MMX, the Next Generation of In-Situ Exploration Mission

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ABSTRACT

The JAXA MMX (Martian Moons eXploration) mission has the objectives to study Phobos, the largest moon of Mars, and to bring back to Earth a sample from its surface, to answer one main question: what is the origin of the Martian moons? This mission will be launched in 2026 and will last five years. MMX spacecraft, the orbiter, developed by JAXA will travel from Earth to Mars and then study Phobos and Deimos moons with a foreseen sample collection of Phobos soil. MMX will carry and drop a small rover, developed by CNES and DLR, on Phobos surface. This rover, called Idefix, delivered close to the sample collection area will perform soil characterization in order to secure MMX spacecraft landing It's designed to drive in very low gravity and low power availability for a hundred days, moving thanks to four wheels and carrying a couple of instruments to study Phobos composition. The electronic elements of the rover are in a nanosat size stack. CNES was in charge of most of the rover internal subsystems, the flight software, the mission analysis and thermal and mechanical architectures. DLR was in charge of the rover chassis, shutters, separation and locomotion systems. CNES and DLR share the system, operations and project lead. The RF communication between the rover and the orbiter is performed thanks to an intersatellite link using two S-band transponders. Their design is a heritage of the Rosetta-Philae mission combined to the needs brought by the nanosatellite markets. The article will present in a first part the development logic and the characteristics of these equipment. The communications during the mission will go through three different phases, each one associated to specific constraints. A second part of the article will focus on these phases and the impacts on the RF link. A third part will focus on the ISL qualifications, tests and measurements performed to comply with the mission and planning constraints.

INTRODUCTION

Recently and for the coming years, more and more missions have visited and will visit small celestial bodies of the solar system. Hayabusa-2 and Rosetta missions were two of them. The upcoming MMX mission from JAXA, aims at studying the Mars moons, Deimos and Phobos, particularly the second one, the bigger and closer natural satellite of Mars to discover its origins. Is it a giant impact on Mars, capture of an asteroid or a co-formation with Mars? Its diameter is about 20 km, located at 6000 km from Mars surface, itself with a 3394 km radius. In comparison, the Moon is much further away from Earth surface, at 384 000 km. Phobos orbit is circular and almost not inclined, only 1° from Mars equator. Its orbital period is 7h39, while Mars one is 24h36. A Mars observer would see Phobos rise twice a day, and cross the sky in less than 4h15 [1] [2].

Phobos was observed and photographed by different space missions, like Mars Reconnaissance Orbiter in 2007 and 2008 (Figure 1), but their main objectives were not to explore this satellite.

Figure 1: Photography of Phobos, Mission: Mars Reconnaissance Orbiter (MRO), Produced by: University of Arizona/HiRISE-LPL

MMX mission will be launched in 2026 and will not only observe distantly Mars moons, but also will carry and drop a rover, called Idefix, on Phobos surface for in-situ exploration and to collect samples of regolith, the dust covering Phobos surface. MMX orbiter spacecraft is developed by JAXA and will travel from Earth to Mars, fly over Phobos and Deimos moons, land twice on Phobos and send back samples to the Earth. MMX orbiter will also serve as a relay of communications to the Earth for Idefix and its own data. Idefix, developed by CNES and DLR, will be delivered close to the sample collection area and will perform soil characterization in order to secure MMX orbiter spacecraft landing on the surface. Idefix is foreseen to work during a hundred days and to move on a hundred meters. DLR developped the chassis, the wheels, the engine and the separation mechanism with the orbiter. CNES was responsible for the solar panels, the On-Board Computer (OBC, Steel Electronique), the Power Control and Distribution Unit (PCDU, EREMS), the batteries (SAFT) and the communication system (Syrlinks, Anywaves) between the rover and the orbiter. CNES provided several internal designs and developments for the cameras, the solar panels, the crashpads, the flight software and the mission analysis. Steel Electronique also provided the RolBox, which is the RF transceiver on the orbiter. Scientific instruments include different cameras from 3D+ looking to the soil (2 NavCams) and to the wheels (2 WheelCams), RAX spectrometer and miniRad radiometer [1][2][3].

ISL SOLUTION

The Inter Satellite link (ISL) used for the MMX mission is inherited from several exploration missions and R&D developments.

