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Development of Observation Strategies from Mission Design to Operations Illustration with Mars Moons Explorer Infrared Spectrometer (MIRS)

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Abstract

MIRS is part of the French contribution to the Martian Moons eXploration (MMX) mission that will be launched in 2024 by the Japan Aerospace Exploration Agency (JAXA). It is a near-infrared imaging spectrometer developed by the French Laboratory of Space Studies and Astrophysics Instrumentation (LESIA), of the Observatoire de Paris – PSL, with close cooperation and financial support from CNES. One of the major mission goals is to understand the origin of Phobos and Deimos, providing important insights into planetary formation and the transfer of matter in the region connecting the inner and outer solar system.

During the four years of the mission, the MIRS control centre will provide precise sequencing of MIRS activities and guidance of its line of sight, with two main drivers: optimize scientific return and comply with the operability constraints of the instrument, the satellite and the system. In this perspective, observation strategies are designed, modelled and tested iteratively throughout all preparation phases of the mission. Discussions on concrete simulation results and illustrations improve mutual understanding, raise unexpressed needs and constraints and promote feedback on the efficiency of the proposed strategies. They also favour a global optimization of the entire system with the refinement of the trajectories and of the scheduling considering the seasons of the Martian system.

This paper describes the whole process of observation strategies development in cooperation with the MMX and MIRS system and scientific teams, as well as the current status and results.

Keywords: Observation Strategies, Optimization, Mission Planning, Instrument Programming, Guidance

Nomenclature

iFOV: Instantaneous Field of View

MIRAGES: MIRS Image Response Assessment by Global and End-to-end Simulations

MIRS: MMX InfraRed Spectrometer

MMX: Martian Moons eXploration mission

OASIS: Optimized Astrophysical Simulator for Imaging Systems

QSO: Quasi-Satellite Orbit

SNR: Signal-to-Noise Ratio

1. Observation Strategies in a nutshell

From the scientific objectives that define what to observe and why, the observation strategies determine when to observe and how. This iterative process continues throughout all the phases of the project, from initial design to operations, and requires a close

cooperation of the observations strategies team with the scientific team and the teams responsible of the main components of the space system: Spacecraft, Trajectories, Instruments, Operations and Ground Segment.

Along with the scientific objectives, expected performance results on the final scientific products are progressively refined, allowing an incremental definition on how and when to observe. Simulations and end-to-end tests are essential to this process as they favour a common understanding of the physical quantities and concepts and provide an assessment of the reachable performance.

During operations, the spacecraft and the instruments are programmed to perform the observations to fulfil the scientific needs while meeting the constraints of the System and instruments. It is mostly an automated process relying on operational

libraries that are implemented, validated and integrated into the Control Ground Segment.

2. Specificities of Interplanetary Missions

The distance from the Earth has a direct impact on communications with the Spacecraft. Firstly, it induces a delay that is not compatible with the real-time commanding of the Spacecraft and Instruments: for instance, for Mars System the one-way delay varies between 6 and 20 minutes. Secondly, it hugely reduces the uplink and downlink rates, so the Spacecraft and Instrument Programming and the selection of the scientific observation data to download have to be conducted with the utmost efficiency. Thirdly, communications are degraded during solar conjunction periods: for instance, for Mars they can last up to 1.5 month and occur every 2.5 terrestrial years.

The distance also has an obvious impact on the time needed to reach the target celestial body: for MMX, 1 terrestrial year will be necessary to reach the Mars System: it will be the opportunity to perform health checks of instruments as well as calibrations and to further refine the observation strategies.

The multiplicity of the instruments is beneficial for the collection of data of different natures and also for scientific and engineering international cooperation, but it increases the competition for the spacecraft's limited resources (on-board software, memory, uplink/downlink bandwidth, power) and multiplies the constraints (thermal, spacecraft pointing).

As the very purpose of interplanetary missions is to unveil the unknown, some level of flexibility has to be considered in order to cope with unexpected events and be able to adjust the entire space system to collect data on unexpected phenomena or opportunities.

3. MMX mission

3.1 MMX Mission Objectives

MMX (Martian Moons eXploration) is an ambitious mission led by the Japan Aerospace Exploration Agency (JAXA), planned to be launched in 2024. Its major objectives are defined in [1, 2, 3].

1. *To settle the controversy on the origin of the Martian moons by close-up observations and samples return*
2. *To shed light on the processes for planetary formation and material transport in the region connecting the inner and outer solar system*
3. *To reveal evolutionary processes of the Martian system in the circum-Martian environments*

To achieve these, MMX will perform remote observations of Mars, Phobos and Deimos as well as Phobos in-situ observations and samples return to Earth thanks to its 13 instruments. The observation phase will last 3 years from August 2025 to August 2028, and Phobos samples will be reach the Earth in 2029.

MMX mission is a fantastic opportunity for French space contribution to strengthen and deepen the fruitful cooperation with JAXA and international scientific teams demonstrated on the Hayabusa2 mission. For MMX, the French contribution consists of:

- MMX InfraRed Spectrometer (MIRS) that will remotely observe Mars, Phobos and Deimos
- A Rover, built in cooperation with Germany, that will act as a scout for the MMX spacecraft and explore Phobos' surface
- Flight Dynamics expertise, from design phases to operations

3.2 MIRS Observation Objectives

MIRS is a near infrared imaging spectrometer made by the French Laboratory of Space Studies and Astrophysics Instrumentation (LESIA) from Observatoire de Paris - PSL in collaboration with four other French laboratories (LAB, LATMOS, LAM, IRAP-OMP) and with close collaboration and financial support from CNES.

The fulfilment of the MIRS mission Objectives (as defined in [1, 2, 3]) will rely on the generation of the following scientific products:

- Global maps of Phobos' composition from High and Medium altitude trajectories (between 200 km and 50 km from Phobos' centre), with a target resolution of 20 m in some areas
- Detailed composition maps of Phobos Landing Candidate Regions (300 m x 300 m) from Medium and Low altitude trajectories (between 100 km and 20 km from Phobos' centre)
- A detailed composition map of a 50 m zone around the 2 Phobos landing sites, with the best possible resolution
- Composition maps of large areas of Deimos, with a target resolution of 100 m
- Global maps of Mars' atmosphere for monitoring
- Multi-temporal maps of large areas of Mars for atmospheric phenomena tracking
- Mars limb maps

Phobos and Deimos surface composition maps will be characterized by spectral signatures, such as hydrous silicate minerals (features at 2.7-2.8 μm), water (ice) (absorption bands at 1.5, 2.0 and 3.0-3.2 μm), minor overtones at 1.4 and 1.8 μm), or anhydrous silicates (bands in the 0.9-1.0 and 2.0 μm regions) as well organic matter (3.3-3.5 μm).

