately 8 cm above the surface by extending its legs. Once in its working range, the RAX internal auto-focus mechanism ensures precise focussing. RAX's observations are contextualized by images from the front WheelCam.

5.1.2 IDEFIX body

The IDEFIX body includes the following parts:

- A chassis, which is the main mechanical structure of the Rover, it is based on carbon fibre, composites and aluminium honeycomb.

- A locomotion system [11], developed at the DLR-Robotics and Mechatronics center. This innovative system includes four legs and four wheels, driven by eight independent brushless motors (one for each wheel, one for each leg) which allows a large diversity of control strategies. The wheels have been designed to drive on regolith with a wide range of characteristic, as there are still many uncertainties concerning the Phobos soil features.

- Four shutters to protect the optical parts of the instruments from dust during AIT, the journey to Phobos, and in particular during the landing on Phobos. The front shutter protects the NavCams and miniRad lens, the bottom shutters protect RAX and the two WheelCams respectively.

- Crashpads: Crashpads have been developed to absorb the energy of the impact on the solar arrays when the Rover will fall on Phobos surface. An innovative solution based on Aluminium foam has been developed especially for this purpose [12]. See picture of the crash pad on fig. 6.

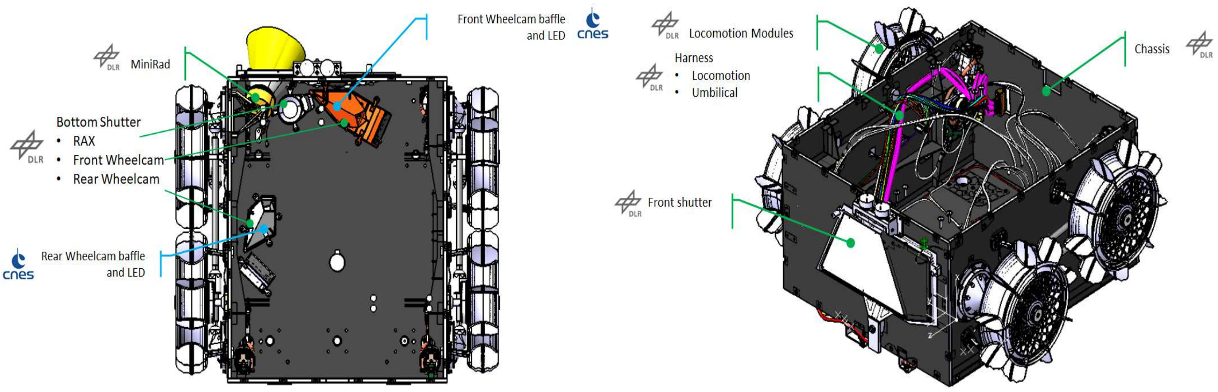

Fig. 5: IDEFIX body overview

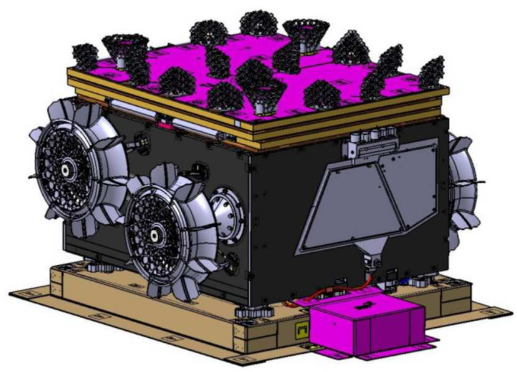

Fig. 6: IDEFIX overview with solar arrays in stow configuration and crashpads on the top

5.1.3 IDEFIX service module

The service module provides the power, thermal and data resources that the Rover need to fulfil its mission. It is composed of:

- A power system: which includes a rechargeable battery with a capacity of 160 Wh, based on SAFT Li-Ion cells (ExoMars heritage design), a deployable solar generator providing up to 50 W to recharge the battery, and a PCDU (made by EREMS) coming from CubeSat development.