It all started with the Rosetta/Philae mission, launched in 2004. The ISL was specifically designed and developed for this mission with drastic objectives for mass and power consumption. In that purpose, the use of COTS (Component Off The Shelf) parts was decided leading to a low cost product widely used afterwards on the Myriade platform family for the TT&C (Telemetry, Tracking & Command) function.

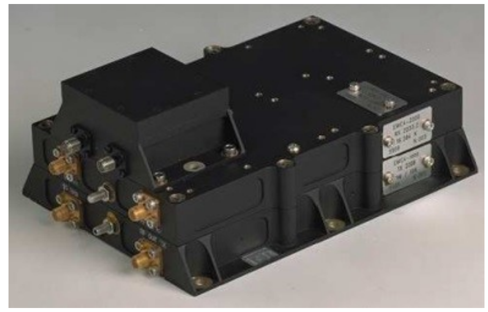

Figure 2: Rosetta ISL transceiver

The transceiver was a full duplex S-band transmission set for digital data developed specifically for space applications (output power: 1 W RF, consumption: 6 W, Rx range: -120/-55 dBm, dimensions: 160 mm x 120 mm x 40 mm, mass: 0.95 kg).

The epic scenario of the Philae mission on the Churyumov-Gerasimenko comet in 2014 [4] offered a good return on experience for the next generation of equipment for this type of exploration missions.

When the mission was completed, CNES worked on improved equipment able to offer new functionalities such as multi-landers communication capacity for one orbiter and ranging capacity to determine the landers location on the explored body in case of a scenario similar to Philae.

At the same time, nanosatellites market was in development driving a wide enthusiasm for the benefits of these platforms. Even if the maturity was not high enough at that time to be embarked on exploration missions, it was just a matter of time before it could happen. The LEO market was dynamic and required communication equipment for TT&C, payload telemetry and ISL. The adopted strategy was to work on communalities between this equipment to offer affordable solutions for the nanosatellite market and exploration missions [6]. The nano form factor perfectly fits the requirement for small landers with low power consumption.

Through R&D activities with industrial partners, a complete set of RF communication equipment emerged and in particular an ISL solution with ranging and compatible with up to 7 landers. It would only require a qualification phase specific to each mission to reach the highest TRL.

When Idefix was selected, it was decided to capitalize on that demonstrator development. However, the schedule was already constrained and it was chosen to focus on the RF capacity and to abandon extra functions like ranging. Goal was to minimize development cost and planning and to favor high reactivity from the provider.

MMX orbiter and Idefix rover will communicate using an ISL RF architecture, composed of 2 parts:

- One first subsystem accommodated on MMX spacecraft.
- A second subsystem accommodated on Idefix.

Equipment are almost symmetrical and link is in full duplex. It is based on a couple of frequencies in the S-band TT&C reserved spectrum. During the mission, the orbiter will be considered as the master in the communication protocol while the rover acts as a slave. Thus, communication from MMX to Idefix will be described as **forward** and consequently, **return** will stand for link from rover to orbiter. An overview of the communication architecture is shown in Figure 3.

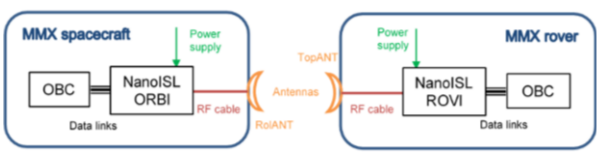

Figure 3: MMX mission RF link architecture

Both subsystems are off-the-shelf products from French industrials.

Transceivers: Based on S-band EWC31 transceivers provided by Syrlinks. Slight HW/SW changes from basic equipment. Syrlinks worked on SPL/PM modulator software IP development as well as code triplication to ensure equipment ruggedness to SEU. All other functions were inherited from the original EWC31 (output power: 2 W RF, consumption: 12 W, Rx threshold: -125 dBm, dimensions: 90 mm x 90 mm x 50 mm, mass: 0.425 kg).

Figure 4: EWC31 transceiver

Antennae: S-band antenna S-LHCP-19V3 provided by Anywaves. The I/F connector differs for each antenna (straight vs. 90°) for a better accommodation.

In order to ensure forward communication (from MMX to Idefix) data rate is low (32 kbps) allowing a better link budget. The low data rate does not represent a limitation as the orbiter will only upload TC plans to the rover for its science activities. On the other hand, the rover will be able to send data at two different rates: low (64 kbps) or high (512 kbps) data rates.

A delta qualification was run on both equipment to ensure compliance with Phobos environment.