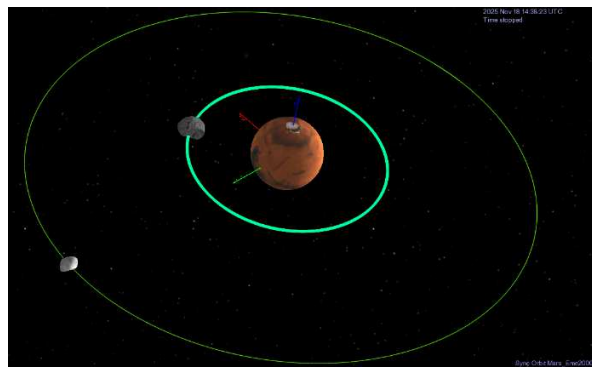
In addition, as explained in [1], the thermal tail will be used to assess the surface temperature and its spatial and temporal variations. From temperature measurements, information about the surface thermal inertia of Phobos will be derived.

3.3 Characteristics of the Martian System

A Martian year lasts around 2 Terrestrial years and Mars' obliquity is around 25°, resulting in seasons with

an average duration twice as long as Earth seasons but with uneven durations, because Mars' orbit has an eccentricity of around 0.09 (0.017 for the Earth).

Phobos' and Deimos' orbits around Mars (Fig. 1.) have a low inclination (respectively 1.08° and 1.79°). They consequently share with Mars a similar evolution of the Sun's elevation over time. The two moons are tidally locked and their periods around Mars are 7h40min for Phobos and 30h18min for Deimos. They are both relatively close to Mars with respective semi-major axes of around 9,400 km (~3 Mars radii) and 23,400 km (~7 Mars radii). As a first order approximation, the eclipses season occurs on Phobos and Deimos when the Sun elevation absolute value with respect to the moon orbit is below Mars' half-polar angle, which is equal to 21° from Phobos, 8° from



Deimos.

Fig. 1. Phobos and Deimos trajectories
 Phobos and Deimos size is multiplied by 100

In Fig. 2, we can see that Phobos' and Deimos' shapes differ significantly from an ellipsoid. This will affect the observation conditions and the possibility to observe some zones: we see in particular that the South Pole of both moons is quite flat and even concave, which will impair their observation from equatorial trajectories.

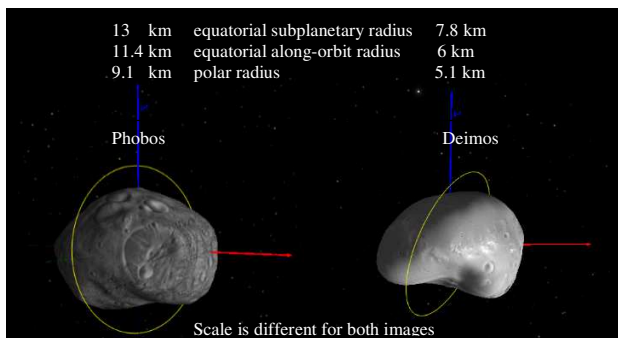


Fig. 2. Phobos in Oct 2025 and Deimos in May 2028
 Sun Terminator, X axis (towards Mars), Z axis towards pole

3.4 MMX and MIRS mission specificities

The 4-year operation of MMX and MIRS demands a good level of automation in order to secure the spacecraft and instruments programming and to reduce

the workload of the operations team in routine. Additionally, a certain level of flexibility will be needed in order to respond to unexpected opportunities. This will be achieved thanks to coordinated adaptations of the long and mid-term planning agreed during the regular meetings of the international scientific teams [2] as well as means external to the ground control centre in order to develop specific observation plans.

As presented in Table 1, MMX will perform global observations of Mars' atmosphere with high temporal resolution and observations of Phobos and Deimos with high geometric resolution.

Table 1. MMX Mission Phases

Phase	Start	Duration (month)	Activities
Cruise	Oct 2024	12	Instrument Health Checks and Calibration
0	Sep 2025	1	Mars atmosphere and Deimos observation
1	Oct 2025	2	Phobos global composition and Landing candidate regions
	Dec 2025	1.5	Solar conjunction
2	Feb 2026	7	Detailed observation of Landing candidate regions
	Sep 2026	3	Phobos global composition and Landing candidate regions
3	Dec 2026	8	Mar 2027: MMX 1st Phobos descent rehearsal Apr 2027: MMX Phobos 1 st descent with sample collection May 2027: MMX 2 nd Phobos descent rehearsal Jun 2027: MMX 2 nd Phobos descent with sample collection
4	Jul 2027	7	Phobos global composition & Mars atmosphere observation
	Mar 2028	1.5	Solar conjunction
5	May 2028	3.5	Mars atmosphere and Deimos observation

Phobos and Deimos high-resolution observations require MMX to be close to them. As we can see in Table 2, even when the Phobos to Deimos distance is the smallest, when MMX is close to a given moon the apparent angle of the other is very low. It justifies the need to have dedicated MMX trajectories for Phobos and Deimos observation.

Table 2. Mars, Phobos and Deimos apparent angles

	From Phobos	From Deimos
Mars apparent angle (deg)	42	17
Maximum Phobos apparent angle (deg)		0.11
Maximum Deimos apparent angle (deg)	0.06	

3.5 MMX Trajectories

Satellite trajectory relative to the observed celestial body is in most cases the major contributor to instrument performance as it drives the following parameters:

- Evolution of distance to target zone, which impacts the geometrical resolution and the size of the projected field of view
- Evolution of instrument projected line-of-sight ground speed that, in some cases, can be adjusted by satellite or instrument line-of-sight guidance. Depending on the instrument integration time and the chosen strategy, it can affect the signal-to-noise ratio, the spatial sampling or the Modulation Transfer Function.
- Number of observation slots and even the observation possibility of a given zone on a given time horizon.
- Observation conditions, such as viewing incidence that impacts the geometrical resolution and the spatial sampling

MMX trajectory [4, 5], during the main mission phases, will be broadly in the same orbital plane as Phobos and Deimos, which themselves have a low inclination with respect to Mars.

During mission phases 1, 2 and 4, MMX will be in quasi-circular and equatorial orbits (Fig. 3a and 3b) around Mars (QSOs), which are very similar to Phobos' orbit around Mars. These trajectories of progressively decreasing distance to Phobos will be used to improve the knowledge of its gravity field and obtain maps of finer resolution (Table 4).

During phases 0 and 5, Deimos being around 2.5 times farther from Mars' centre than Phobos, it will be observed during fly-bys, from elliptical orbits around Mars.