- A communication system: The RF communication between the rover and the orbiter is performed thanks to an Inter Satellite Link protocol using two S-band transponders provided by Syrlinks [13]. Their design is a heritage of the Rosetta-Philae mission combined to the needs brought by the CubeSat markets. Data rate for uplink communication (commanding) is 32 kbps. Data rate for downlink communication (Telemetry) can be selected at 64 kbps (weak signal) or 512 kbps (strong signal). The mounted S-band Antenna, made by Anywaves, has a significant heritage in LEO mission.

- An On Board Computer: Developed by Steel Electronique, comes from CubeSat development (Angels). The CPU is based on a Zync-based processor, and the mass memory capacity is 2x128 Gbit, which is big enough to store all the data that will be produced during the mission.

- A thermal system: Due to the limited availability of electrical power, the design prioritizes minimizing power dissipation within the service module to reduce the need for additional heating. As a result, thermal control relies on minimizing heat leaks, achieved through insulating conductive coupling and multilayer insulation (MLI) within the chassis, and heaters for worst-case cold conditions. Dedicated heaters commanded by the MMX spacecraft are also used to keep the Rover in good thermal condition for when the Rover is attached on the spacecraft and in OFF configuration.

- A Sun Acquisition Sensor: the SAS, provided by LENS R&D, is a passive instrument composed of four photodiodes, used to detect the position of the sun. This information will be used to determine the Rover's attitude and the need to reorient the Solar Arrays, to get more energy.

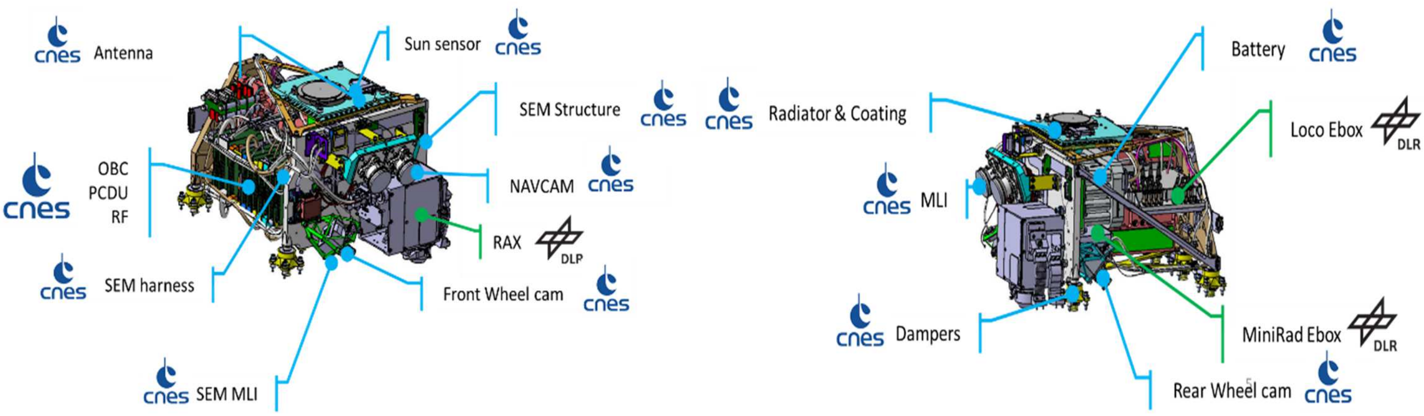

Fig. 7: IDEFIX service module overview

Fig 8: picture of IDEFIX ready to be embarked on the MMX probe © CNES

5.2 Rolbox

The Rolbox is the electronic box making the data interface between the Rover and the MMX spacecraft. When the Rover is attached to the MMX spacecraft the data are exchanged with the Rover through a dedicated umbilical, when separated the data are exchanged by RF.

The Rolbox is composed of OBC, PCDU and RF electronic boards similar to those used into IDEFIX, as well as for the antenna.

