

RESEARCH ARTICLE

Open Access



Science operations of IDEFIX, the MMX Phobos rover

Stephan Ulamec^{1*} , Patrick Michel², N. Murdoch³, P. Vernazza⁴, M. Grott⁵, J. Knollenberg⁵, S. Schröder⁵, H.-W. Hübers⁵, Y. Cho⁶, O. Prieto-Ballesteros⁷, J. Biele¹, S. Tardivel⁸, F. Buse⁹, H. Miyamoto⁶, C. Krause¹, D. May¹, C. Delmas⁸, J. Baroukh⁸, S. Mary⁸ and M. Grebenstein⁹

Abstract

IDEFIX, a rover to be delivered to the martian moon Phobos, is part of the Martian Moons eXploration (MMX) mission by the Japan Aerospace Exploration Agency, JAXA. MMX will explore both moons of Mars remotely but will also land on Phobos and collect samples from its surface and return them back to Earth. The IDEFIX rover will be released from the main spacecraft during its landing rehearsal at an altitude of about 40 m. It will fall to the surface, probably bounce several times and upright itself after having come to rest by applying an autonomous sequence of the deployment of its locomotion system. This sequence is followed by deployment of the solar generator and recharging of the batteries. After commissioning, on-Phobos operations are planned for at least 100 (Earth-) days. Sequences of science operations (instrument measurements), driving, battery charging and communications with Earth (via the main spacecraft) will alternate in a way to maximize scientific return and fulfill technical demonstration goals. IDEFIX accommodates a payload of four scientific instruments: a Raman spectrometer (RAX), a stereo pair of cameras looking forwards (NavCams; also used for navigation), a radiometer (miniRAD), and two cameras looking at the wheel-surface interface (WheelCams). MMX will be launched in autumn 2026, the Rover delivery to Phobos is currently planned for late 2028, before the first touch down of the spacecraft and sample collection. The Rover is a contribution by the Centre National d'Etudes Spatiales (CNES) and the German Aerospace Center (DLR) with additional contributions from INTA (Spain) and JAXA (Japan).

Keywords Phobos, Mars Moon eXploration MMX, Rover, IDEFIX, Science operations, In-situ

*Correspondence:

Stephan Ulamec
stephan.ulamec@dlr.de

¹ German Aerospace Center, DLR, Space Operations and Astronaut Training, MUSC, 51147 Cologne, Germany

² Laboratoire Lagrange, Université Côte d'Azur, Observatoire de La Côte d'Azur, CNRS, Cedex 4, 34229, 06304 Nice, CS, France

³ Institut Supérieur de L'Aéronautique et de L'Espace, ISAE-SUPAERO, Université de Toulouse, 31055 Toulouse, France

⁴ Aix Marseille Université, CNRS, CNES, Laboratoire d'Astrophysique de Marseille, Marseille, France

⁵ German Aerospace Center, DLR, Institute of Space Research, 12489 Berlin, Germany

⁶ University of Tokyo, Tokyo 113-0033, Japan

⁷ Centro de Astrobiología, INTA-CSIC, 28850 Torrejón de Ardoz, Spain

⁸ Centre National d'Etudes Spatiales, CNES, 31401 Toulouse, France, Germany

⁹ German Aerospace Center, DLR, Institute of Robotics and Mechatronics, 82234 Weßling, Germany

1 Introduction

The MMX Rover IDEFIX, a contribution by the Centre National d'Etudes Spatiales (CNES) and the German Aerospace Center (DLR) to the Martian Moons eXploration (MMX) mission by the Japan Aerospace Agency, JAXA, which will investigate the martian moons Phobos and Deimos (Kuramoto et al. 2022; Kawakatsu et al. 2024) will be a bridging element between remote observations from (quasi-) orbit and analysis of samples, returned to Earth. Technologically, IDEFIX is a wheeled rover demonstrator for low-gravity bodies and, as a scout, can help to assure a safe landing of the MMX spacecraft later-on. By investigating undisturbed surface areas of Phobos, IDEFIX offers unique possibilities to also investigate scientifically the physical properties of the surface material and its

response to the wheel interactions, as well as to characterize the homogeneity of the surface in the 100 μm to tens of meter range.

The minimum success of the IDEFIX mission is defined by the first successful landing on a martian moon, including a demonstration of uprighting as well as mobility on Phobos.

In addition to the science objectives (described below) the success criteria can be listed as:

- Successful landing and uprighting (World's first landing on Phobos)
- Gather landing site de-risking data for the MMX Spacecraft (JAXA mission goal for IDEFIX)
- Images of the surface with mm to sub-mm resolution (NavCam, Wheelcams)
- At least one successful RAX measurement (first scientifically valuable RAMAN spectrum of Phobos, first mineralogical science of MMX mission)
- At least one MiniRad measurement sequence covering a full diurnal cycle
- Mobility: Successful first drive with a Wheelcam acquiring images in movie mode (World's first driving on a milli-g gravity body, regolith science)
- Autonomous driving demonstration (Auto-Nav Science)

Note, that there is, e.g., no requirement for a minimum distance for the rover to travel, as this will be highly dependent on a currently unknown terrain and the actual scientific needs (in this context see Lorenz 2020).

The scientific objectives of IDEFIX are explained in detail in (Michel et al. 2022; Ulamec et al. 2023), the outline of the MMX mission is described by Nakamura et al. (2021) with adaptations to a launch date in 2026 by Kawakatsu et al. (2024).

2 Scientific objectives of IDEFIX

The scientific objectives of IDEFIX are embedded in those of the overall MMX mission (Kuramoto et al. 2022). They do complement the science that can be performed remotely with the instruments onboard the main MMX spacecraft or the returned samples (Michel et al. 2022; Ulamec et al. 2023).

The data provided by the rover instruments (see below) are of particular interest regarding regolith properties and dust grain dynamics in the low-gravity environment of Phobos, surface processes like space weathering and potential electrostatic dust lofting, the geological history and the composition of Phobos and its thermal and mineralogical properties. The data set obtained by the rover in-situ will provide ground truth and a geological context for the samples that are going to be returned to Earth.

They will help understanding the origin and history of Phobos.

The Rover will perform (Ulamec et al. 2023):

- Characterization of the surface terrain by close-up and high-resolution imaging
- Regolith science (e.g., geometrical properties like the grain size distribution, mechanical properties like surface strength and cohesion, and dynamical properties)
- Measurements of the mineralogical composition of the surface material (by Raman spectroscopy)
- Determination of the thermal properties of the surface material (surface temperature, emissivity, thermal conductivity, layering)

Measurements at various locations on the surface of Phobos will help to determine the heterogeneity of the surface material.

By characterizing the regolith mechanical properties and high-resolution local terrain and rock maps, the risk of the landing (and sampling) of the main spacecraft can be reduced, the rover, thus, acts as a scout for the MMX sampling mission.

2.1 Overall rover system

The overall IDEFIX system consists of the flight segment to be launched aboard the MMX spacecraft as well as two complementary ground segments, described in more detail in Sect. 3.

The communication between the rover ground segment and the flight segment is linked via the JAXA ground segment, ground stations and the MMX main spacecraft (Ulamec 2019).

The IDEFIX flight system consists of the rover (see Fig. 1), which will be released and operate on the surface of Phobos as well as the Mechanical Ejection and Separation System (MECSS) and the RolBox, which remain on the mothership. The spacecraft mounted MECSS attaches the rover to the spacecraft, provides the electrical interfaces during flight and will assure reliable ejection of the rover from the spacecraft. The spacecraft-stationary RolBox, equipped with a dedicated onboard computer, links the rover to the spacecraft using the RF and antenna systems. It is able to accommodate telecommands and telemetry in a flexible way, as link times from MMX to either Earth ground stations, or the rover, vary in a complex way, e.g., due to limited visibility periods.

2.2 Instruments (NavCam, WheelCam, RAX, miniRAD)

The rover design allows the accommodation of four PI (Principal Investigator) instruments (see Table 1), which are:



Fig. 1 IDEFIX rover flight model, during integration at MELCO in Kamakura, Japan

2.2.2.1 NavCams

The navigation cameras consist of a stereoscopic pair with a field of view (diagonal) of 122°, an angular resolution of 1mrad (1 mm at a distance of 1 m) and a depth-of-field of approximately 35 cm to infinity. Each camera is equipped with a 2048×2048 pixel CMOS detector and RGGB Bayer filters. The spectral response of each camera, which integrates the characteristics of both the detector and the optics, ranges from approximately 400 nm to 800 nm. For a full description of the cameras, we refer the reader to (Théret et al. 2024; Virmonitois et al. 2025, submitted), as they were already present, with the same characteristics, on the Emirate Lunar Mission (ELM) Rashid rover (Almaeeni et al. 2021). They have been geometrically and radiometrically calibrated (Vernazza et al. 2025, this issue).

By providing stereoscopic images of the area around IDEFIX up to the horizon, the navigation cameras aim to provide answers to many of the main scientific questions of the MMX mission concerning the surface geology of Phobos (see Vernazza et al. 2025, this issue). Specifically,

the collected images will allow digital terrain models (DTMs) to be delivered with a ground sampling dimension better than 1 cm/pixel for the first meter. These high-resolution DTMs along with the images themselves will be used to i) produce a photo-geologic map of each imaged scene, ii) constrain the surface roughness/waviness, iii) characterize the size, shape and distribution of particles/boulders larger than a few mm in diameter and those of small impact craters, iv) identify groove-like patterns, v) attempt to constrain the load bearing strength of the regolith, vii) determine the morphology and texture (clasts, joints) of boulders and/or outcrops, viii) understand the effects of space weathering on Phobos (in terms of albedo and spectral slope), ix) assess the presence of foreign material on Phobos, x) study erosion processes affecting rocks, including fragmentation by impacts and thermal cycling, xi) quantify dust transport across the surface and finally xii) shed some light on the origin of the color dichotomy if both blue and red materials are present in the field of view.