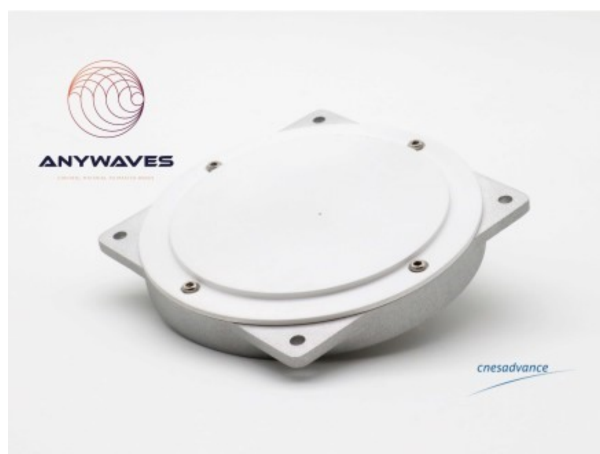

Figure 5: S-band TT&C antenna

COMMUNICATION PROTOCOL

The communication between the rover and the RolBox is driven by a handshake communication protocol illustrated in Figure 6. Communication sessions shall be autonomously managed by the space segment as they cannot be predicted precisely enough to be scheduled using time-tagged TC.

First, the orbiter (RolBox) starts transmitting a carrier wave, while the rover is only, and always, listening. When the rover acquires the orbiter signal, it triggers its carrier_lock register and switch its transmitter to carrier wave mode too. Then, the same process occurs with modulation mode with idle frames sent until the link quality is considered high enough to send data frames. Then a handshake takes place at software level between the orbiter and the rover to initiate the TC plan upload and TM downlink.

The previous sequence considers that the rover and the RolBox are on as well as their RF equipment, transmitters in stand-by mode (no transmission).

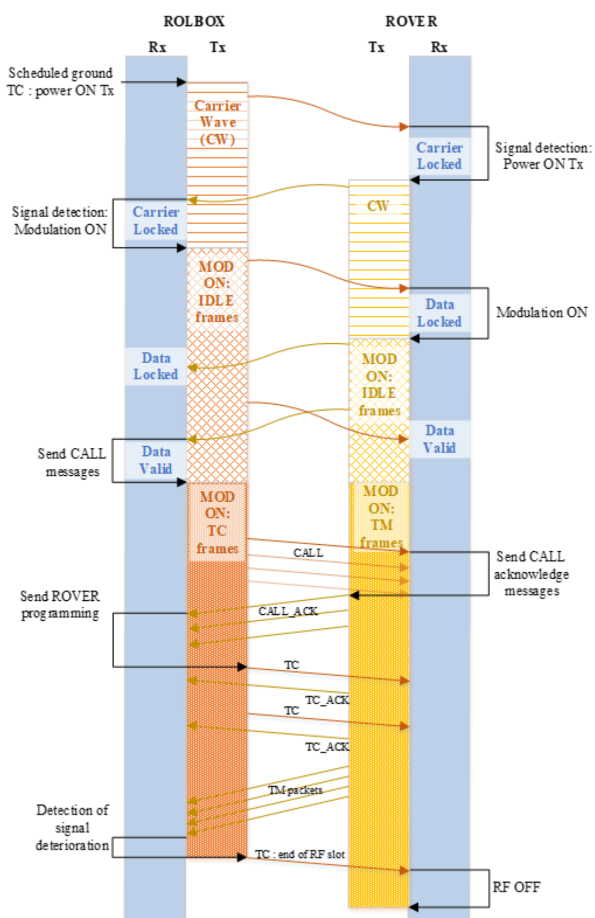

Figure 6: Protocol overview

MISSION PHASES AND IMPACTS ON COMMUNICATIONS

Idefix will go through three main operational phases:

- Hitchhike (Launch and cruise)
- Separation, Landing, Uprighting and Deployment (SLUD)
- Phobos surface

Hitchhike

Launch of MMX spacecraft is planned at the end of 2026 from Tanegashima base in Japan. Cruise from Earth to Phobos will last 1 year. Then during at least 18 months, the orbiter will fly over Mars's moon in order to characterize it and identify the best place to drop the rover for touchdown. During this phase, the rover will be connected to the orbiter with the MECSS (Mechanical, Electrical, Communication Support System), and will be off most of the time. However, it will be switched on several times to ensure battery maintenance and limit its ageing, and to check the good health of all rover subsystems via umbilical link.. The basic functional check sequence will also include RF communications tests.