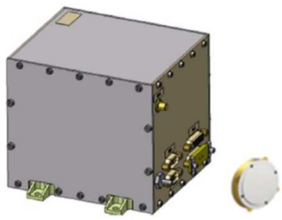

Fig. 9: Rolbox and the S band antenna

5.3 MECSS

The MECSS is the mechanical interface with the spacecraft, and the system that will make the separation from it, thanks to HDRMs and a push off mechanism. The MECSS is made of Carbon honeycomb, its design is a heritage from the separation system of the MASCOT/Hayabusa-2 probe.

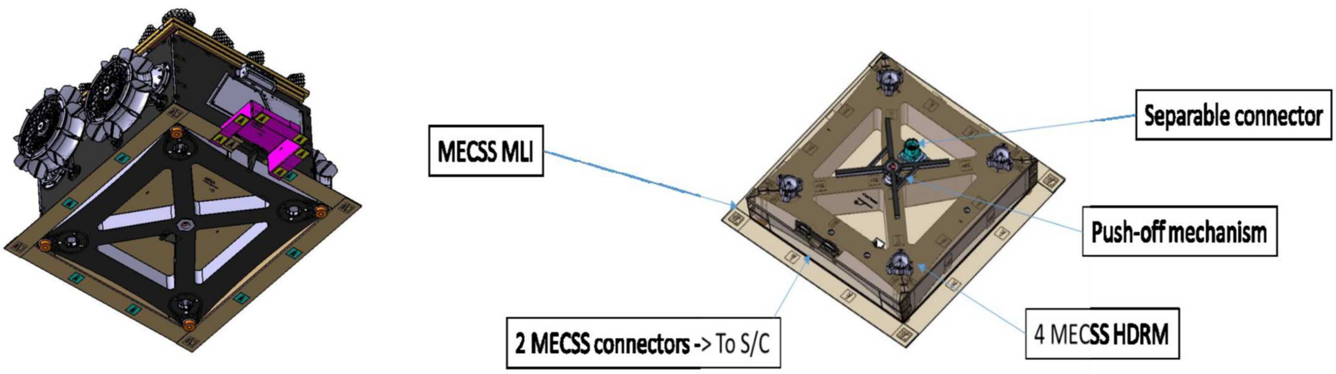

Fig. 10: MECSS pictures

6. Rover mission profile

The Rover will be launched with the MMX spacecraft in October 2026, from Tanegashima JAXA Space Center in Japan, with the H-3 launcher. The journey to Mars will last almost a year, the insertion of the probe into orbit of the red planet is planned for August 2027. The Rover will not be delivered to Phobos immediately, actually when in orbit around Mars the MMX probe will first start the observation of Phobos, that will provide valuable information for the selection of the landing sites. Currently the landing of the Rover is scheduled in late 2028/early 2029, but this date may change depending on the evolution of the main MMX mission strategy and constrains. Once on Phobos surface the Rover will execute its mission for at least 100 days. In case the MMX probe performs its own landing within the 100 days, the mission of the Rover will be put on hold for few days. After the 100 effective days, the Rover could extend its mission, depending on the availability of the spacecraft to relay the communication between the Rover and Earth.

The Rover will go through three main operation phases, the so call “Hitchhiking” phase, from Launch to Rover separation, the SLUD (for Rover Separation, Landing, Up righting and Deployment) phase, and then the On Phobos phase, the ultimate goal and most exiting phase of the mission. All these phases have operational specificities that is explained in the next sections.

6.1 Hitchhiking phase

Hitchhiking phase is the period from launch to when the Rover will be switched ON prior to its landing on Phobos’ surface. During this phase IDEFIX and the Rolbox are OFF most of the time. Despite the OFF status the MMX spacecraft provides electrical power for the heaters to keep IDEFIX internal equipment in the right temperatures range.