2.2.2.2 WheelCams

The two WheelCams (Murdoch et al. 2025, this issue) are placed on the underside of the rover, each looking at a different rover wheel. Each WheelCam instrument consists of the detector, the optics and a set of co-located LEDs. The WheelCam image sensors (Virmonitois et al. 2025, submitted) are panchromatic and consist of a 2048 by 2048 array, with each pixel having a 5.5 μm pitch. The optics provide a field of view of 32.5° and a pixel resolution of approximately 100 μm at the center of the image. The WheelCam optics are tilted with respect to the detector providing a focus on a plane positioned near the ground with a depth-of-field of about ±5 cm relative to this plane. As the field of view of the WheelCams will almost always be in the shadow the WheelCams are equipped with 4 white LEDs intended for use while driving and 3 color LEDs (590 nm, 720 nm, 880 nm) to allow for multispectral imaging. The electro-optical performance of the flight model WheelCams has been fully characterized at several temperatures and a full

Table 1 MMX Rover instruments

	Type	Mass [kg]	PI institute(s)
NavCams	Stereo navigation cameras	0.4	LAM, Marseille
WheelCams	Wheel cameras	0.22	ISAE-SUPAERO, Toulouse
RAX	Raman spectrometer	1.51	DLR, Berlin; INTA, Madrid, UVA, Valladolid and Univ. Tokyo
miniRAD	Radiometer	0.34	DLR, Berlin

geometrical calibration has also been performed (Murdoch et al. 2025, this issue).

The WheelCams are protected by a transparent shutter (like the other instruments). The shutter will be opened after the deployment and uprighting sequence is complete. The WheelCams can be operated in both an imaging and a movie mode, the latter is intended to be used during driving.

The WheelCams will capture in-situ images of Phobos' surface, enabling the examination of the mechanical and dynamic properties of its regolith by observing the surface and the interactions between the rover wheels and the regolith. These observations will aid in interpreting data collected by the instruments onboard the main MMX spacecraft and help mitigate risks associated with the spacecraft's sampling operations. The specific WheelCam science objectives are (i) Determine the physical properties of the regolith particles, (ii) Determine the bulk mechanical properties of the regolith, (iii) Determine the dynamical behavior of the regolith, (iv) Observe layering in the shallow sub-surface, (v) Constrain on the mineralogical composition of the surface material, (vi) Assess space weathering, (vii) Determine regolith geological classes and (viii) Constrain the absolute local gravitational acceleration. For a full description of the WheelCams and the associated science objectives the reader is referred to Murdoch et al (2025, this issue).

2.2.3 RAX—Raman Spectrometer for MMX

RAX is a compact Raman spectrometer that was developed specifically for the MMX IDEFIX rover for in-situ mineralogical analysis (Hagelschuer et al. 2019, 2022; Cho et al. 2021). It has a volume of about 1 dm³, a mass of 1.5 kg and is placed at the underside of the rover measuring downwards to the ground (see flight model of spectrometer unit in Fig. 2). After the rover has lowered its body height and placed the RAX instrument into its working range of 80 mm, the integrated opto-mechanical autofocus is used, focusing the green (532 nm), frequency-doubled Nd:YAG laser for excitation (Rodriguez et al. 2019) onto the surface. A spot of 50 µm is analyzed there. Backscattered light is then collected back through the autofocus subsystem, Rayleigh light is filtered out and the remaining photons are guided through the RAX spectrometer module onto a 3D-plus CMOS detector (Sellier et al. 2019). RAX covers a spectral range of 535 to 680 nm which corresponds to a Raman shift of 90 to 4000 cm⁻¹ with a resolution of about 10 cm⁻¹. A so-called Verification Target (VT) is also part of the payload. This deuteriated polyethylene terephthalate (PET) pellet (Moral et al. 2023) is attached to the MECCS plate and can be measured as long as the rover is attached to the main spacecraft to demonstrate and monitor the functionality and

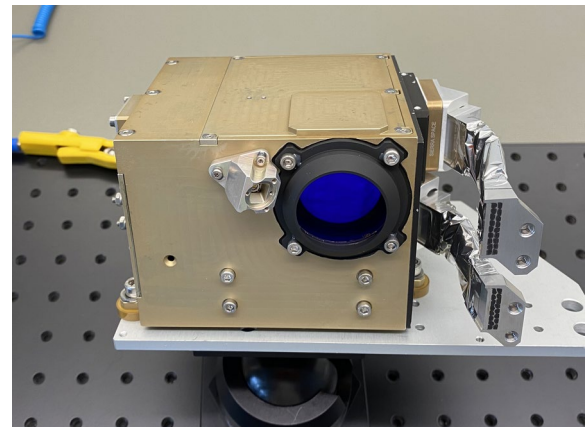


Fig. 2 The “Raman for MMX” (RAX) spectrometer flight model (FM) for in-situ mineralogical analysis on Phobos. Integrated into the rover, the bluish instrument window where the laser is exiting and the backscattered signal is entering the RAX instrument, is facing downwards to the ground. On its left side in the picture, the RAX light emitting diode (LED) can be seen that can be used to illuminate the sample. On the right side, the two thermal heat switches can be seen

performance of RAX during cruise. For improved data quality, two thermal heat switches are connecting RAX via graphene straps to the rover chassis to transfer heat away when the instrument becomes too warm (> 18 °C).

The spectral range of RAX enables detection of a wide variety of minerals, capturing vibrational features ranging from low-frequency lattice modes to high-energy bond stretches involving hydrogen atoms. Both primary and altered mineral phases can thus be identified. During instrument performance testing we measured signal-to-noise ratios (SNRs) of 41 for silicon (521 cm⁻¹), 60 for calcite (1086 cm⁻¹), and 28 / 34 for olivine (820 cm⁻¹ and 850 cm⁻¹) with a laser power of 20 mW on a spot size of 50 µm for integration times of 1 s and for instrument temperatures of +40 °C. This temperature is the worst case in terms of noise and measurements on Phobos are expected to be obtained at much lower temperatures, considerably improving the SNR of the Raman features. The SNR of the strongest Raman feature (1570 cm⁻¹) in the data of the RAX VT is approximately 300 measured at -45 °C (Hagelschuer et al. 2022).

2.2.4 miniRAD

The miniRAD instrument will measure the thermal infrared surface emission in six wavelength bands to determine surface brightness temperature within the instrument's field of view. Figure 3 shows the flight model. The instrument measures radiative flux using thermopile sensors (Kessler 2005) and the design is based on the Rosetta MUPUS thermal mapper (Spohn et al.

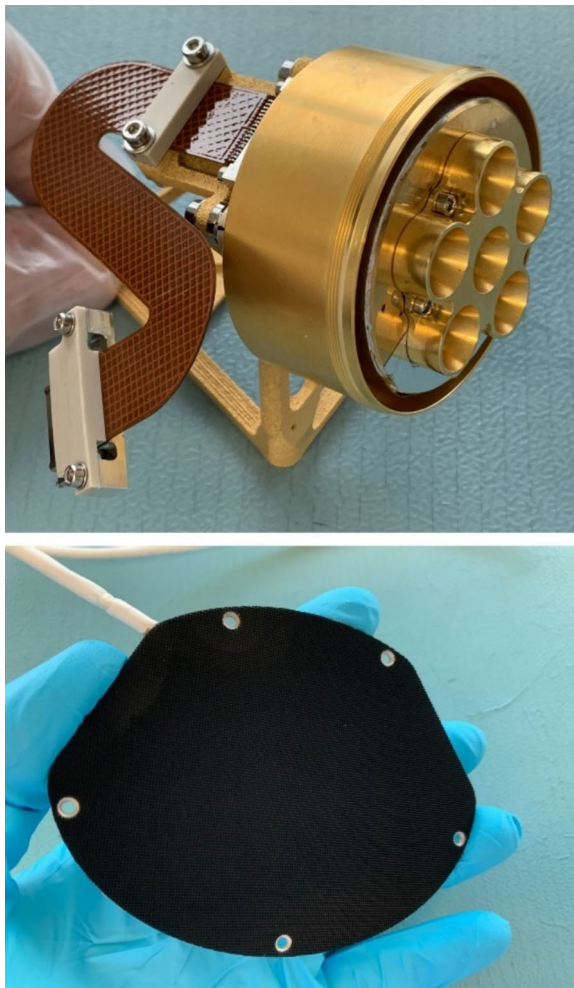


Fig. 3 Top: The miniRAD sensor head showing six apertures for the individual infrared sensors as well as the mounting bracket and flexible harness, which serve to thermally decouple the sensor head from its environment and enhance the sensor head's temperature homogeneity. Bottom: The miniRAD calibration target, which is mounted on the IDEFIX shutter and will be used for in-flight calibration during cruise. The target is micro-structured for maximum emissivity and can be temperature controlled to provide a defined stimulus to the miniRAD sensors. Details of the instrument design are discussed in Knollenberg et al. (2025)

2007, 2015), MARA, the radiometer aboard MASCOT (Ho et al. 2017, 2021), a small lander of the JAXA Hayabusa2 mission (Grott et al. 2017, 2019), and the InSight radiometer (Spohn et al. 2018; Müller et al. 2020). Each sensor has a field of view of 45° and will observe a spot at a distance of 25 to 150 cm in front of the rover.

The miniRAD instrument will investigate the thermophysical properties regolith and boulders along the rover's traverse, performing measurements for complete diurnal cycles while the rover is stationary. Using thermophysical models (e.g., Hamm et al. 2018), the

miniRAD measurements will enable the determination of surface thermal inertia (Hamm et al. 2020), regolith porosity (Ogawa et al. 2019; Grott et al. 2020), boulder porosity (Grott et al. 2019), the presence of surficial dust layers (Biele et al. 2019; Hamm et al. 2023), as well as regolith and boulder emissivity in IR bands which constrain mineralogy (Hamm et al. 2022). Furthermore, the sub-pixel surface roughness will be constrained. The instrument design and calibration as well as the scientific objectives and associated measurements are discussed in detail in Knollenberg et al. (2025, this issue).

3 IDEFIX design and subsystems

The IDEFIX rover will be the first ever element to land on the surface of Phobos and to rove on a low-gravity body. It has been designed to cope with the extreme conditions, in terms of low gravity and thermal environment. Surface properties are hardly known (Miyamoto et al. 2021), and thus, the rover has to cope with a wide range of possible parameters. Not only does IDEFIX need to survive in the environment for several months, operate its payload and allow communications with ground via the MMX mothership, it will also provide mobility. Earlier concepts for mobility on Phobos were focused on hopping (e.g., Ulamec et al. 2011), IDEFIX however is a wheeled rover. It will move slowly but allow the investigation of a certain range around its landing spot. The actual distance, IDEFIX will traverse is strongly dependent on the terrain it will find and the actual timeline of operations dividing activities between, measurements, battery charging, communications and roving.