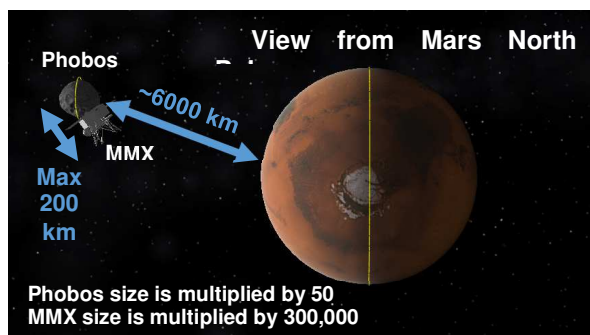


Fig. 3a. MMX Distances from Mars and Phobos on Quasi-Satellite Orbits (QSOs)

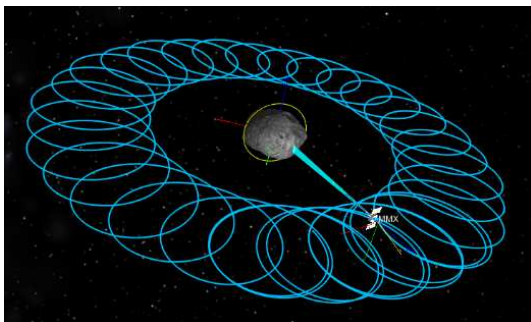


Fig. 3b. MMX trajectory in an inertial frame centred on Phobos, for a duration of 240 h for a medium altitude Quasi-Satellite Orbit (100 km x 50 km)

4. How to Observe

From the instrument measurement principle, the main expected performance, the initial version of the spacecraft trajectories and the shape models of the target celestial bodies, the instrument characteristics and its line-of-sight guidance principles are defined. Performance is then assessed and analysed to improve, when possible, the design of the various space system components: Spacecraft, Trajectories, Instruments, Operations and Ground Segment. The whole process is refined throughout the project thanks to the progressive clarification of the scientific objectives and of the space system components design and constraints.

4.1 Instrument measurement principle

MIRS is a spectrometer [1] that uses the well-known push-broom acquisition principle (Fig. 4). A single detector acquisition (2D matrix) provides the image of each point of the slit in the second direction (spectral) by the collection of photons during a time interval called the integration time. The second spatial dimension results from the motion of MIRS Line-of-Sight in the cross-slit direction. The image-cubes (X, Y, λ) are reconstructed by the Ground Segment. MIRS design allows remote observation of Mars, Phobos and Deimos as well as close observation of Phobos down to 400 m altitude.

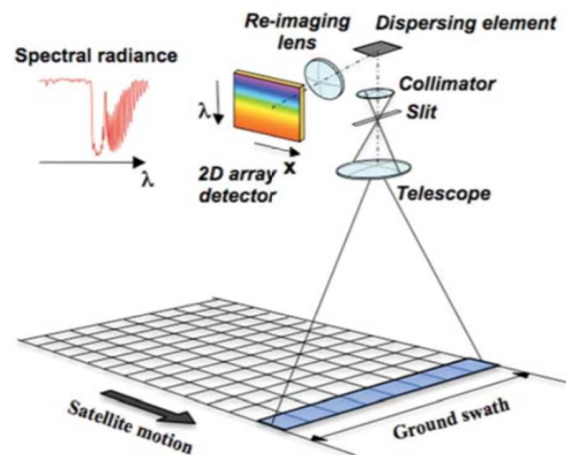


Fig. 4. MIRS push-broom acquisition principle

4.2 Performance criteria and Observation Conditions

The main performance criteria identified for MIRS products are the following:

- Spectral Resolution
- Spatial Resolution
- Signal-to-Noise Ratio

Fig. 5 presents the Observation Conditions that drive those performance criteria.

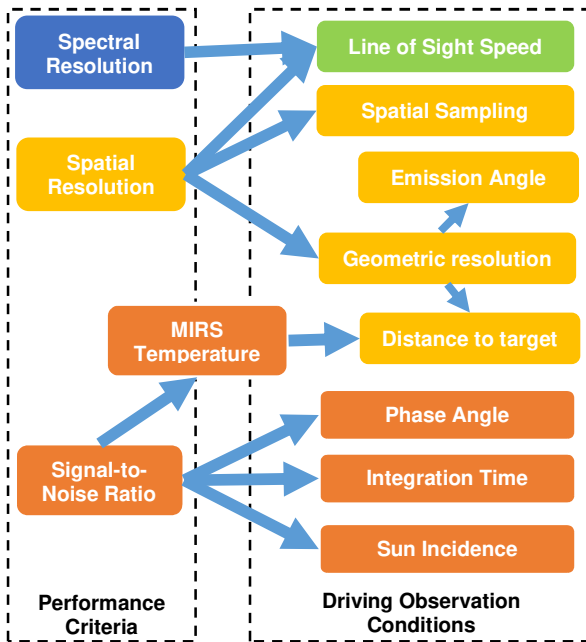


Fig. 5. Performance criteria and driving Observation Conditions

MIRS Line-of-Sight displacement during the integration time shall not exceed the chosen spatial sampling in order to avoid degrading the Modulation Transfer Function, which has an impact on the Spatial and Spectral resolutions.

The setting of the Spatial Sampling is a compromise between the Spatial Resolution on one hand and the data volume and necessary time to cover a target zone on the other hand.

Geometrical resolution depends on distance to target and emission angle. To obtain the best geometrical resolution, both parameters shall be minimized as much as possible.

Signal-to-Noise ratio is improved by favouring low phase and sun incidence angles, which are respectively:

- The angle between observed point to Sun direction and local normal
- The angle between the light incident onto the observed point by the Sun and the light reflected from the observed point

A longer integration time can also be beneficial, but it increases the necessary time to cover a zone. MIRS being an infrared spectrometer, its temperature also has an impact: the closer MMX will be to Phobos the more it will be subject to Phobos' infrared radiation.

4.3 Definition of the Instrument characteristics

MIRS instantaneous field of view (iFov) has been chosen as the best compromise between the geometric

resolution and the number of images necessary to perform a global map of Phobos for latitudes within $\pm 30^\circ$ from a medium altitude QSO. Obtaining such a map at the end of phase 1 of the MMX mission will be a major asset for the characterization of Phobos' global composition and the selection of the landing candidate regions. Simulations were performed with several values of iFov to calculate the best reachable coverage of Phobos together with the subsequent necessary number of images to cover the wished area. Fig. 6 and Table 3 present the best obtainable resolutions for the selected iFov of 0.35 mrad. It cannot be guaranteed that it will be possible to build an observation plan that will reach this performance as there may be a time competition between the best opportunities of different areas, but it provides crucial information on the topographical variation of the best reachable resolution as well as an ideal objective.

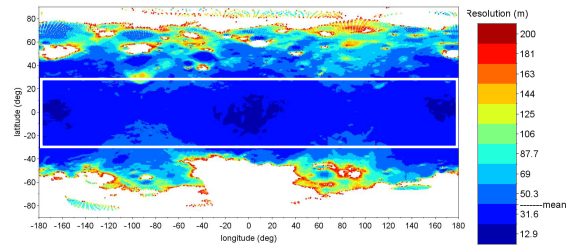


Fig. 6. Phobos QSO-M Nov 2025
 Best achievable resolution

Zone within $\pm 30^\circ$ latitude is in the white rectangle

Table 3. QSO-M Nov 2025 Coverable surface within $\pm 30^\circ$ latitudes at several resolutions

Resolution (m)	100	40	30	20	10
% of coverable surface within $\pm 30^\circ$ latitudes	99	94	78	38	0

As the number of pixels along-slit is an off-the-shelf characteristic of the detector, the choice of the iFov determines the along-slit field of view, which is 3.3° for the selected iFov of 0.35 mrad. Table 4 illustrates the Phobos polar angle from MMX closest distance to the body surface for each envisaged QSO. We can see that even on the farthest trajectory this along-slit Field of View is not sufficient to get a global coverage. It is therefore necessary to have the capability to modify the MIRS Line of Sight in the along-slit direction.