Periodically all along this phase, the Rolbox and IDEFIX will be switched ON for health check and maintenance. More specifically a functional check of all IDEFIX subsystems is planned to be performed every 3 months, this functional check will also be the occasion to calibrate the instruments in space environment. The execution of the functional check on IDEFIX will last up to 10 hours, but the preparation and the retrieval of the data will require several days. Additionally, a battery maintenance is required to be performed every 6 months to keep the battery healthy. This maintenance will consist of fully charging the battery for several days and then on reducing the charge to its storage level. Hitchhiking phase will be the only phase in which the IDEFIX software update will be possible if necessary. By the end of the Hitchhiking phase IDEFIX will be prepared for the landing, the battery will be fully charged, some settings which depend on the landing site (such as the SKA algorithm), and on the result of the functional check (such as the SA deployment system) may require to be applied.

In addition to the operation on the Rover, the hitchhiking phase will be dedicated to prepare on ground the Phobos exploration phase. This preparation will mainly be dedicated to train the operators, and to refine the operation plans, taking into account fresh information coming from the Phobos surface observation made by the MMX probe, and from the selected landing site.

In this regard, the selection of landing site is one of the crucial preparation activities that will occur during the Hitchhike phase. Because the release of the Rover on Phobos will take place during a rehearsal of the landing of the MMX probe, the process of selection involves a combined effort to identify a convenient landing site for the MMX probe and the Rover. The choice is influenced in priority by criteria which ensures a safe landing and survivability, such as the topography of the ground, the rock distribution, the sun illumination, the practicality for communication, in addition to that science interest can also be taken into account. The selection will consist of making a preselection of few dozen convenient sites and making a progressive elimination of these sites considering the new data products resulting from MMX probe observations and the different criteria for both Spacecraft and IDEFIX Rover.

In the Rover team, the selection of the landing site is handled as part of the overall LSS process by a specialized team called LARD (LSS Assessment, Ranking, and Decision). This team is supported by the CNES Flight Dynamics team, which calculates most of the required products. The CNES FD team will leverage its expertise gained from previous missions, such as landing site selection for Philae (on board the European probe Rosetta) and MASCOT (on board the Hayabusa-2 probe).

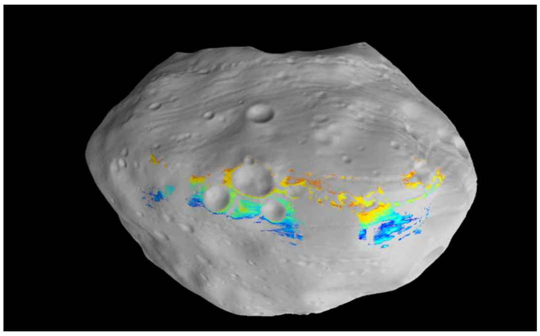

Fig 11: example of map of convenient landing sites produced by Rover FD team

6.2 SLUD phase

The SLUD is a short, but very critical, phase dedicated to the landing of IDEFIX. It will be executed at the occasion of the MMX spacecraft landing rehearsal. During this phase the MMX spacecraft will descent to the Phobos surface to an altitude of about 50m to separate the Rover, and then it will quickly go back to its usual observation altitude.

The SLUD phase starts when IDEFIX will be switched ON before its separation from the spacecraft (about 10hrs before separation), and ends when it is able to survive on Phobos. (i.e. when solar arrays are deployed and pointed towards the sun).

During the pre-separation sequence an IDEFIX and Rolbox health check will be performed, the Rover battery will be fully charged to 100%, and IDEFIX's internal temperature will be increased to the highest tolerated value to avoid excessive energy consumption for heating after separation. In the minutes before the separation the RF link will be activated between the Rolbox and IDEFIX, and the power supply from the spacecraft will be disconnected.

When scheduled, and if all conditions are satisfied, the MMX spacecraft activates the separation actuator located on the MECSS to release IDEFIX. About 1 to 2 minutes after separation IDEFIX will crash gently on the Phobos surface, without attitude control, at a speed of less than 1 m/s. IDEFIX has been designed to withstand this type of landing, and the crash pads provide additional protection for the solar panels.