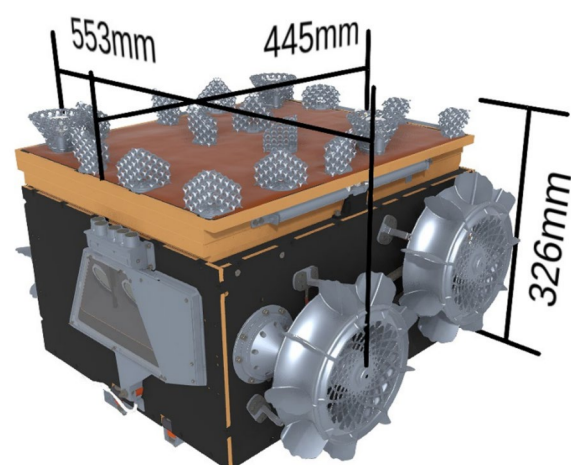


Fig. 4 View of rover in cruise configuration with dimensions. In this configuration IDEFIX is mounted to the MMX spacecraft panel from which it will be released in order to land on Phobos. This is also the configuration during descent and bouncing. Note the crushable structures on top of the (backside) of the solar panel to protect it at touch down

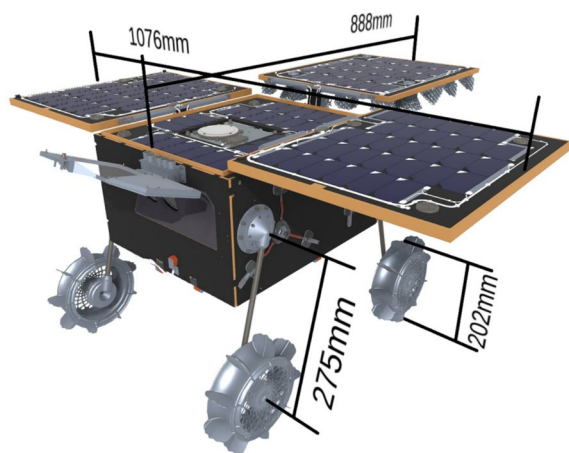


Fig. 5 IDEX in on-Phobos configuration with dimensions. The legs and the solar generator are deployed and the shutters (only front shutter can be seen here) are open

The design of IDEX is shown in Fig. 4 in its cruise configuration, with the solar generator, shutters as well as its “legs” folded. Figures 5 and 6 show the rover fully deployed in the on-Phobos configuration.

An inner compartment – the so-called Service Module (SEM) – thermally isolates thermally sensitive electronics from the outside. It provides the electronics, batteries, and scientific instruments. The SEM is integrated into the lightweight carbon fiber chassis carrying the locomotion subsystems needed for locomotion and uprighting of the rover after the freefall landing as well as the solar generator (folded during landing) and its deployment mechanism.

The thermal control of IDEX is challenging due to the cold environment of Phobos and the limited electrical power available for heating and rover operations.

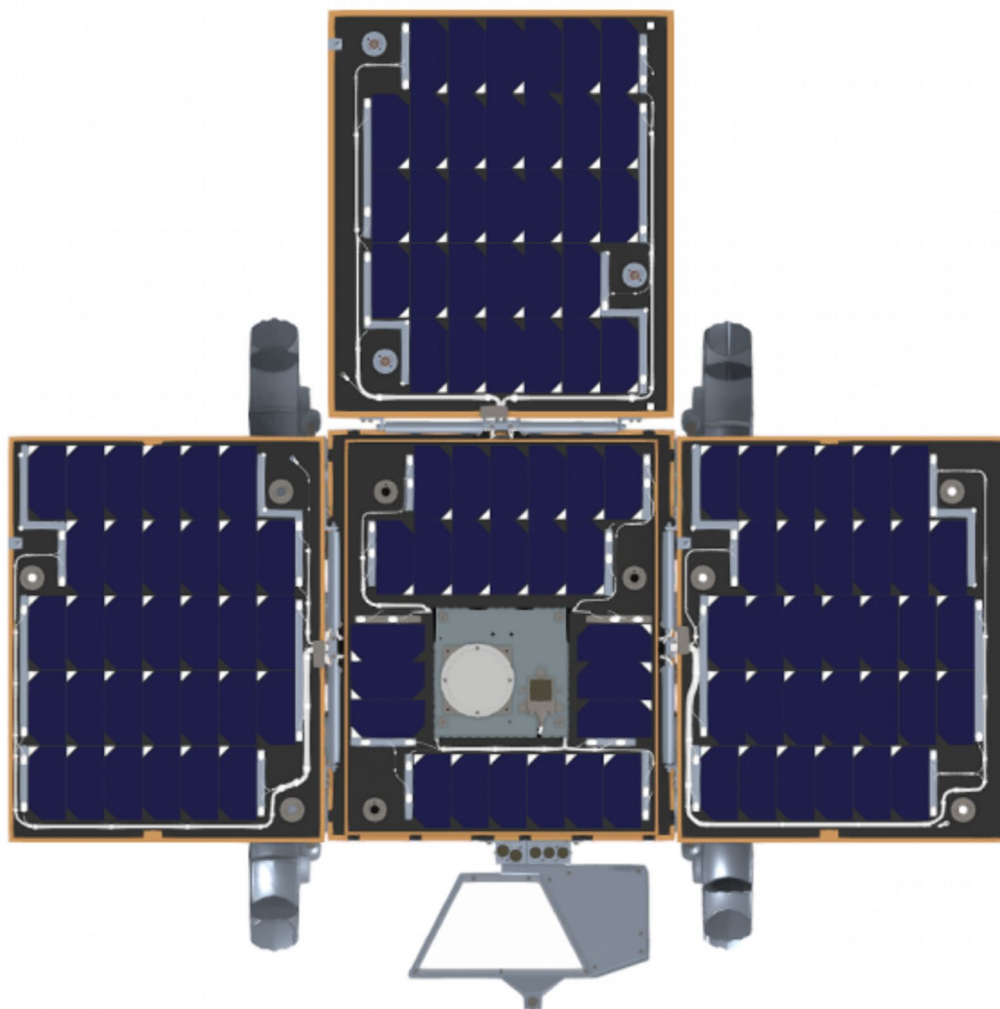


Fig. 6 IDEX top view with solar generator and shutters deployed. Visible is the assembly of solar cells on the four panels and the patch antenna for communications

Good thermal insulation is required to keep power dissipated by the units inside the SEM as much as possible inside the MLI and thus to reduce the need of additional heating power. All the thermal leaks between the internal module, the chassis and the environment have to be minimized. During cruise, the rover will be heated by the orbiter via an umbilical.

On the surface of Phobos the operational modes have to be chosen carefully to keep the instruments and electronics within the thermal limits and minimize the required heating power.

Thermal and power requirements have an effect on the landing site selection as they limit the latitudes on Phobos where the rover can be operated.

The power system of IDEFIX consists of a solar generator with four solar panels (three deployable and one fixed to the top panel of the rover) with a total area of 0.36 m² (Ijpelaan et al. 2021), one rechargeable battery and one power control and distribution unit (PCDU). An umbilical connection between the rover and the MMX mothership will supply power (and provide communications lines) during the hitchhiking phase.

After separation, communications with the MMX spacecraft will be established via an S-band RF system. The data rate for telecommand is 32 kbit/s and for telemetry with two possible rates, 64 kbit/s or 512 kbit/s (Durand et al. 2024).

The overall mass of the rover flight segment (incl. the units on the main S/C) is about 27.5 kg. (see Table 2 for a mass breakdown). The rover itself has a mass of 23.47 kg including 2.44 kg of scientific payload.

For more details on structure, thermal concept and power system / power management the reader is kindly referred to, e.g., Ulamec et al. 2019, Temmen et al. 2024, Durand et al. 2024, Ijpelaan et al. 2021, André 2023 (thermal).

Here, we focus on the locomotion, as this is most relevant for science operations.

4 Locomotion Concept

One of the major endeavors of IDEFIX is to demonstrate locomotion on the surface of Phobos under extremely low gravity (0.0030 to 0.0068 m/s²) with wheels. The rover locomotion subsystem (LOCO) will not only move the rover on the surface but also is crucial to upright it after landing (and bouncing) as well as adapting the distance of the instruments (most importantly RAX) to Phobos' surface. LOCO comprises four individually actuated wheels (allowing skid- steering) of about 200 mm diameter mounted to four individually actuated 275 mm long legs (Barthelmes et al. 2024). With this arrangement, see Fig. 7, the rover can upright itself after landing regardless

of the orientation when it comes to rest and explore the surface of Phobos. The uprighting procedure is based on a universal sequence of multiple unfolding and refolding of the legs. Each of these repetitions has a high likelihood of orienting the rover from any side toward the belly. This method requires no sensors to identify the rover's orientation on the surface (Buse et al. 2022). LOCO provides four primary modes of operation: driving, alignment, uprighting, and passthrough (Skibbe et al. 2024). In driving mode, the four wheels are differentially driven while the legs are stationary, allowing the rover to follow straight lines, curves, or point turns. In alignment mode, the legs and wheels are moved to change the height and orientation of the rover's chassis with respect to the surface with minimal change in position; this is, for example, used to aim cameras and instruments or to put the rover into an optimal orientation toward the sun for battery charging. In uprighting mode, the leg angles can be adjusted into the desired position while the wheels are rotated in a coordinated way, for example, to always roll on the surface. This mode is used during the autonomous uprighting phase as well as for manual corrections. A passthrough mode allows manual commanding of each wheel and leg individually. Even though the locomotion system is capable of higher velocities, the expected

Table 2 IDEFIX Mass breakdown

Unit	Mass [kg]	Mass [kg]
miniRAD Sensor and electronics	0.31	
RAX	1.51	
NavCams	0.40	
WheelCams	0.22	
Sum: Scientific Payload		2.44
SEM structure	2.52	
Chassis structure	3.57	
Shutters	0.61	
Solar Generator	3.76	
Locomotion (shoulder, leg, wheel, HDRM)	4.52	
Locomotion e-box	0.64	
Thermal H/W (incl. MLI)	0.60	
OPR e-box (incl. OBC, PDCU, and RF board)	1.66	
Batteries	1.43	
Antenna	0.13	
Harness	1.57	
SAS (sun sensor)	0.02	
Sum: Rover System		21.03
Sum: landed (system + payload)		23.47
MECSS	2.53	
Rolbox (incl. antenna)	1.49	
Sum: on Orbiter		4.02
Sum IDEFIX		27.49