Table 4. Phobos polar angle from QSOs

QSO	H	M	LA	LC
Minimum MMX distance to Phobos ground (km)	88	37	20	6.6
Phobos polar angle at minimum distance (deg)	10	21	35	54
MIRS nadir resolution at minimum distance (m)	31	13	7	2

4.3 Definition of the Instrument Line-of-Sight Guidance

4.3.1 Roles assignment to the Spacecraft and to the Instruments

An instrument line of sight is guided thanks to its internal mobile parts, if any, and to the spacecraft's pointing. MMX instruments are located on the MMX – Z face, and typical MMX bodycentric pointing during observations will consist in (Fig. 7):

- Aiming the $-Z_{MMX}$ axis at the centre of the observed body (Mars, Phobos, Deimos)
- Aligning the $-Y_{MMX}$ axis with the component of the angular momentum of either Phobos', Deimos' or MMX's (depending on the observed celestial body) orbit around Mars that is orthogonal to Z_{MMX}

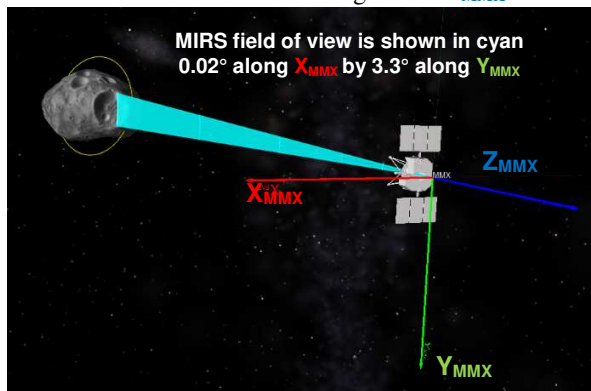


Fig. 7. MMX Pointing during Phobos observation

MIRS includes a one-axis internal scanner allowing a $\pm 20^\circ$ modification of its Line-of-Sight. It might seem natural to use it to adjust the MIRS Line-of-Sight in the along-slit direction in order to observe non-equatorial latitudes of Mars, Phobos and Deimos, but the best and chosen solution is somewhat different. Firstly, TENGOO (Telescopic Nadir Imager for Geomorphology) camera, a high-resolution visible telescope whose purpose is to reveal the geomorphological features of Phobos and Deimos, has an even narrower field of view along Y_{MMX} (1.1°) and no internal scanner. It therefore requires MMX to perform the necessary rotation around its X axis (roll rotation) with respect to the bodycentric pointing in order to observe non-equatorial latitudes. Secondly, considering MMX trajectories relatively to the target celestial bodies, the MIRS line-of-sight speed has to be adjusted:

- To decrease it when integration time is not respected with the best spatial sampling, which is the case for low-altitude QSOs
- To increase it in order to cover a larger zone in less time: typically for Mars observation but also for Phobos landing site observation during MMX vertical descent. It will also be used during Phobos

global mapping and Deimos observation in order to observe some regions in less time.

Consequently, the MIRS internal scanner rotation axis is cross-slit. This choice also provides more observation opportunities with specific conditions of phase angle and local time, which are necessary for thermal inertia characterization. Eventually, it facilitates MIRS calibration on stars by allowing an increase of the Signal-to-Noise ratio thanks to series of scans.

4.3.2 Spacecraft pointing modes definition

Spacecraft pointing modes dedicated to observations are jointly developed in order to meet the instruments' needs such as, for instance, the pointing mode for Mars limb observation by TENGOO and MIRS that require an MMX roll and pitch offset with respect to the Marsocentric pointing. The definition of spacecraft pointing modes not dedicated to observations and a way to estimate the duration of the slews between any pointing modes are also important for the sizing of the instruments, particularly for their thermal analysis and for the calculation of their observation plans. A good mutual understanding on these aspects is ensured by exchanging attitude predictions on a series of agreed sequences, as well as estimated duration of the slews.

4.3.3 Availability of the Spacecraft pointing modes

The availability of the pointing modes is driven by the instrument and spacecraft constraints on sun dazzling avoidance, thermal control and power management. For MMX, as instruments are located on the $-Z$ face, all bodycentric pointing modes are available only when the Sun-Target Celestial Body-MMX angle is below 90 degrees. This condition is not sufficient when an additional roll is applied: in that case, a condition on $Sun^{Azimuth}$ in Satellite frame has to be added (see Appendix A): $Sun^{Azimuth} \leq \cos^{-1}(\tan(Sun^{Elevation}) \tan(roll))$

In case an additional pitch is applied to MMX bodycentric pointing, its allowed amplitude can be expressed as a function of MMX position in the Sun-Mars rotating frame, as illustrated in Fig. 8.

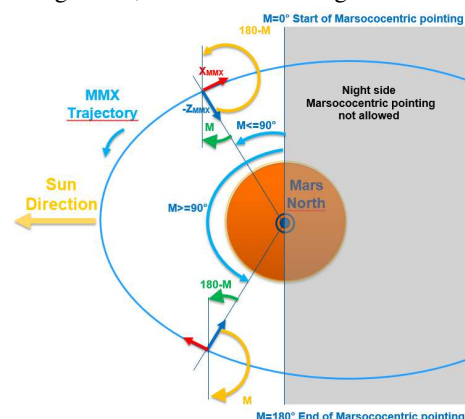


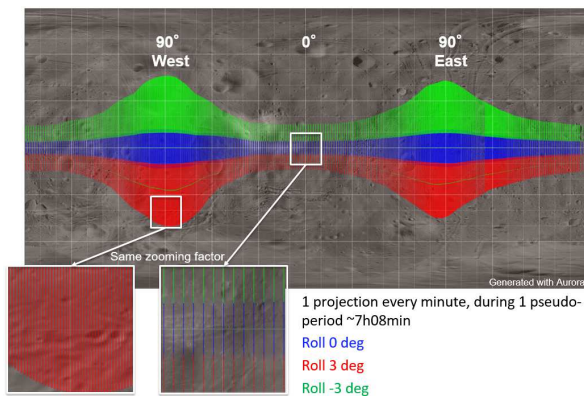
Fig. 8. Restrictions on MMX pitch with respect to Marsocentric pointing as a function of MMX position in Sun-Mars rotating frame – M is the component in the MMX orbital plane of the Sun-Mars-MMX angle

Sun avoidance on the $-Z$ face is also applicable to all slews between any pointing modes, so the direction has to be chosen accordingly and in some cases will not correspond to the smallest rotation direction.

In some cases, depending on the Sun's elevation with respect to MMX's orbital plane around Mars (which itself depends on Mars seasons as MMX trajectories are equatorial around Mars), limitations on MMX's roll amplitude apply in order to maintain the power generation by the solar arrays at a sufficient level.