SLUD

This phase is very critical because it will be done in full autonomy and the attitude of the rover cannot be predicted and controlled. The operations to prepare the SLUD phase will begin a few days before. The rover will need to be warm and its battery fully charged before the separation from the orbiter. The communication will be lost before the end of the SLUD phase because the orbiter will lose the line of sight with the rover. Some details of the different steps are provided below.

Separation: End of 2028, the orbiter will approach Phobos surface and drop IDEFIX from less than 100 m of altitude, with a velocity of 20 cm/s. During the fall, it will take pictures and send them immediately to the orbiter through the RF link in low data rate mode. Thanks to the low Phobos gravity, the rover will fall with a speed lower than 1 m/s, during 1min 30sec but in an uncontrolled attitude. After the orbiter dropped IDEFIX, it will go up, at an altitude of 200 km maximum.

Landing and uprighting: Because of the low velocity during, the rover will land very softly: the impact on Phobos is equivalent of a drop from 1 cm of the ground on Earth, but will make bounces anyway. The direct consequence of the uncontrolled descent and bounce is an uncontrolled touchdown position. Taking this state into account and with its battery fully charged, the rover is able to deploy its wheels and put itself in the right way, up, from any landing position (Figure 7).

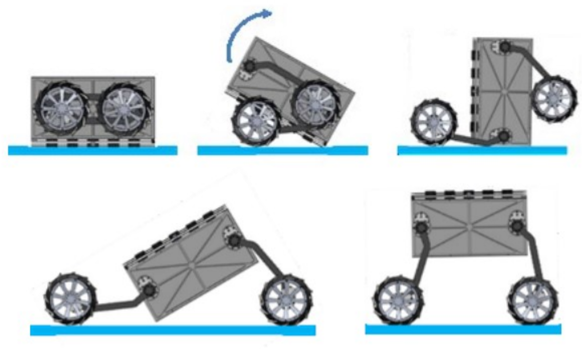

Figure 7: Uprighting from upside down ([5])

Deployment: After uprighting, IDEFIX will automatically open its solar panels, and lean towards the sun. It will wait in this position until the next orbiter pass to communicate on its health state.

For all SLUD steps, communication has to be functional even with the folded solar panels and with the already mentioned uncontrolled attitude. The antenna has an omnidirectional pattern but severe losses were expected with the folded solar panels so qualification tests were required to validate the RF communication capacity. Radiated tests were conducted in an anechoic chamber to measure the antenna gain reduced by the panels.

The antenna gain value at 3σ was simulated and confirmed by measure and was -26.8 dBi. It is representative of an uncontrolled attitude of the rover, providing a value covering the worst case (99.73% of the gain values in the antenna pattern are above this value). Link budget showed that the RF link is guaranteed with this value up to 2 km with a 10 dB margin and low data rate (64 kbps). It allows 140 seconds of visibility with the orbiter. The RF communication is still possible at 5 km or more, but with a lower link budget margin.

Phobos

Once IDEFIX ready on the surface, starts the exploration and science phase, which will last a hundred days. During this time, it will drive on Phobos. A first objective will be to characterize the surface of Phobos in order to de-risk the future orbiter landing by studying the regolith properties. A second objective is to explore the moon. Observations and movements will be daily programmed on Earth by CNES and DLR exploitation teams from their respective mission control centers and sent to the orbiter, which will relay the commands to the rover. JAXA, NASA and ESA Deep Space Network (DSN) will be used to reach MMX. During 100 days, IDEFIX will drive up to 100 meters. Computed link budgets for the Phobos surface phase guarantee 6 passes per day, and more than 2 hours of cumulative communications in low and high data rate. Figure 8 and Figure 9 show the range in kilometers of the accessible RF link, for 32 and 512 kbps and for different orbiter and rover antenna pointing.