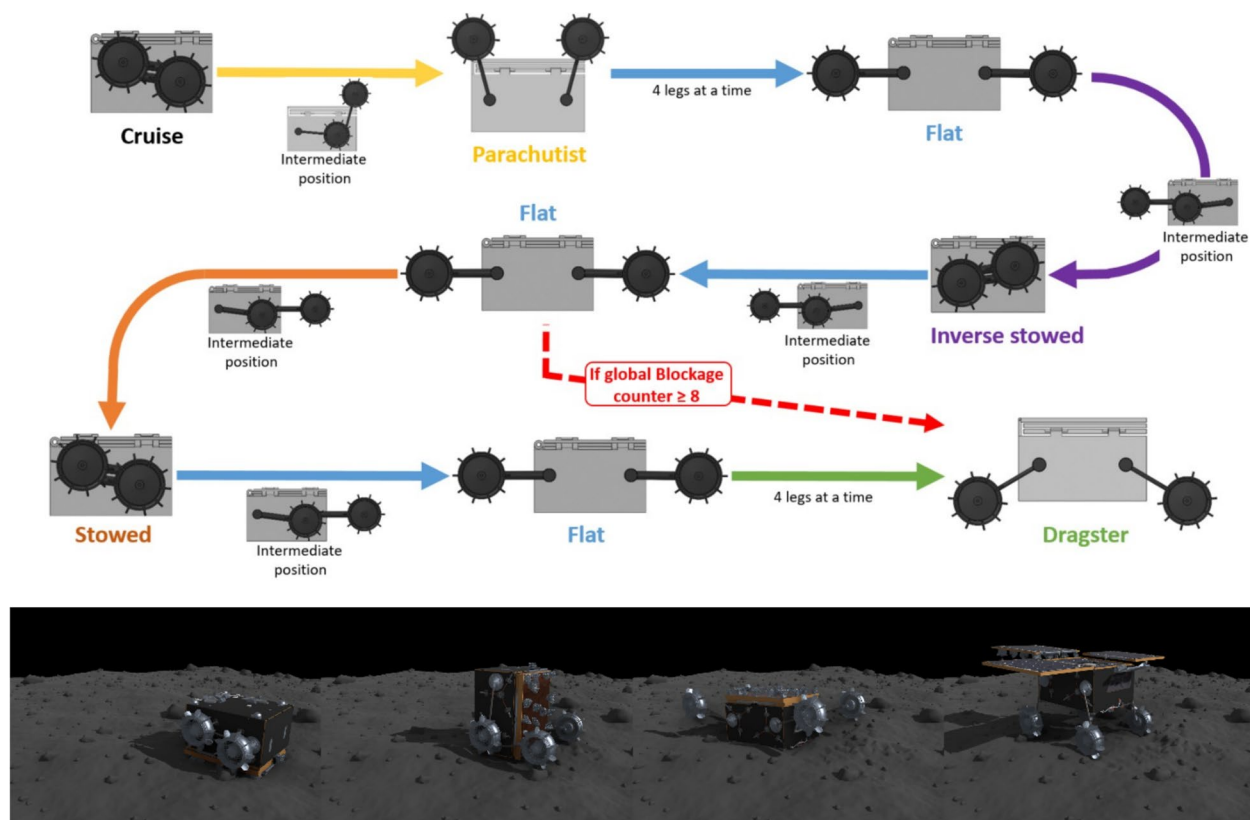


Fig.7 Sequence of autonomous uprighting. (top) schematic of and (bottom) impression of rover in simulated environment

nominal driving velocity is 1 mm/s to avoid tipping over when stopping abruptly. This velocity results from a combination of microgravity dynamics and uncertainty in regolith behavior. At higher velocities, the risk of the rover toppling about its front axis during an emergency stop increases significantly. In case of entrapment of the rover after successful uprighting, the individually actuated legs and wheels can be used to shift the weight distribution and lift individual wheels from the regolith. To cross areas of particular soft regolith, inching locomotion can be applied.

Two experimental autonomous navigation systems are developed, one by DLR and one by CNES; these are designed to extend the driving range beyond what is possible to reach with day-by-day manual commands.

The LOCO system records the impact on the surface during landing (and bouncing) by four 3-axis ADXL356 MEMS accelerometers from Analog Devices. The data is logged into internal memory and will be requested after the rover is successfully deployed on the surface; an abridged version is relayed in real-time to the ascending mothership to verify immediately that the landing has been successful. Further, the two CRM200 gyroscopes from Silicon Sensing provide roll and pitch rates during

descent and will be used to detect excessive roll or pitch during driving to ensure safe traverses. Together with images from the spacecraft, these data will help reconstructing the landing and bouncing trajectories to constrain mechanical properties of the landing site.

Demonstrating wheeled roving on the surface of a milli-g body is one of the key technological goals of the rover. As the real mechanical behavior of natural regolith at Phobos's gravity is somewhat uncertain and traction between wheels and soil must be extremely small (due to the low weight of IDEFIX, ~ 0.1 N), the commissioning of LOCO ("learning how to drive") is extremely important and must be done very carefully. Accordingly, the total distance covered during the rover mission of nominally 100 days, is difficult to estimate. The engineering requirement is to cover a distance of 100 m.

5 Rover operations

The description of MMX rover operations is divided into different parts. The ground segment with its different elements and key players is the backbone of IDEFIX operations, both in cruise as well as on Phobos. The concept is designed to get the highest science return considering the given constraints and available resources. The rover

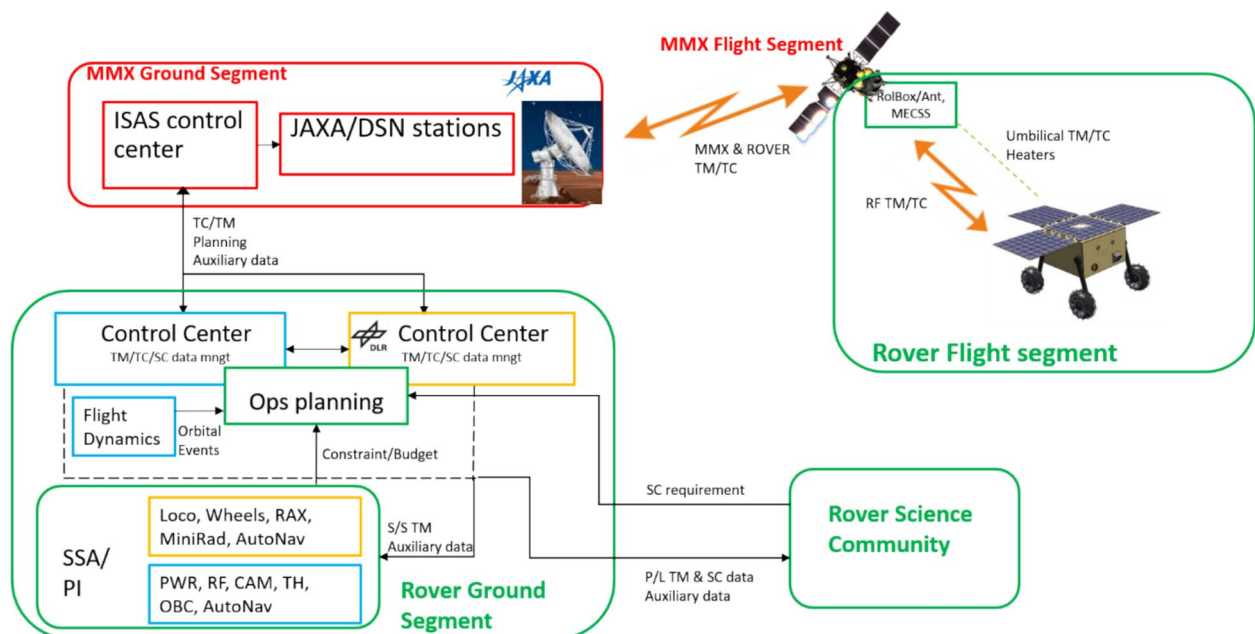


Fig. 8 Sketch of the rover ground segment and connection to the JAXA ground segment

operational concept takes advantage of the fact that two control centers are involved: one at CNES (FOCSE in Toulouse), and one at DLR (GRCC in MUSC Cologne). The two control centers both provide backup to each other to secure resources and guarantee redundancy, and they also enable the rover operational planning and execution to be performed in parallel.

5.1 Ground segment

The rover ground segment is built of different parts and groups as shown in Fig. 8. Two main elements are the two control centers the rover is operated from. One control center is FOCSE, located at CNES Toulouse. The second one is the GRCC, located at DLR Cologne. Both centers will have the full ability to operate the rover and will work with alternating responsibilities. During the cruise/hitchhike phase, every 3 months flight events of the rover are planned. These flight events will be executed alternating between the two centers. During the on-Phobos phase the centers work in parallel, while one center performs the operational activities at the rover in space (prime center) the other center plans the activities for the upcoming about 7 days (secondary center). After a week the roles of the two centers will be swapped. While one center (now prime, former secondary) will execute the activities they planned, the other center (now secondary, former prime) will in parallel start the planning for the upcoming week. The operational responsibilities swap accordingly.

To guarantee the compliance of products from the two centers several tools are used in common, starting from the same data bases, commanding tools as well as the same instance for the planning tool.

The commanding and planning products will be the same independent of the generating center.

For telemetry analysis the two centers will use their own usual and approved tools. But also, in this case the two centers will use the same system database, which defines the telemetry channels and calibration functions to be used.

Part of the rover control center are the SSA/PI teams. These SSA/PI teams support both centers just as the rover FDS team, which will be located in Toulouse at CNES, will support both centers. The SSA/PI and FDS teams will not be duplicated.

The rover ground segment will not communicate with the rover directly. All rover telecommands and telemetry will be relayed by the spacecraft and the JAXA ground segment in Sagami-hara.