4.3.4 Instrument guidance definition

On Phobos QSOs and during Deimos fly-bys, MMX's distance and relative velocity with respect to the target will significantly evolve with time. Fig. 9 shows MIRS projected slits on Phobos with 1-minute intervals, from a medium altitude QSO, for three roll angles, with the MIRS scanner in fixed canonical



position.

Fig. 9. MIRS projected slits on Phobos at 1-minute intervals on Phobos QSO-M for MMX roll 0° , -3° , 3°

We observe an increase of MIRS projected slit size with the roll angle absolute value, which is the result of an increase of the distance to the observed point coupled with an increase of the incident angle.

We also observe a dependency on the subsatellite longitude:

- the spatial sampling is larger for longitudes around $0^\circ/180^\circ$, shorter for longitudes around $-90^\circ/90^\circ$
- the MIRS projected slit is respectively smaller and bigger

Consequently, the basic principle of push-broom acquisition does not ensure a regular spatial sampling and degrades either the resolution or the data volume. To ensure the regularity of the spatial sampling, we therefore have two solutions:

- Temporal Guidance: maintain the scanner immobile during an observation and adjust the start time of each image

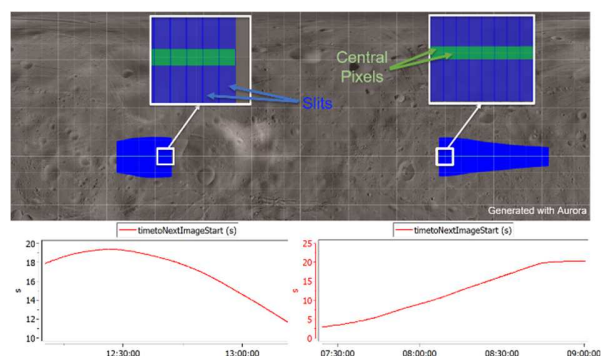
- Scanner Guidance: maintain a constant duration between each image start time and adjust the scanner angle

For a given integration time, fixed scanner angle and spatial sampling, Temporal Guidance is available for an observation if the duration between each image start time is above the integration time. Otherwise, we can choose a) to adjust one of the three parameters or b) to use the Scanner Guidance, if the scanner angle span and maximum rates are complied with during the observation. For many observations, both guidance modes are available and a choice has to be made: Temporal Guidance has the advantage of not modifying the viewing incidence, therefore improving the geometric resolution, whereas Scanner Guidance has the advantage of covering the target zone in less time, which can bring opportunities for other observations.

When the target speed relative to the MIRS slit projection is close to 0 deg/s , Scanner Guidance is the only option: it should be the case during MMX final descents to Phobos and stars observation.

The development of Temporal or Scanner Guidance requires complex calculations with, among other things, intersections with an ellipsoid or a shape model, which cannot be performed with the capacities of the on-board processors used today for interplanetary missions. The guidance profiles therefore have to be calculated on-ground and transferred to MMX with the best compromise between accuracy and quantity of information. Future interplanetary missions will very probably attempt to introduce more on-board autonomy, which could allow more reactivity for opportunistic observations and reduce the uplink data volume: even in that prospect, the versatility of ground commanded observations would still be an asset.

A basic method to transfer the guidance profile to MMX and MIRS would be to send one telecommand for each sample, which would represent a considerable amount with for instance more than 4,000 images for one west-east coverage on QSO-M with Temporal Guidance. Therefore, to optimize the number of telecommands, the profiles will be approximated by polynomials. For each observation, the degree will be adjusted to reach the best accuracy with the minimum number of coefficients to upload. Fig. 10 illustrates the variation of the Temporal Guidance profiles for each



observation.

Fig. 10. Example of **Temporal** Guidance profiles for two observations on Phobos QSO-M

4.3.5 Strategy adjustment to comply with Spacecraft and Instrument kinematic capabilities

Having defined the Line-of-Sight Guidance, it is necessary to check that the required rates for instrument internal parts and Spacecraft pointing do not exceed their respective kinematic capabilities. Adjustments of the trajectories and Line-of-Sight guidance might be necessary when these constraints are not satisfied initially, as was the case for Deimos observation, for example. In order to compare the geology of Phobos and Deimos, the best possible resolution is necessary for observations of Deimos, which require a close MMX fly-by. However, the closer the fly-by the higher the MMX rates are for maintaining Deimocentric pointing. In order to get both a large coverage of Deimos and high-resolution maps on several regions, Deimos fly-by trajectories have been adjusted to have a first period with farther fly-bys coupled with Deimocentric pointing observations (large regions with medium resolution) and a second period with closer fly-bys coupled with inertial MMX pointing (small regions with high resolution).

4.4 Validation and Performances assessment

Instrument guidance definition is both an upstream and a downstream process with respect to the scientific objectives and the various space system components. Once the first elements that have a direct impact on the design of the spacecraft and the instrument have been defined, further analyses are made to characterize the errors on the ideal line-of-sight guidance brought by each component of the space system, to estimate the uplink/downlink and observation time budgets and to simulate the quality of the final products.

4.4.1 Errors on the Line-of-Sight Guidance

We distinguish the pointing error, which induces an offset with respect to the target and the stability error, which in turn degrades the instrument modulated transfer function with unwanted high-frequency variation of the line of sight. The pointing error can be mitigated by adding margins on the zone to be observed but there is no simple way to cope with the stability error.

On MIRS, the main contributor to the stability error is MMX attitude control. Phobos descent trajectories are under assessment but orbit control could also be a contributor in that case.

The contributors to the pointing errors are MMX, MIRS scanner, the orbit control accuracy, the polynomial approximation of MMX attitude and MIRS Scanner Guidance profiles, the time quantization of MMX and MIRS flight software, and the precision of the target celestial body shape and orientation models.

To explain the role of orbit control accuracy, we simply need to consider that at a given date, if MMX is at a different position than the one used to calculate its attitude, the pointing direction towards the target celestial body will be biased. For Phobos the orbit control accuracy has an important impact on the pointing error as MMX is very close to Phobos during QSOs and there is, still today, a level of uncertainty on the Phobos gravity model.

The order of magnitude of each of these contributors will be progressively refined during the following phases of the project in order to take sufficient margins on the zones to be observed and improve the estimations of the budgets for uplink, downlink and observation time.

4.4.2 Uplink/Downlink and Observation Time budgets

The assessment of the necessary budgets for data volume, total observation duration and number of observations (Table 5) helps check that the Observation Objectives and strategies are compliant with instrument and system design and allocations. It is initiated as early as possible in the project and continuously refined.