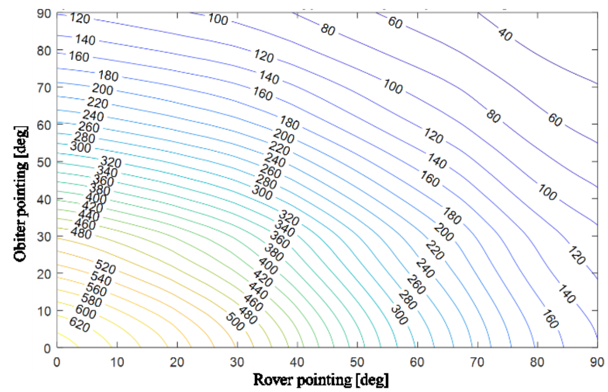

Figure 8: Range of the RF link, data rate of 32 kb/s

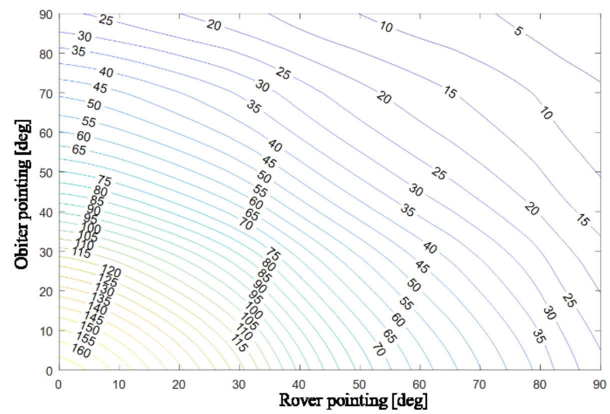

Figure 9: Range of the RF link, data rate of 512 kb/s

Mid-2029 up to 2030 late summer, MMX orbiter will land 2 times on Phobos to collect soil samples, then will perform a fly-by over Deimos, the other Mars moon, and finally come back to Earth in 2031.

RF SUBSYSTEMS QUALIFICATION, TESTS AND MEASUREMENTS

Qualification

An extended qualification has been achieved on antennae and transceivers. Although very few data are available on Phobos soil characteristics, it is known that thermal range is very high in function of the season and the latitude. Therefore, transceivers were qualified with a representative Mechanical Ground Support Equipment (MGSE) and an extended thermal range [-40°C; +60°C] at thermal interface level. The same MGSE was used for extended vibration and shock qualification at levels predicted from model simulations.

Antennae qualification temperature range was also extended to +/- 120°C during Thermal Vacuum (TVAC) test and conformance to mechanical levels were also checked during dedicated vibrations and shock tests.

AIT performances tests

During all the Assembly, Integration and Test (AIT) period, RF performance tests and health checks were performed at each level of integration, and before and after tests such as vibrations, shocks, transports, thermal cycling and EMC tests. Similar tests are foreseen to be achieved in Japan to track any deviation after material travel. Performances measurements were done with RF equipment only and then connected to the antenna, and for rover and RolBox RF subsystems apart. For RF tests with the antenna, a specific antenna cap was used. Measures validated the following specifications:

Table 1: Measures and specifications

Measure	Specification for ORBI/ROLBOX	Specification for ROVI/ROVER
Transmission tests		
RF output power	33 dBm	
Spectrum	The spectrum has 2 lobes and 1 carrier	
Carrier frequency	2077.4 MH_Z	2256 MH_Z
Bandwidth and data rate ($BW = 8*R_S$)	$R_S = 32$ kb/s → BW = 256 kH_Z	$R_S = 64$ kb/s → BW = 512 kH_Z & $R_S = 512$ kb/s → BW = 4096 kH_Z
Reception tests		
With a signal generator with PRBS signal, and check the required signal level for detection and lock of the signal for each mode.	Carrier acquisition threshold < -120 dBm Data acquisition threshold < -108 dBm	

Communication verifications were done with both RF subsystems together:

- First in conducted configuration: connected via RF harness plugged on the antenna caps, and with regular and variable attenuators between them, to protect each other from a high RF input level and to simulate the loss of signal.

- Then in radiated configuration: signal detection and lock always worked, so even by taking one away from the other, and covering antennae with absorbers, cutting the signal off was not possible.

Flight Software and Command Control validation

Communication verifications with both RF subsystems, in conducted configuration, allows validating the RF flight software described before. When switching the carrier on, on the orbiter, the following operations described in the communication protocol paragraph were done automatically: rover switched its carrier on, then orbiter switched the modulation on, then rover switched the modulation on. When the link was established, the rover sent some pictures to the orbiter.

RF communication test for SLUD phase

RF communication tests were performed in CNES anechoic chamber to validate the link during SLUD phase meaning an uncontrolled rover attitude and with solar panels covering the RF antenna. Simulations were done but they are not precise enough to confirm if the RF link was possible and at which data rate, because of the multiple involved materials and the structure complexity. A representative model of the rover was then built (Figure 10) for the measurements in the anechoic chamber with a mechanical interface to be attached to the facility arm (Figure 11).