5.2 Operational constraints

The operations of the rover face various constraints in addition to coping with the harsh and presently unknown terrain of Phobos' surface.

The rover will be part of the general operational strategy and planning cycles of the MMX spacecraft but also the specific MMX constraints for the communication unit, RolBox, have to be considered. Energy and downlink

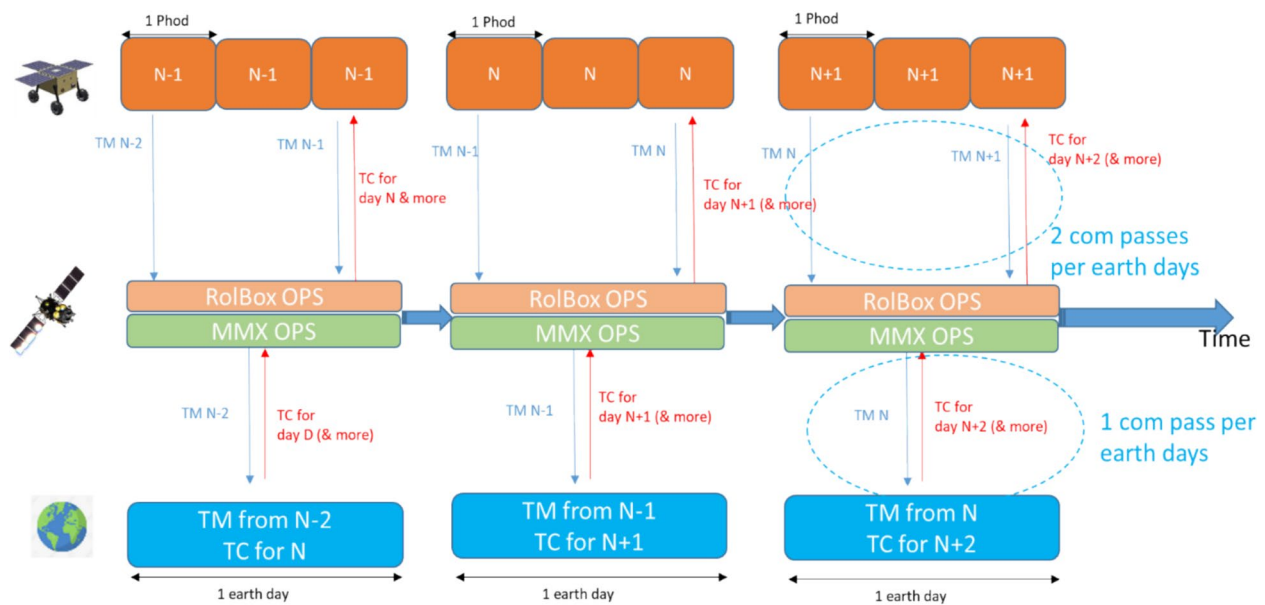


Fig. 9 Sketch for data uplink and downlink constraints for the rover after separation during the on-Phobos phase

capabilities will have to be shared with the other MMX instruments.

After rover separation additional constraints arise for the rover operations and planning.

The communication to the rover will be relayed via the mother spacecraft. The baseline of the activity and operations planning are one communication pass between Earth and the MMX spacecraft per Earth day. During one Earth day the MMX spacecraft will communicate twice with the rover. No direct Earth-Rover link is possible. Thus, all rover commanding as well as the returned telemetry have to be relayed via the mother spacecraft. (Fig. 9). This scenario leads to the fact that ground loops will take at least 2 Earth days if new commanding is depending on the full downlink of data from a before executed activity in space.

IDEFIX operations are power critical and an important constraint is the available energy. Power is generated with the solar generator and also used to charge the onboard battery to guarantee stable thermal control and allow roving or science operations. After energy consuming activities, like driving, several Phobos days (PhoDs, one PhoD is 7.65 h) will have to be considered for charging. The rover is equipped with a so-called SKA sub-unit (attitude control system) to secure the energy charging abilities of the rover. Around noon on Phobos the SKA system will adapt, if necessary the rover orientation of the solar cells toward the sun. This has as a consequence that locomotion activities like driving have to be planned during the morning on Phobos.

Thermal aspects as well as visibilities between rover and spacecraft are crucial factors for the rover operations planning.

Another important aspect needs to be mentioned. During the 100 days of the rover main mission there are also critical MMX spacecraft activities that are planned, including sampling and landing of the main spacecraft. In such phases, the spacecraft has limited communication abilities to the rover as the priorities have to be on the safe and successful landing and sampling activities. In addition, it is considered to put the rover in a safe configuration and, if possible, also in a safe position (minimizing the risk of damage or degradation due to MMX spacecraft thruster plumes or ejected dust). “Safe configuration” in this context means that the rover performs no critical and complex operations and is ensured not to become power critical during this phase, when the communication passes to the mother spacecraft are limited or even non-available at all, for several days. During landing, sampling but especially departure of the spacecraft from the surface of Phobos significant amounts of ejected particles from the surface have to be expected. If possible, the rover will try to “hide” at sufficient distance from the landing site of the MMX spacecraft to prevent the solar cells from getting covered with dust. Currently, the landing site selection and separation maneuver are designed to limit this as much as possible (see Sect. 4.4).

5.3 Mission phases and planning

IDEFIX operations in the frame of the MMX Mission are divided into different phases:

Pre-launch phase: the rover flight model is already attached to the spacecraft and various tests will be performed preparing the rover for the launch.

Flight operations are mainly divided into three main phases:

5.3.1 Hitchhike phase

The hitchhike phase is defined as the timeframe from launch until the separation, descent, landing and uprighting (SLUD) phase starts. The term “hitchhike phase” has been chosen as the cruise phase covers the transfer of the MMX spacecraft from Earth to the Mars system. However, after entry into the martian system while the MMX spacecraft is in quasi satellite orbits (QSO's) around Phobos, the rover is still attached to MMX preparing for its actual mission on the surface of Phobos, when the spacecraft instruments already start their science operations. During this phase the rover will be powered by the main spacecraft. The hitchhike phase will contain different rover activities scheduled every 3 months.

Main activities during hitchhike phase are:

- Post-launch commissioning (health check + battery discharge to its storage level)
- Regular health checks of rover subsystems, (every 3 months)
- Battery maintenance (charge/discharge cycle), (every 6 months)
- Locomotion maintenance (every 6 months)
- Instrument calibration (at least once)
- RolBox and/or rover software update, (depending on demand: once or twice)
- Before Rover separation: full charging of the battery and final preparations for SLUD,

The hitchhike phase operations will be performed alternately between the control centers in Cologne (DLR/MUSC) and Toulouse (CNES). The responsibility will change every 3 months after the respective flight events have been executed. The respective secondary will work as a support and backup, respectively.

5.3.2 SLUD (Separation, Landing, Uprighting and Deployment) phase

The SLUD phase covers the time from a few hours before landing and until a few hours after the deployment of the rover, when the locomotion system and the solar cells have been deployed and IDEFIX stands in a stable position on the surface of Phobos. During this phase the main spacecraft will descent toward the Phobos surface, in the frame of the rehearsal for the actual spacecraft landing maneuver. In a free fall maneuver of the main spacecraft the rover will be released about 40 m above the surface.

The rover will tumble ballistically toward the surface of Phobos. No attitude control is foreseen during descent. After a first touch down the rover will most probably bounce several times until it comes to rest (a sequence similar to the MASCOT landing, see Ho et al. 2021). An automated sequence will then perform the uprighting of the rover (see chapter 3) and the deployment of the solar generator. During this activity it has to be assumed that the main spacecraft is out of site of the rover, so no communication can take place in this critical timeframe. The spacecraft will come into visibility of the rover again only after this uprighting and deployment sequence will have been completed. The battery is designed to fully support this activity. Of course, the available energy onboard of the rover is limited before the solar cells are exposed to the sun. Consequently, this is a critical operation of the rover mission if it comes to possible contingencies (limitation of available energy and presumably no commandability or chance to retrieve telemetry).

These operations will be performed by the French operation center FOCSE. The German center in Cologne MUSC (GRCC) will act as backup.

5.3.3 On-Phobos phase

The on-Phobos phase covers the entire operations of the rover IDEFIX on the surface of Phobos after the SLUD phase has finished.

One main aspect at the beginning of this phase is the commissioning of the rover. In several steps the different system components as well as the scientific instruments will be checked. First scientific measurements will be performed as well as first driving activities. With the first driving and wheel motions the interaction of the wheels with the soil are also planned to be recorded. One main aspect for these activities is to characterize the surface properties and the behavior of the material. These results shall support the landing and sampling of the main spacecraft. This commissioning phase with all its different elements is planned to last up to 28 Earth days.

The exact schedule and the necessary ground loops are presently subject of iterations. After the commissioning the main exploration phase of the rover is foreseen. With the images obtained by the NavCams and the area images of the orbiter cameras (including DTM's), the team will identify the interesting targets in reach of the rover. The mobility team will provide assessments of possible driving routes on the surface as well as the potential driving risks. Different locations will be target of scientific investigations. MiniRad and RAX will investigate as many different locations and specific objects (e.g., particular rocks) on Phobos, as possible. During the driving as well as in dedicated experiments the wheel-soil interaction will be investigated in particular with the WheelCams.