Table 5. MIRS Data Volume, Observations Duration and Number of Observations (+++ highest priority, + lowest priority)

1 Kbyte = 8 x 1,000 bits 1 Gbyte = 8 x 1,000,000,000 bits		Data volume Compressed	Observations Duration	Number of Observations
Phase	Observations	Gbytes	hours	none
Cruise	Calibrations	0.02	0.4	293
0	Instrument Health Checks and Calibration	11	79	395
1	Mars atmosphere and Deimos observation	10	156	740
2	Phobos global composition Landing candidate regions	15	242	840
3	Phobos global composition Detailed observation of Landing candidate regions	3	19	108
4	Phobos global composition Mars atmosphere observation	25	358	1,330
5	Mars atmosphere Deimos observation	35	258	1,272
Total Phobos & Deimos		40	690	2,668
Total Mars		58	423	2,310
Total		98	1,112	4,978
Percentage Phobos & Deimos		41 %	62 %	54 %
Percentage Mars		59 %	38 %	46 %

4.4.3 End-to-end image generation validation

As we have explained in this chapter, the development of the spacecraft and instrument guidance functions and their execution in order to observe the target zones with given conditions is a complex process. In order to ensure that the envisaged ways to observe are adequate, that the identified errors on line-of-sight guidance do not significantly degrade the expected performance and in order to identify unexpected phenomena in advance, end-to-end image generation simulations are a precious asset. From a list of chosen critical observations, MMX and MIRS line-of-sight guidance functions are calculated on the Observation Strategy simulator (Aurora). Its outputs are provided to the OASIS simulator [10] of the Laboratoire d'Astrophysique de Marseille (LAM), to calculate the scenes as they could be observed radiometrically. With

these realistic scenes, a simulator of MIRS Instrument response (MIRAGES) produces scenes as MIRS would observe them (Fig. 11).

The resulting MIRS images are analysed by the scientific team to verify their adequacy to meet the scientific objectives. Fig. 12 shows an example of a scene as it could be observed in QSO-H and the resulting instrument response, both at $0.9 \mu\text{m}$.



Fig. 11. End-to-end-simulation chain

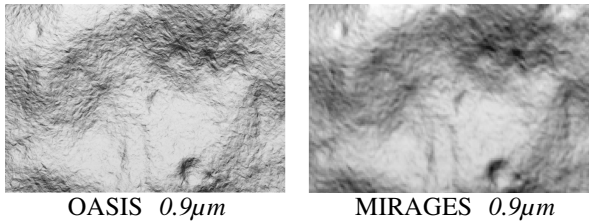


Fig. 12. Simulated scene at $0.9 \mu\text{m}$ by OASIS and resulting MIRS observed scene by MIRAGES

In a later stage, MIRAGES outputs will be processed by MIRS Pipeline in order to generate MIRS products, which will add another level of validation. Another great advantage of such end-to-end image simulations is that they ensure that all teams have the same understanding of the critical concepts and physical values. Among other things, the coherence of the observation conditions will be verified all along the chain: on MIRS Guidance functions, OASIS realistic scenes and eventually on MIRS products.

5. When to Observe

Once the targets and the ways to observe have been defined, the remaining challenge is to create spacecraft and instrument observation plans that meet the scientific objectives and comply with all constraints. To achieve this, the first step is to determine the slots available for observation. Then each target is broken down into observation units – an observation unit is a zone that can be observed with 1 satellite and 1 instrument command, for each of which the list of all opportunities on the next programming horizon is calculated. Eventually, the observation plan is built by selecting, for each observation unit, the opportunity which maximizes the compatibility between observations and optimizes the observation conditions.

5.1 Determination of the slots available for observation

From the availability conditions of the Spacecraft pointing mode to observe a given celestial body, we can deduce a first level of the available slots. For a mission

like MMX that aims to observe several different celestial bodies, there can be a competition between the available slots, in which case a choice has to be made: for MMX, the priority is given to Phobos over Mars in phases 1, 2 and 3. In phase 4, Mars observation has the priority. During phases 1, 2, 3 and 4, MMX being in Quasi-satellite Orbit close to Phobos, Deimos cannot be observed with sufficient resolution for composition analysis as its apparent angle is at most 0.06 deg (Table 2.), which corresponds to ~ 3 MIRS iFov. Deimos is therefore observed in phases 0 and 5 during fly-bys, when MMX is in elliptical orbit around Mars: there is no competition between Mars and Deimos observation slots, because when MMX is close enough to Deimos to get a satisfactory resolution (around 1,000 km, see Table 6 and Fig. 13), Mars pointing mode is not available.

Table 6. Deimos apparent equatorial angle

Distance MMX-Deimos	km	3000	2000	1000	100
Deimos apparent equatorial angle	deg	0.3	0.4	0.9	8.9
Deimos apparent polar angle	deg	0.2	0.3	0.6	5.8
MIRS nadir resolution	m	1050	700	350	35

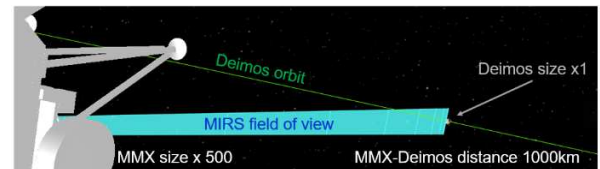


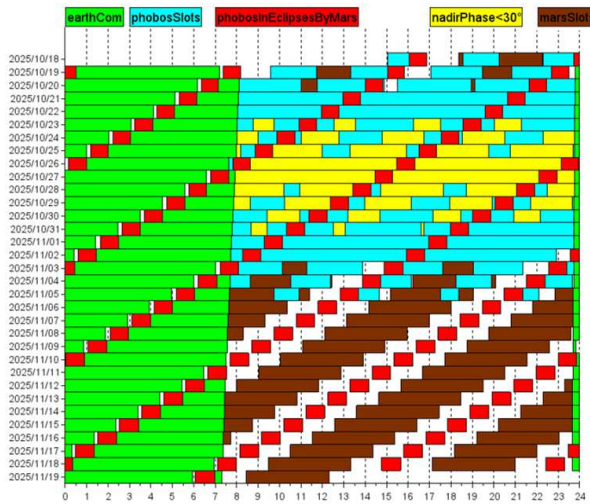
Fig. 13. MIRS field of View and Deimos from 1,000 km distance

All the system constraints which limit observation time are then applied in order to obtain the final list of slots available for observation. Earth communications (typically every 24 h) are necessary for ranging, platform operations and health-checks, as well as for observation plans upload and telemetry download: these slots last several hours and cannot be used for observation, as they require specific pointing to orient the high-gain antenna towards the Earth. For optical instruments, Sunlight on the observed zone is necessary, therefore Sun eclipses by Mars for Phobos and Deimos observation or night periods for Mars observation have to be removed. The same applies for all the necessary satellite maintenance operations that will be further defined in the later stages of the MMX project: station-keeping and orbit transfer manoeuvres, reaction wheels' desaturation, health-checks, etc.