Throughout the descent and for a few dozen of seconds after its touchdown the IDEFIX Rover will continuously transmit telemetry to the Rolbox, which remains on the MMX spacecraft. However, this transmission will be interrupted once the MMX spacecraft ascends back to its observation altitude, moving out of the IDEFIX's field of view.

After several bounces, and at a predefined time of about 15 min, IDEFIX will up right itself using a specific sequence of movements of its legs and wheels (allowing it to ensure that it is in the right direction regardless of the final landing orientation). Then the solar arrays will be deployed. In case IDEFIX estimates that its current orientation is not sufficient to charge the battery, it will automatically perform an attitude manoeuver, using its legs, to reach an orientation optimizing the charge of the battery over a Phod [14].

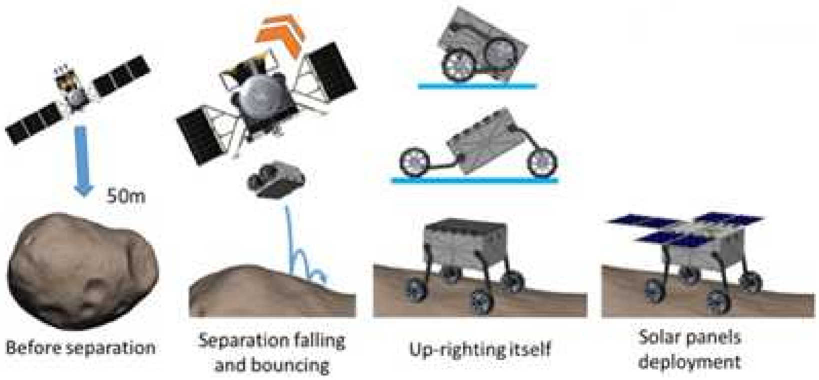

Fig 12: sequences of the SLUD phase

RF communication between the IDEFIX and the Rolbox will be recovered only a few hours later, when the spacecraft will fly again above the landing site. The Phobos exploration phase can start.

6.3 On Phobos phase

The On Phobos phase will start by a commissioning sub phase in which IDEFIX will finalize its "On Phobos" configuration (sensor shutter opening) and be functionally tested. The duration of the commissioning sub phase will be about 1 month, during which science and experimental activities will already begin. After commissioning, IDEFIX will continue its mission for about 2 months.

During this phase, the Rover will carry out the following key activities:

- Survive: When fully charged, IDEFIX's battery can sustain operations on Phobos for approximately two Phobos days (Phods). To survive beyond this period, it must generate energy from sunlight via its Solar Arrays. The efficiency of power generation depends on optimizing the Solar Arrays' orientation toward the Sun, which may need adjustment after any movement or in response to attitude instability (e.g., due to an uneven surface). The attitude control system (SKA) of IDEFIX will autonomously manage Solar Arrays optimization [14], though adjustments can also be made via commands if necessary. However, due to design constraints, repositioning the Solar Arrays is only possible around local noon. We must point out that the Solar Arrays are not mobile, and that re-pointing them requires a change in IDEFIX's attitude.

- Communicate: Establishing and maintaining communication with the Rover Control Center is critical and must be carefully managed to ensure regular contact. Direct communication between Earth and IDEFIX is not possible; instead, all transmissions are relayed through the MMX spacecraft. This requires close coordination with spacecraft operations, as communication opportunities depend on the spacecraft's position, attitude, and its availability to operate the Rolbox communication system.
  Typically, a communication link between IDEFIX and the Rolbox will be available for two out of three Phods. One Phod out of three is reserved for communication between the MMX spacecraft and Earth. During these Earth-communication periods, the spacecraft will be unable to communicate with IDEFIX.

- Drive: Driving sessions [15] could be done for either moving IDEFIX on the Phobos surface, or in the purpose to "disturb" the regolith grains to study them. The speed of IDEFIX will be about one millimetres per second, to prevent it from turning upside down due to the low gravity. Rover movement could be piloted by commands coming from the Rover Control Center, or be piloted autonomously by one of the two auto navigation systems. One auto navigation system is developed by the DLR, at the Institute of Robotics and Mechantronics in Weßling, and the other one is developed by the CNES in Toulouse, and is an adaptation of the autonomous navigation software originally developed for the ExoMars rover.