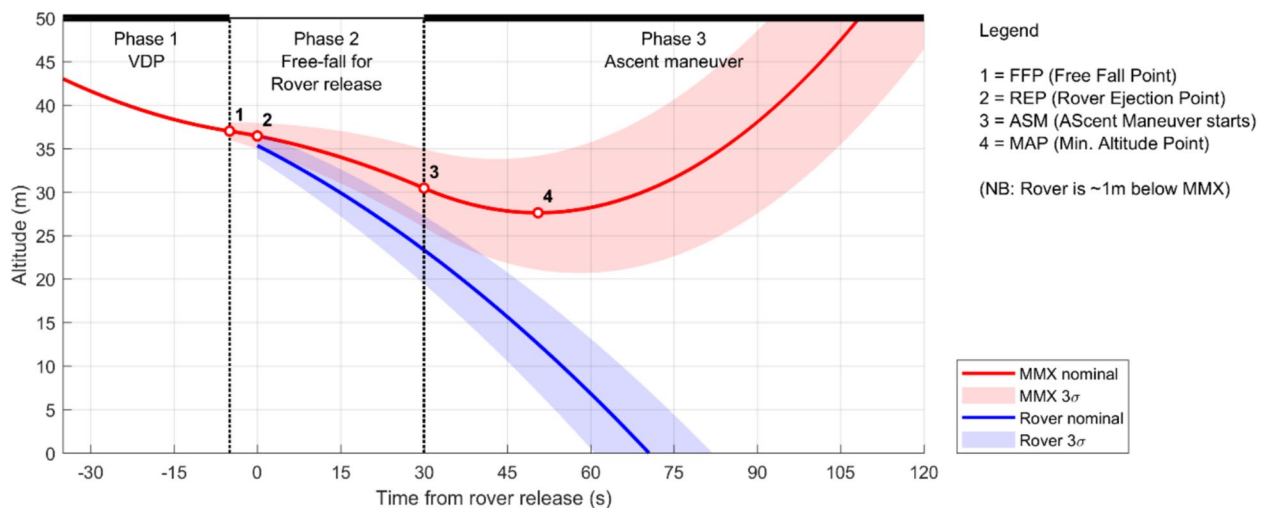


Fig. 10 Example of a release scenario. The altitude of release depends on effective gravity at the landing site

These have to be planned carefully to allow an efficient data download strategy to Earth.

Early in the on-Phobos phase, driving will be performed manually. A special team on the ground together with the operations team will do the planning, risk assessment and commanding of the driving sessions. The different expertise necessary for planning a safe driving are assembled in the mobility group, as mentioned above. After the first successful driving attempts the auto-navigation systems are foreseen to be exercised. The rover has two auto-navigation systems onboard. One system from CNES, one from DLR. In a first phase, the two systems shall demonstrate their abilities to drive a rover in this presumably harsh low-gravity environment. Auto-navigation systems have already been tested on rovers on Earth as well as on Mars but up to now not on a small body like Phobos. In a second phase of the exploration phase the auto-navigation system will be used to optimize and increase the driving capabilities of the rover. This should allow to drive larger distances with the rover toward the end of the 100-day lasting main mission.

5.3.4 Special operations

In addition to driving the rover in a yet unknown terrain, the RAX measurements are a major challenge for operations. To position the instrument at the right distance to the ground to be in focus (within the range of the auto-focus system), a complex interaction between the locomotion system and the RAX instrument is required. The locomotion system and its movements in the shoulders will enable the rover to move to different altitudes above the surface while the RAX instruments is measuring to meet the necessary focus. Several days with supporting

ground loops are planned for this activity at each location, where RAX measurements will be performed.

MiniRad measurements are more straight forward to be commanded but the operation team, using NavCam images, needs to take care that the selected target area (or specific object) is in the FoV, as requested. The miniRad FoV is aligned with the NavCam field of view. In a sophisticated ground loop the camera and miniRad teams can verify the correct orientation of the rover and possible adaptations can be commanded to the locomotion subsystem.

5.4 Landing site selection

As the delivery of IDEFIX will take place in the frame of the (first) MMX landing rehearsal, the rover Landing Site Selection (LSS) will follow closely that of its mothership MMX, although it departs from it on some aspects.

The main MMX spacecraft and the rover will land in the same region, i.e., an area of about 300×300 m that is investigated for landing zones (see Fig. 11 for clarifying areas and zones). MMX will drop the rover at the end of a rehearsal of its own landing, see Fig. 10. The zone for the MMX landing is rather small (20×20 m²) as it performs a controlled landing into it. The zone of the rover, however, is comparably large, up to 100 m in diameter at 3σ , because of the possibly extended bouncing phase that will follow its release from an altitude of about 40 m. The spacecraft and rover landing zones must be sufficiently separated since the spacecraft will land before the 100-day mission of the rover has elapsed. There would be a high chance of catastrophic loss should the rover be close to or, in a dramatic extreme case, under the spacecraft at landing. So, MMX and the rover will land in the same region but not in the same spot and that creates unique

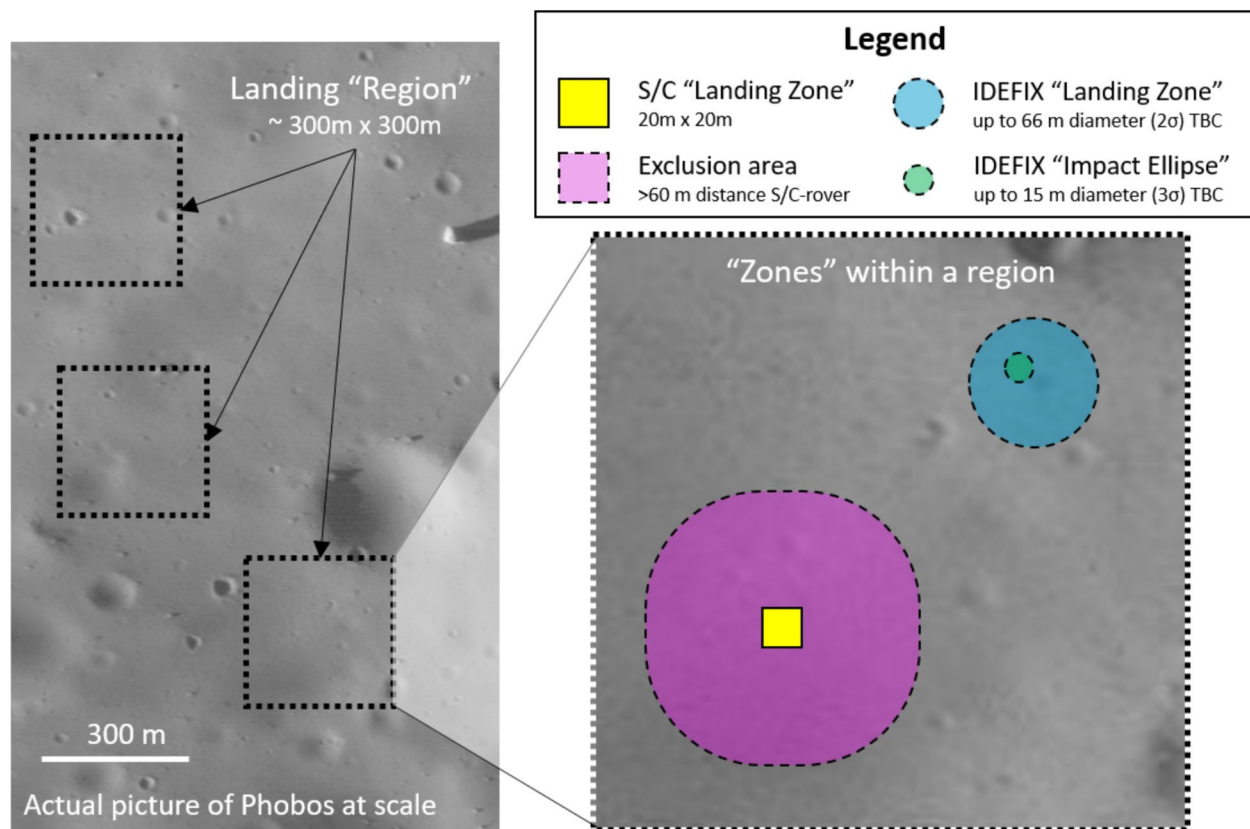


Fig. 11 Regions and zones on Phobos, at scale

interactions and challenges to both LSS observations and processes. See Fig. 11 for a visual understanding of these concepts.

The LSS will mostly take place during the first half of 2028. As the spacecraft lowers its orbit from QSO-H and QSO-M to QSO-La and eventually QSO-Lc, three phases of increasingly detailed observation will come to refine the selection. From this observation data and higher order products generated by JAXA (e.g., digital elevation models, rock maps, etc.), the CNES Flight Dynamics team will compute specific LSS products and advise the IDEFIX team for the definition of landing zones and their ranking. This selection is ultimately submitted to the global LSS workflow, governed by JAXA. The final decision rests on JAXA to guarantee the safety and science return of the overall mission.

The rover LSS criteria can be summed up as nine elimination constraints and five quality indices. The nine constraints are: no Mars visibility (mainly for thermal reasons), bounds on geocentric latitude, bounds on geodetic latitude, a minimum on Sun horizon angle, a maximum admissible surface slope, a maximum terrain roughness, a maximum rock density, sufficient distance to MMX landing site and a minimum length of

communication slots. If any of these constraints is violated, a landing site is not admissible for IDEFIX. As the regions, or even the rover landing zone, are quite large, it is likely that portion of a landing zone violate these constraints. Each region or zone is therefore associated with a Hazardous Area Ratio (HAR) that quantifies the percentage of the region or zone that violates at least one constraint. To be admissible, a HAR might typically be of less than 10%, though the precise threshold is TBD and may need to be adjusted based on-Phobos reality.

When a site is admissible, the quality indices allow an automatic scoring to be performed, though their relative weights are currently not defined, yet. The five quality indices are encodings of: solar power available, communication slot duration, terrain slope, terrain roughness and distribution of rocks. Among these, one may note there is no science quality criteria. That is because the rover LSS objectives are primarily driven by the safety of the rover, with the underlying assumption that the global LSS process steers toward scientifically interesting areas and that any site on Phobos will have major science relevance to IDEFIX. Moreover, heritage from Philae or MASCOT have shown that

scores are only coarse predictors of the actual safety or appeal of a landing site (Ulamiec et al. 2015; Lorda et al. 2020).

For that purpose, any ranking, either of regions or zones, will be issued by the LSS Assessment Ranking and Decision group, within the IDEFIX team, including rover PIs and instrument PIs. This group will analyze each region and zone, using the scores only as indicators of suitability. Note that these decisions are internal to the rover team and are then subject to the global LSS flow of MMX.

6 Conclusions

In a very short time, and under difficult conditions, the IDEFIX rover has been developed and delivered. Integration on, and tests with the MMX spacecraft are ongoing, as well as the detailed preparation of operations, for cruise and on-Phobos phases. Assuming that the last tests, the launch and critical SLUD (separation-landing-uprighting-deployment) phases are successful, we are looking forward to the first wheeled rover mission on a small body, Mars' moon Phobos. IDEFIX will become an important element of the overall MMX mission.