In Fig. 14, we represent the slots available for Mars and Phobos observation during phase 1 QSO-H, considering the Usada Ground station for Earth communications. The horizontal axis is Earth time and the vertical axis Earth days. This shows that:

- Earth communication slots are interrupted by Mars occultations

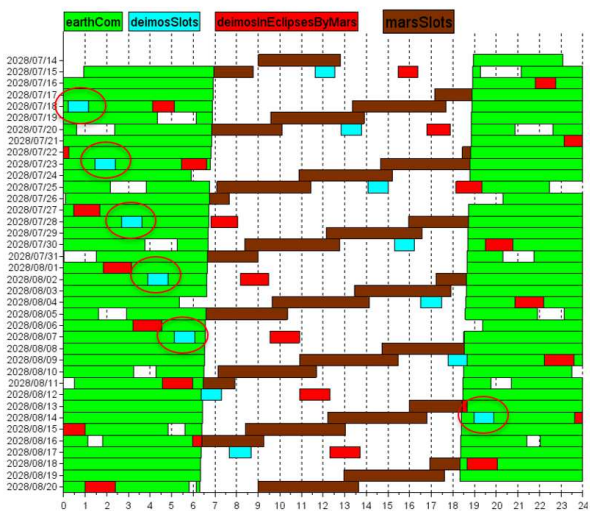
- Sun eclipses by Mars on Phobos last around 1h and are shifted by 1h every day: Phobos's period is 7h40 and $3 * 7h40 + 1h = 24h$
- MMX's period around Mars is also very close to 7h40, so Mars observation slots are also shifted by 1h every day
- Phobos can be observed only during the first half of QSO-H (as the period of the Sun-Phobos-MMX



angle is 30 days in QSO-H) and only 9 days have slots with a phase angle below 30° in Phobocentric pointing.

Fig. 14. Slots available for Phobos and Mars observation in phase 1 QSO-H

The period of the Sun-Phobos-MMX angle varies greatly with the distance to MMX of the QSO: in QSO-M, Phobos can be observed during two earth days every four earth days.



The analysis of available slots for Deimos has shown that with the sole use of the Usada Ground station, several Deimos observation opportunities would

be in conflict with Earth communications (conflicts circled in red in Fig. 15), which is problematic as the number of opportunities is limited. To mitigate this, the use of other Ground stations or the possibility of interrupting an Earth communication slot to perform Deimos observations are under assessment.

Fig. 15. Slots available for Deimos and Mars observation in phase 5 from 14/07/2028 to 20/08/2028

5.2 Breakdown of targets into observation units and determination of observation opportunities

Targets can be of any size whereas the area that can be covered by a given instrument during an observation is limited by its field of view, therefore requiring a breakdown into observation units. For MIRS, the along-slit field of view is 3.3°, and there is currently no explicit limitation of the cross-slit field of view as it uses a push-broom principle (but we expect, at some point, to have a constraint on the maximum duration of an observation). Fig. 16 illustrates a target area on Mars that is broken down into seven stripes, each of which is observed three times to provide a multi-temporal observation of atmospheric phenomena tracking. As the very purpose of this kind of observation is to track the evolution of a phenomenon over time, the resulting set of observation units has to be carried out in a row, so the determination of the observation opportunities is made on the target zone before the breakdown.

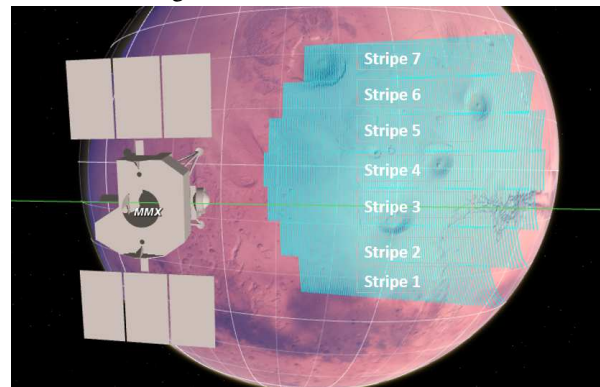


Fig. 16. Mars tracking observation by MIRS

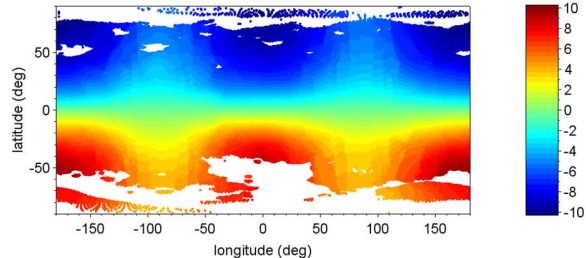
For Phobos global mapping from QSO-H and M, from MMX's trajectory and a model of Phobos's shape, we can calculate the necessary roll angle with respect to a Phobocentric attitude to reach a given latitude with the MMX Line of Sight: Fig. 17 presents the resulting map for QSO-M.

Considering a 3.3° along-slit field of view and a 0.3° latitudinal overlap, we can deduce that the coverage of -45°/45° Phobos latitudes in QSO-M requires:

- 3 complete longitudinal stripes with respective MMX roll angles of 0°, -3°, 3°
- 2 longitudinal stripes for the zone [-120°, -60°] U [60°, 120°] with MMX roll angles -4.5° and 4.5°

- 2 additional longitudinal stripes for the zone $[-180^\circ, -120^\circ]$ U $[-60^\circ, 60^\circ]$ U $[120^\circ, 180^\circ]$ with MMX roll angles -6° and 6°

Considering, among the slots available for Phobos observation, the ones which meet the observation



conditions that guarantee good performance, the coverage of a complete longitudinal stripe with one observation unit is not possible: it will require several smaller stripes.

Fig. 17. Required roll angle (deg) with respect to a Phobocentric pointing in QSO-M

For candidate Landing regions observation (size 300 m by 300 m) on QSO-M, LA and LC, no breakdown is needed because, along-slit, they are completely covered by the MIRS field of view, and the time needed for the cross-slit coverage (around 10 minutes) is short compared to the duration of the available observation slots.

5.3 Development of the Observation plans

From the set of observation units and their list of observation opportunities, we can build the observation plan. The problem is trivial in the very specific case when there is no conflict between the best observation opportunities of each of observation unit, but the general problem is actually combinatorial. Most of the time, the cardinality is such that brute force approaches are not applicable. We therefore have to find ways to reduce the complexity with specific properties of our problem, and develop efficient algorithms to find satisfactory solutions.

By analysing the MMX trajectories and the available observation slots and taking into account priorities for each mission phase, we can determine that there is no competition for the respective observation of Phobos, Deimos and Mars: their respective observation plans can be developed independently.

5.3.1 Mars

For Mars, the process of translating the scientific objectives into observation targets is on-going. From the first analyses, observations will mostly consist of a global map at every phase, multi-temporal observations of a couple of specific areas each Martian day for a couple of weeks, and the observation of Mars limb. It is not a combinatorial problem as such: the scientific team will attribute a priority to each kind of observation and within each kind there is no competition.