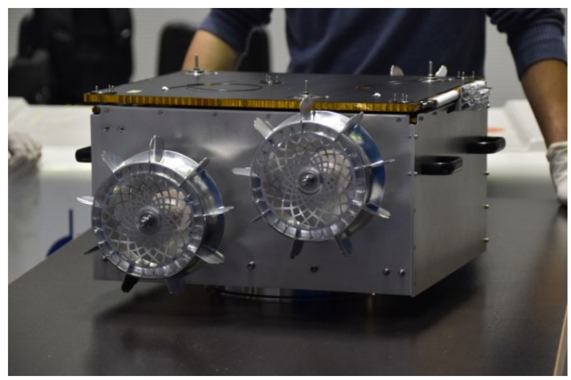

Figure 10: Representative model of Idefix

The antenna gain was measured in all directions: the gain at 3 σ is -26.9 dB. The result is very close (less than 1 dB) from the simulations. Antenna impedance-matching (S_{11}) was also measured to check if the power reflected by the solar panels does not risk damaging the S-band equipment.

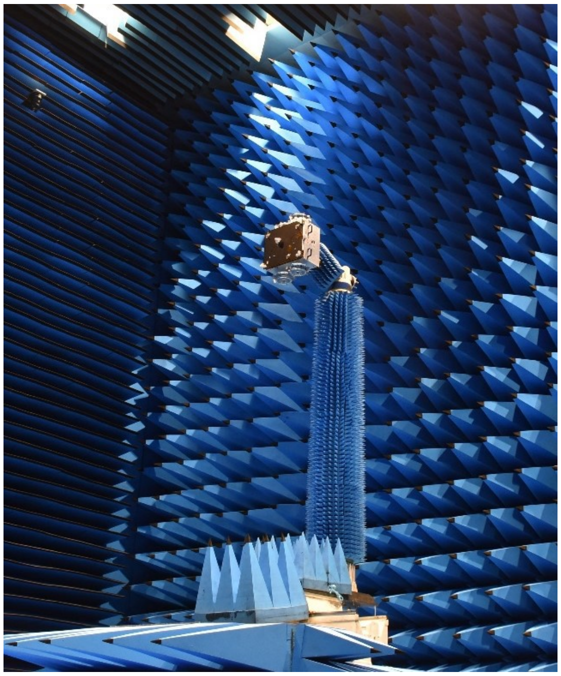

Figure 11: The model attached to the arm in anechoic chamber

RF compatibility test for RolBox and EMC

During development phase, it was highlighted by JAXA that some MMX RF equipment might be on during RF communication and predictions showed that their levels would exceed receiver interference mask by more than 20 dB. A fine measurement mask was provided by JAXA to CNES and a test was performed in CNES laboratory to check receiver behavior. A representative interferer was added to the rover signal and receiver characteristics were checked. Hopefully, no degradation was observed on signal threshold level and signal quality indicator remained unchanged. Thus, if a similar case occurs, both teams are confident that interference should not happen. However, a full EMC test in Japan is already planned in 2024 to ensure a full compatibility between all equipment.

CONCLUSION

The forthcoming JAXA MMX mission, that will be launched in 2026, will carry the French-German Idefix rover to drop it on Phobos, after a more than 2-year long journey. CNES has the responsibility of the RF communication link between the orbiter and the rover. There is one RF subsystem on each vehicle, each one composed of a S-band transceiver (EWC31, Syrlinks) and of an omnidirectional S-band antenna (Anywaves). The only difference between transceivers are their carrier frequency for channel separation and their data rates. A protocol and flight software were implemented by CNES in order to let both RF systems communicate autonomously when possible: the predicted orbit is not precise enough to compute time-tagged commands. Qualification tests were performed to validate the RF link and its resilience during all the operation phases. RF performances were tested in conducted and radiated configurations, during all the AIT period at CNES facilities and currently continues in Japan during integration of the rover into the MMX spacecraft. Specific verification tests had to be done to check the RF link during the critical separation phase of the rover, when its solar panels are covering the antenna thus degrading the link budget. Good behavior of the link was also checked taking into account the perturbations of the other instruments on MMX.

Previous exploration missions experience allowed designing an ISL adapted for this Phobos exploration mission. Performed tests give a high confidence on the RF link performances for the mission. Idefix is ready for the next launch window in late 2026!

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