Abbreviations

CMOS	Complementary Metal–Oxide–Semiconductor
CNES	Centre National d'Etudes Spatiales
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DTM	Digital Terrain Model
FDS	Flight Dynamics System
FOCSE	French Operations Centre for Science and Exploration
FoV	Field of View
GRCC	German Rover Control Center
HAR	Hazardous Area Ratio
HDRM	Hold Down and Release Mechanism
INTA	Instituto Nacional de Técnica Aeroespacial
JAXA	Japan Aerospace eXploration Agency
LOCO	Locomotion subsystem
LSS	Landing Site Selection
MECSS	Mechanical Electrical Communication and Separation Subsystem
MMX	Martian Moons eXploration
MUSC	Microgravity User Support Center (at DLR in Cologne)
OBC	Onboard Computer
PCDU	Power Conditioning and Distribution Unit
QSO	Quasi Satellite Orbit (QSO-H, QSO-M, QSO-L for high, medium and low)
SKA	Système für die Kontrolle of the Attitude (attitude control system)
SLUD	Separation, Landing, Uprighting and Deployment
SSA	Subsystem Authority

Acknowledgements

MMX is a JAXA mission with contributions from NASA, CNES and DLR. The Rover will be provided by CNES and DLR with additional science contributions from Japan and Spain. Contributions from YC were supported by Japan Society for Promotion of Science Grant-in-Aid (Grant numbers JP19K14778, JP20H00194, and JP21H04515). From the Spanish side, the project is partially funded by the MINECO Project Reference PID2019-107442RB-C3 and -C2. The authors would like to thank the teams of MMX and the Rover as well as the programmatic support to realize this project.

Author contributions

The authors wish it to be known that, in their opinion, the first two authors (SU and PM) should be regarded as joint first authors. MGro, JK, SS, HWH, YC, OPB, NM, PV have mainly contributed to the instrument sections. FB mainly contributed to Sect. 3. CK, DM and CD have mainly contributed to Sect. 4. ST mainly contributed to Sect. 4.4. HM, JBi, JBa, SM and MGr have contributed to the overall context and IDEFIX/MMX interface and management topics. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. IDEFIX is a contribution by CNES and DLR to the JAXA MMX project. Contributions from YC were supported by Japan Society for Promotion of Science Grant-in-Aid (Grant numbers JP19K14778, JP20H00194, and JP21H04515). From the Spanish side, the project is partially funded by the MINECO Project Reference PID2019-107442RB-C3 and -C2. NM acknowledges financial support from the French space agency (CNES) in the context of the MMX Rover mission.

Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interest.

Received: 25 November 2024 Accepted: 8 October 2025

Published online: 23 October 2025

References

- Almaeeni S, Els SG, Almarzooqi H (2021) To a dusty moon: rashid's mission to observe lunar surface processes close-up. In: 52nd lunar and planetary science conference. Lunar and Planetary Science Conference, p 1906
- André M (2023) MMX rover: thermal control design and validation of a rover on phobos martian moon. In: 52nd international conference on environmental systems ICES-2023–238 16–20 July 2023, Calgary, Canada
- Barthelmes S, Buse F, Chalon M, Deutschmann B, Hacker F, Holderried R, Kolb A, Langofer V, Fonseca Prince A, Sedlmayr H-J, Skibbe J, Vodermayr B (2024) Characterization of the MMX rover locomotion flight model for check-out and parameterization. In: 2024 IEEE aerospace conference, AERO 2024. IEEE. IEEE Aerospace Conference, Big Sky, Montana, USA. <https://doi.org/10.1109/AERO58975.2024.10521019>
- Biele J, Kühr E, Senshu H, Sakatani N, Ogawa K, Hamm M, Grott M, Okada T, Arai T (2019) Effects of dust layers on thermal emission from airless bodies. *Prog Earth Planet Sci*. <https://doi.org/10.1186/s40645-019-0291-0>
- Buse F, Pignède A, Bertrand J, Goulet S, Lagabarre S (2022) MMX rover simulation - robotic simulations for phobos operations. In: 2022 IEEE aerospace conference (AERO), Big Sky, MT, USA, pp. 1–14. <https://doi.org/10.1109/AERO53065.2022.9843391>
- Cho Y, Böttger U, Rull F, Belenguer T, Börner A, Buder M, Bunduki Y, Dietz E, Hagelschuer T, Hübers H-W, Kameda S, Kopp E, Lieder M, Lopez G, Moral Inza A, Paproth C, Perez Canora C, Pertenais M, Peter G, Prieto Ballesteros O, Rockstein S, Rodd-Routley S, Rodriguez Perez P, Ryan C, Santamaria P, Säuberlich T, Schrandt F, Schröder S, Stangarone C, Ulamec S, Usui T, Weber I, Westerdorff K, Yumoto K (2021) In-situ science on Phobos with the Raman spectrometer for MMX (RAX) onboard the MMX rover: preliminary design of instrument and feasibility of Raman signal detection. *Earth Planets Space* 73:232. <https://doi.org/10.1186/s40623-021-01496-z>
- Durand C, Rousseau F, Dudal C, Baroukh J, Yoshikawa K (2024) MMX, the next generation of in-situ exploration mission. In: 38th annual small satellite conference
- Grott M, Knollenberg J, Borgs B, Hänschke F, Kessler E, Helbert J, Maturilli A, Müller N (2017) The MASCOT radiometer MARA for the Hayabusa2 mission. *Space Sci Rev* 208:413–431. <https://doi.org/10.1007/s11214-016-0272-1>
- Grott M, Knollenberg J, Hamm M, Ogawa K, Jaumann R, Otto KA, Delbo M, Michel P, Biele J, Neumann W, Knapmeyer M, Kühr E, Senshu H, Okada