- MiniRad measurement: Prior the measurement IDEFIX can be moved to point the sensor toward the wished ground target. Measurement is planned to be performed on the same target during a full Phod, in order to browse all the temperature condition of the soil.

- RAX measurement: RAX sensor requires to be focused on its target to provide a valid measurement. This need for focus makes the experiment delicate, as the rover's body will need to be raised (by moving the legs) and then gradually lowered to place the RAX sensor within the necessary autofocus range.

- Images capture: NavCam and/or WheelCam images are required for almost all Rover activities. They will be used to check IDEFIX safety by observing the environment, to make Regolith science (images are raw material for this study), to check result of any Rover movement, to act as eye for auto navigation, to provide scene context for MiniRad & RAX measurement.

The implementation of these activities is subject to different constraints [16]. For example, because of power restrictions, all these activities, except images acquisition, will be executed one at a time, and depending on the mean illumination of the actual landing site it may require several Phods to recharge the battery before resuming or changing activity. Another example is that Data volume will require also to be managed carefully to not generate bottlenecks in data pipes. So activities that produce big volume of data should not be scheduled jointly.

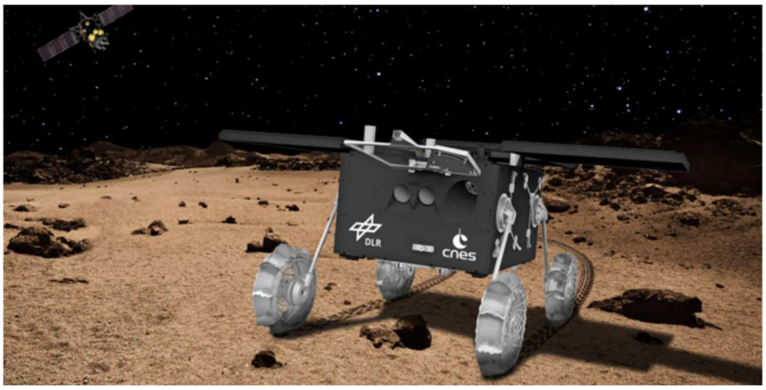

Fig 13: Artist view of IDEFIX exploring Phobos

7. MMX Rover operation organisation

As explained previously, two control centers, one at CNES and one at DLR, has been deployed to operate the IDEFIX Rover. Each of both control centers host Ground and Flight operators, in charge of the operations coordination, operation planning, on board resources management, commanding and mission data storage and distribution [16]. The two control centers will alternate the responsibility of the operation, except during the SLUD due to the short duration of this phase. Independently of which control center is on duty, the operation will be conducted exactly on the same manner with the same rules, same constraints, same or similar tools and equal operational interfaces.

Alongside these operators, a Flight Dynamics Team at FOCSE -CNES -Toulouse, provides information required for the Rover operation, such as the orbital events for IDEFIX (sun illumination, RF communication slot prediction, instrument dazzling prediction, etc.), and IDEFIX position and attitude.

Designers of the Rover systems are also deeply involved in the operations, as they are expected to provide inputs to the control centers for what concerns the handling of their unit, to check and approve the operational plans and to make detailed analyzes of the data generated by their unit. This group also includes the Mobility Team [15], which is not responsible for a unit, but is in charge of the movement and of the navigation of IDEFIX on the surface of Phobos.

The science teams will mainly be involved in the mission-objective aspects. They will have to define the experiment “targets” and to analyze the instrument measurements.

Each group plays a crucial role in ensuring the success of the mission, from system operations to scientific discoveries.