- T, Helbert J, Maturilli A, Müller N, Hagermann A, Sakatani N, Tanaka S (2019) Low thermal conductivity boulder with high porosity identified on C-type asteroid (162173) Ryugu. *Nat Astron* 3:971–976. <https://doi.org/10.1038/s41550-019-0832-x>
- Grott M, Biele J, Michel P, Sugita S, Schröder S, Sakatani N, Neumann W, Kameda S, Michikami T, Honda C (2020) Macroporosity and Grain density of rubble pile asteroid (162173) Ryugu. *J Geophys Res*. <https://doi.org/10.1029/2020JE006519>. <https://doi.org/10.1002/essoar.10503201.2>
- Hagelschuer T, Böttger U, Buder M, Cho Y, Gensch M, Hanke F, Hübers H-W, Kameda S, Kopp E, Kubitz S, Moral A, Paproth C, Pertenais M, Peter G, Rammelkamp K, Rodríguez Pérez P, Rull F, Ryan C, Säuberlich T, Schrandt F, Schröder S, Ulamec S, Usui T, Vance R (2019) The Raman spectrometer onboard the MMX Rover for Phobos. In: 70th international astronomical congress, IAC 2019
- Hagelschuer T, Böttger U, Buder M, Cho Y, Gensch M, Hanke F, Hübers H-W, Kameda S, Kopp E, Kubitz S, Moral A, Paproth C, Pertenais M, Peter G, Rammelkamp K, Rodríguez Pérez P, Rull F, Ryan C, Säuberlich T, Schrandt F, Schröder S, Ulamec S, Usui T, Vance R (2022) RAX: the raman spectrometer for the MMX phobos rover. In: 73rd international astronomical congress, Paris, IAC 2022
- Hamm M, Grott M, Kürt E, Pelivan I, Knollenberg J (2018) A method to derive surface thermophysical properties of asteroid (162173) Ryugu (1999JU3) from in-situ surface brightness temperature measurements. *Plan Space Sci* 159:1–10. <https://doi.org/10.1016/j.pss.2018.03.017>
- Hamm M, Pelivan I, Grott M, de Wiljes J (2020) Thermophysical modelling and parameter estimation of small Solar system bodies via data assimilation. *MNRAS* 496:2776–2785. <https://doi.org/10.1093/mnras/staa1755>
- Hamm M, Grott M, Senshu H, Knollenberg J, de Wiljes J, Hamilton VE, Scholten F, Matz KD, Bates H, Maturilli A, Shimaki Y, Sakatani N, Neumann W, Okada T, Preusker F, Elgner S, Helbert J, Kürt E, Ho T-M, Tanaka S (2022) Mid-infrared emissivity of partially dehydrated asteroid (162173) Ryugu shows strong signs of aqueous alteration. *Nat Comm*. <https://doi.org/10.1038/s41467-022-28051-y>
- Hamm M, Hamilton VE, Goodrich CA (2023) Evidence for the presence of thin and heterogenous dust deposits on Ryugu's Boulders from Hayabusa2 MARA and sample data. *Geophys Res Lett*. <https://doi.org/10.1029/2023GL104795>
- Ho T-M, Baturkin V, Findlay R, Grimm C, Grundmann J-T et al (2017) MASCOT - the mobile asteroid surface scout onboard the Hayabusa2 Mission. *Space Sci Rev* 208:339–374
- Ho T-M, Jaumann R, Bibring J-P, Grott M, Glaßmeier K-H, Moussi A, Krause K, Auster U, Biele J, Cordero F, Cozzoni B, Dudal C, Fantinati C, Grundmann T, Hamm M, Herčík D, Kayal K, Knollenberg J, Küchemann O, Lange C, Lange M, Lorda L, Maibaum M, Mimasu Y, Cenac-Morthé C, Okada T, Pilorget C, Reill J, Saiki T, Sasaki K, Schlotterer M, Schmitz N, Termtanasombat N, Toth N, Tsuda Y, Ulamec S, Wolff F, Yoshimitsu T, Ziaich C et al (2021) The MASCOT lander aboard Hayabusa2: the in-situ exploration of NEA (162173) Ryugu. *Planet Space Sci* 200:105200. <https://doi.org/10.1016/j.pss.2021.105200>
- Ijpelaan F, Biele J, Lagabarré S, Buse F, Tardivel S (2021) Challenges of the MMX rover mission to phobos. In: global space exploration conference, GLEX 2021, St Petersburg
- Kawakatsu Y, Kuramoto K, Usui T, Sawada H, Ootake H, Baba H, Imada T, Ikeda H, Nakamura T et al (2024) Launch Year Change of Martian Moons Exploration (MMX) and its Recent Status, 75th International Astronautical Congress (IAC). Italy, Milan
- Kessler E (2005) Proceedings of sensor 2005 12th international conference, Vol. I, Nürnberg, pp 73–78
- Knollenberg J, Hamm M, Ihring A, Ziese R, Biele J (2025) The miniRAD instrument for the MMX IDEFIX Rover. *Prog Earth Planet Sci PEPS* 12:53. <https://doi.org/10.1186/s40623-021-00717-3>
- Kuramoto K, Kawakatsu Y, Fujimoto M, Araya A, Barucci M-A, Genda H, Hirata N, Ikeda H, Imamura T, Helbert J, Kameda S, Kobayashi M, Kusano H, Lawrence DJ, Matsumoto K, Michel P, Miyamoto M, Morota T, Nakagawa H, Nakamura T, Ogawa K, Otake H, Ozaki M, Russel S, Sasaki S, Sawada H, Senshu H, Tachibana S, Terada N, Ulamec S et al (2022) Martian moons exploration MMX: sample return mission to phobos elucidating formation processes of habitable planets. *Earth Planets Space* 74:12–43. <https://doi.org/10.1186/s40623-021-01545-7>
- Lorda L, Canalias E, Martin T, Garmier R, Moussi A, Biele J, Jaumann R, Bibring J-P, Grott M, Auster H-U, Ho T-M, Krause C, Maibaum M, Cozzoni B, Ulamec S, Wolff F, Tsuda Y, Okada T, Mimasu Y (2020) The process for the selection of MASCOT landing site on Ryugu: design, execution and results. *Planet Space Sci* 194:105086
- Lorenz R (2020) How far is far enough? Requirements derivation for planetary mobility systems. *Adv Space Res* 65(5):1383–1401
- Michel P, Ulamec S, Böttger U, Grott M, Murdoch N, Vernazza P, Sunday C, Zhang Y, Valette R, Castellani R, Biele J, Tardivel S, Groussin O, Jorda L (2022) The MMX rover: performing in-situ surface investigations on Phobos. *Earth Planets Space* 74:2–15. <https://doi.org/10.1186/s40623-021-01464-7>
- Miyamoto H, Niihara T, Wada K, Ogawa K, Senshu H, Michel P, Kikuchi H, Hemmi R, Nakamura T, Nakamura AM, Hirata N, Sasaki S, Asphaug E, Britt DT, Abell P, Ballouz R-L, Banouin O, Baresi N, Barucci MA, Biele J, Grott M, Hino H, Hong PK, Imada T, Kameda S, Kobayashi M, Libourel G, Mogi K, Murdoch N et al (2021) Surface environment of Phobos and Phobos simulant UTPS. *Earth Planets Space* 73:214
- Moral AG, Mora J, Prieto-Ballesteros O, Ercilla O, Lopez-Reyes G, Canora C, Bonales LJ, Fernandez-Sampedro M, Sanz-Arranz JP, Herrera A, Alonso R, Rull F, Böttger U, Cho Y, Schröder S, Hübers H-W (2023) Deuterated PET: the new verification target of the Raman spectrometer for the MMX mission to explore Phobos. *J Raman Spectroscopy* 54:1268–1279. <https://doi.org/10.1002/jrs.6569>
- Mueller NT, Knollenberg J, Grott M, Kopp E, Walter I, Krause C, Hudson T, Spohn T, Smrekar S (2020) Calibration of the HP³ radiometer on InSight. *Earth Space Sci* 7(5):e01086. <https://doi.org/10.1029/2020EA001086>
- Murdoch N, LaLuca V, Sunday C, Tardivel S, Bertrand J, Thérêt N, Vivet D, Amsili A, Robin C, Delton P, Duchene A, Douaglin Q, Maillard A, Virmontois C, Vernazza P, Jorda L, Groussin O, Miyamoto H, Vincent J-B, Flahaut J, Biele J, Barnouin O, Hartzel C, Buse F, Barthelmes S, Ulamec S, Michel P, Baroukh J (2025) The WheelCams on the IDEFIX rover. *Prog Earth Planet Sci PEPS* 12:54. <https://doi.org/10.1186/s40645-025-00725-3>
- Nakamura T, Ikeda H, Kouyama T, Nakagawa H, Kusano H, Senshu H, Kameda S, Matsumoto K, Gonzalez-Franquesa F, Ozaki N, Takeo Y, Baresi N, Oki Y, Lawrence DJ, Chabot NL, Peplowski P, Barucci MA, Sawyer E, Yokota S, Ulamec S, Michel P, Kobayashi M, Sasaki S, Hirata N, Wada K, Miyamoto H, Imamura T, Ogawa N, Ogawa K, Iwata T et al (2021) Science operation plan of Phobos and Deimos from the MMX spacecraft. *Earth Planets Space* 73:227. <https://doi.org/10.1186/s40623-021-01546-6>
- Ogawa K, Hamm M, Grott M, Sakatani N, Knollenberg J, Biele J (2019) Possibility of estimating particle size and porosity on Ryugu through MARA temperature measurements. *Icarus* 333:318–322. <https://doi.org/10.1016/j.icarus.2019.06.014>
- Rodríguez P, Marín A, Benito M, Prieto JAR, Moral A, Canchal R, Gallego P (2019) Screening and characterization of the flight laser modules for the ExoMars Raman laser spectrometer. *Ciencias Planetarias y Exploración del Sistema Solar*, 54
- Sellier C, Gambart D, Perrot N, Garcia-Sanchez E, Virmontois C, Mouallem W, Bardoux A (2019) Development and qualification of a miniaturised CMOS camera for space applications (3DCM734/3DCM739). In: international conference on space optics—ICSO 2018 (Vol. 11180, pp. 1134–1140). SPIE
- Skibbe J, Buse F, Krenn R, Lund A (2024) LOCO - Software for the MMX Rover Locomotion System. In: 2024 IEEE aerospace conference, AERO 2024. 2024 IEEE Aerospace Conference, Big Sky, Montana. <https://doi.org/10.1109/AERO58975.2024.10521275>
- Spohn T, Seiferlin K, Hagermann A, Knollenberg J, Ball AJ, Banaszkiwicz M, Benkhoff J, Gadowski S, Gregorczyk W, Grygorczuk J, Hlond M, Kargl G, Kuehrt E, Kömle N, Krasowski J, Marczewski W, Zarnecki JC (2007) MUPUS - a thermal and mechanical properties probe for the rosetta lander philae. *Space Sci Rev* 128:339–362. <https://doi.org/10.1007/s11214-006-9081-2>
- Spohn T, Knollenberg J, Ball AJ, Banaszkiwicz M, Benkhoff J, Grott M, Grygorczuk J, Hüttig C, Hagermann A, Kargl G, Kaufmann E, Kömle N, Kuehrt E, Kossacki KJ, Marczewski W, Pelivan I, Schrödter R, Seiferlin K (2015) Thermal and mechanical properties of the near-surface layers of comet 67P/Churyumov-Gerasimenko. *Science* 349:6247. <https://doi.org/10.1126/science.aab0464>
- Spohn T, Grott M, Smrekar SE, Knollenberg J, Hudson TL, Krause C, Müller N, Jänchen J, Börner A, Wippermann T, Krömer O, Lichtenheldt R, Wisniewski L, Grygorczuk J, Fittock M, Rheershemius S, Sprowitz T, Kopp E, Walter I, Plesa AC, Breuer D, Morgan P, Banerdt WB (2018) The heat flow and physical properties package (HP³) for the InSight mission. *Space Sci Rev* 214:5–96. <https://doi.org/10.1007/s11214-018-0531-4>

- Temmen K, Reershemius T, Spröwitz T (2024) Shutter development and qualification for the DLR CNES rover onboard the Martian Moon Mission MMX, ECSSMET, Noordwijk
- Théret N, Cucchetti E, Robert E, Virmondois C, Millancourt C, Douaglin Q, Amsili A, Belloir J-M, Amilineni S, Khoory M et al (2024) Enhanced image processing for the caspex cameras onboard the Rashid-1 rover. *Space Sci Rev* 220(5):60
- Ulamiec S, Kucherenko V, Biele J, Bogatchev A, Makurin A, Matrossov S (2011) Hopper concepts for small bodies landers. *Adv Space Res* 47:428–439
- Ulamiec S, Biele J, Blazquez A, Cozzoni B, Fantinati C, Gaudon P, Geurts K, Jurado E, Küchemann O, Lommatsch V, Maibaum M, Sierks H, Witte L (2015) Rosetta Lander – Philae: landing preparations. *Acta Astron* 107:79–86
- Ulamiec S, Michel P, Grott M, Böttger S, Schröder U, Hübers H-W, Cho Y, Rull F, Murdoch N, Vernazza P, Prieto-Ballesteros O, Biele J, Tardivel S, Arrat D, Hagelschuer T, Knollenberg J, Vivet D, Sunday C, Jorda L, Groussin O, Robin C, Miyamoto H (2023) Science Objectives of the MMX Phobos Rover. *Acta Astron* 210:95–101
- Ulamiec S, Michel P, Grott M, Böttger U, Hübers H-W, Murdoch N, Vernazza P, Karatekin Ö, Knollenberg J, Willner K, Grebenstein M, Mary S, Chazalnoël P, Biele J, Krause C, Ho T-M, Lange C, Grundmann T, Sasaki K, Maibaum M, Küchemann O, Reill J, Chalon M, Barthelmes S, Lichtenheldt R, Krenn R, Smisek M, Bertrand J, Moussi A, Delmas C, Tardivel S et al. (2019) A rover for the MMX Mission to Phobos. In: 70th international astronomical congress, IAC
- Vernazza P, Jorda L, Tardivel S, Baroukh J, Groussin O, Pimorin C, Poulain A, Chabaud P-Y, Robert E, Bertrand J, Luluca V, Remeteau E, Théret N, Virmondois C, Murdoch N, Beck P, Rüsch O, Flahaut J, Charnoz S, Lasue J, Barucci M-A, Doressoundiram A, Michel P, Ulamiec S (2025) Surface science on Phobos with the navigation cameras of the MMX IDEFIX rover. *Prog Earth Planet Sci* 12:46. <https://doi.org/10.1186/s40645-025-00708-4>
- Virmondois C et al. (2025) CASPEX: Camera for space exploration. submitted to *Space Science Reviews*

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.