For all phases of the mission, the commands and telemetry required to operate IDEFIX will be relayed by the MMX spacecraft, which is controlled by the MMX control center at ISAS in Sagamihara (Japan). In practice, the Rover Control Center must supply the JAXA control center with the Rover commands, the JAXA control center then uploads these commands to the MMX spacecraft (among other commands for spacecraft operation), the MMX spacecraft transmits the commands to the Rolbox, and the commands are later sent to IDEFIX, when a communication link can be established between the Rolbox and IDEFIX. The same applies in the opposite direction for the telemetry. This chain of commands and telemetry makes real-time operations impossible. Indeed, the average delay between the sending of the command by the Rover Control Center and the retrieval of the TM acknowledging receipt of this command is between 2 and 3 terrestrial days.

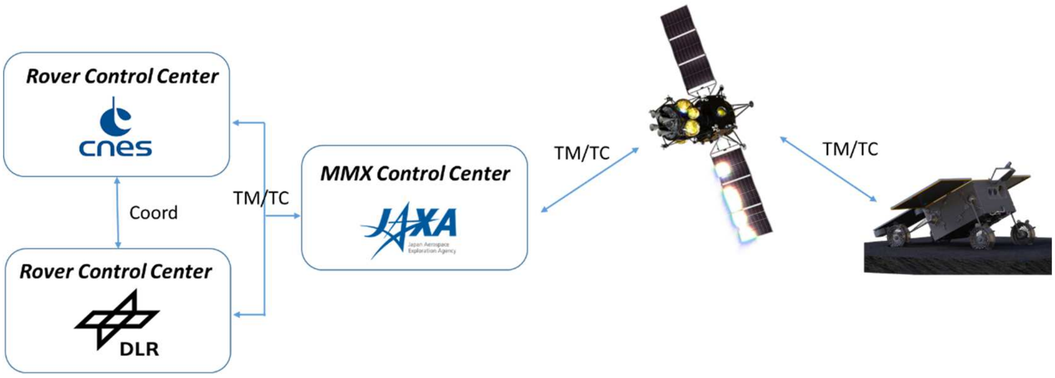

Fig. 14: Communication chain between the RCCs and IDEFIX

8. Project progress

Manufacturing of IDEFIX, Rolbox and MECSS has been completed, and these units have been integrated into the MMX spacecraft. They already have completed a series of tests, ranging from simple interface tests with the MMX spacecraft, to space environment resistance tests (thermal and vacuum test) with the spacecraft. In addition to the participation to the MMX test campaign, IDEFIX must follow until the launch its own maintenance program, and perform periodic functional checks and battery maintenance, similarly as what it is required in flight during the hitchhiking phase.

DLR and CNES Rover Control Centers have been developed, and tested in the hitchhiking configuration. The Hitchhiking activities for the rover have been prepared, and operators have started the training for this phase. Intensive, representative training for the Hitchhiking operations, known as Operational Qualification, is scheduled to take place within the six months prior the launch next year.

Although less pressing, due to the landing planned for late 2028, preparation for the operations of the SLUD and Phobos exploration phase has also begun, to take advantage of the still fresh knowledge of the recent development of IDEFIX, and to avoid the teams being overwhelmed during the hitchhiking phase, as there will also be the operations of this phase to be carried out.

9. Conclusions

The IDEFIX rover is an ambitious, but risky mission. Following the CubeSat philosophy, it enables significant scientific returns at a relatively low cost. This approach required to make compromises on reliability (e.g. there is no redundancy) and added constraints on where IDEFIX can land (IDEFIX cannot survive everywhere on Phobos).
The short development timeline was achievable thanks to the availability of CubeSat technology and heritage from instruments previously flown on other missions. The manufacturing of IDEFIX and its additional systems is now finished and these devices behaved as expected during all the qualification tests performed so far.
The project has entered a new chapter, with the development of the two control centers and preparations for the operation. Preparations for the hitchhiking activities are well advanced, and those for the subsequent phase have begun. An extraordinary adventure is ahead.

Acknowledgements

The authors would like to thank the complete rover team, including the teams responsible for the subsystems and instruments, and the DLR and CNES agencies for supporting project. Particular thanks go to JAXA great support and cooperation and the wonderful integration into MMX team.

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