5.3.2 Phobos global maps for composition in phase 1

The best conditions for observations dedicated to composition are met when the phase angle is low and at a local solar time of around 12h. The minimization of the phase angle implies that the angle between the Observed Point to MMX and the Observed Point to Sun directions is minimum, while a local solar time close to 12h implies that the Sun azimuth at the Observed Point is close to 0° : based on these 2 conditions, we deduce that relatively to the Observed point, the MMX azimuth and the Sun azimuth will both be close to 0° , which means a 0° scanner angle and therefore a minimum distance between MMX and the observed point, which favours good geometrical resolution. Consequently, as MMX's trajectories around Phobos are equatorial in that phase, the zones that have similar longitudes are in competition, whatever the latitude. An efficient approach to build a Phobos global mapping observation plan is to use a greedy algorithm, giving the priority to the low absolute values of latitude:

1. Identify all slots available for Phobos observation

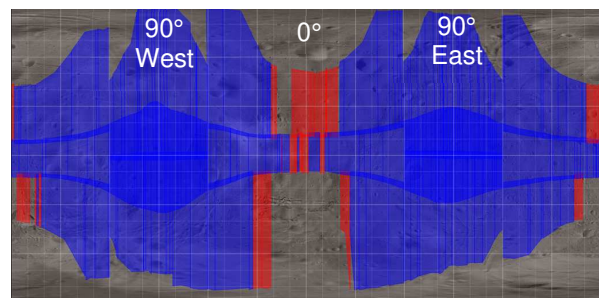
2. Among these slots, identify those with a phase angle below a given value when MMX is in Phobocentric pointing and the MIRS scanner angle is fixed at 0°

3. For each of the necessary roll coverages, starting with 0° and with an increasing absolute value, build the longest possible west-east coverage with the remaining slots with low phase angle

4. For each of the necessary roll coverages, for each of the non-covered longitudes, find the observation slots with the best remaining phase angle with a scanner angle 0° (or with a different angle if none are found).

The resulting coverage for QSO-H is presented in Fig. 18. Around longitude 0° (towards Mars), the southern latitudes are not covered while northern latitudes are better covered but with high phase angles. It is explained by the fact that phase 1 is scheduled during the Mars eclipse season on Phobos, which dramatically reduces the number of available slots to observe longitude 0° , leaving only a few remaining slots with high phase angles (Fig. 19).

To mitigate this, the MIRS scanner will be used but the resolution will be degraded and local time will be different from 12h. Another option is to complete the



coverage outside the eclipse period, in a later phase.

Fig. 18. Obtained coverage in QSO-H with the proposed greedy algorithm with a fixed 0° scanner angle phase below 30° - phase between 30° and 60°

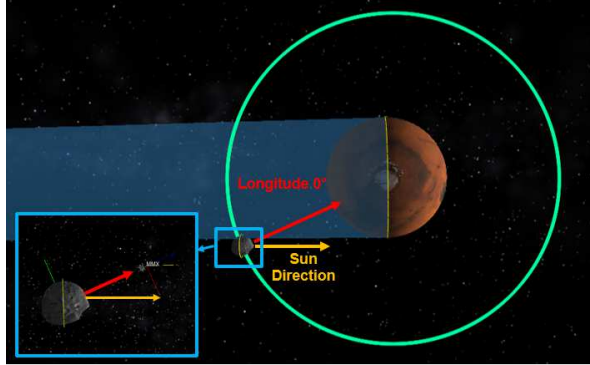


Fig. 19. Minimum reachable phase angle with fixed 0° scanner angle during Mars eclipse season on Phobos

5.3.3 Candidate landing regions composition maps

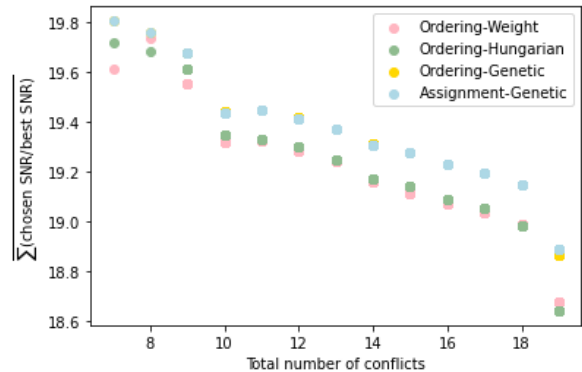
In order to select the two best landing sites, 20 candidate landing regions will be observed from the Low altitude QSOs. Those 20 regions will be selected thanks to the multi-instrument observation of Phobos in phase 1, including MIRS global maps. Once the 20 regions have been selected, the aim is to build an observation plan that covers them all with, for each one, the best possible observation conditions. To quantify the quality of the observation conditions we calculate an estimation of the Signal-to-Noise Ratio (SNR) using a simple model that takes the phase and sun incidence angles into account. To measure the quality of the resulting observation plan, we will calculate the sum, for all the regions, of the ratio between the SNR of the selected observation slot and the SNR of the best slot. This quantity is consistent with the number regions and is equal to it when the best slot is selected for each of them.

For each region, we have to choose if we observe it and, if the answer is yes, we have to choose its observation slot among the ones available. It might be surprising, at first, to consider not observing a given region, but as there are conflicts between observation slots of different regions, there are several solutions in which not all regions can be observed. Therefore, the cardinality of the problem corresponds to the product of all the numbers of observation slots + 1 (where + 1 corresponds to the choice not to observe the region). If we call N_i the number of slots of region i and if we have R regions, the cardinality is equal to $\prod_{i=1}^R (N_i + 1)$. If we consider an average of 20 observation slots per region and 20 regions, the cardinality is $\sim 2.8^{26}$, therefore "brute force" cannot be envisaged as a solution.

Two different approaches are assessed. The first is to find the best ordering between the landing candidate

regions to submit to a greedy algorithm in order to maximize the quality of the resulting observation plan: the cardinality corresponds to the number of orderings of the 20 sites, which is $20! \sim 2.4^{18}$. The second is to directly find the best assignment between candidate landing regions and slots. For the first approach, we compare the results of 3 ordering methods: a simple weight function (inverse of the sum of the quality factors of all its observation slots), a perfect matching (hungarian) algorithm and a genetic algorithm with an order cross-over operator. For the second approach, several algorithms will be compared among which a genetic and a simulated annealing algorithm.

In Fig. 20, we compare the efficiency of each of the three algorithms for the first approach (ordering) and of a genetic algorithm for the second approach (direct assignment). The comparison is made on 1,000 different sets of 20 candidate landing regions randomly located in the areas towards Mars and anti-Mars (geocentric latitude within $-30^\circ/30^\circ$, longitude towards Mars within $-30^\circ/30^\circ$, longitude anti-Mars within $[165, 180] \cup [-180, -165]$). The genetic algorithms provide statistically better results than the others. They only take 30 seconds to compute the solution for 1 set of landing candidate regions, which is totally acceptable for a use during



operations in the Control Ground System.

Fig. 20. Statistical efficiency comparison of algorithms on 1,000 sets of 20 candidate landing regions the box extends from the first quartile (Q1) to the third quartile (Q3) of the data, with a line at the median. The whiskers extend from the box by 1.5 x the inter-quartile range (IQR). Flier points are those past the end of the whiskers

The solution calculated by the ordering-weight algorithm, even if statistically inferior to a more exhaustive search, is very interesting as it is extremely fast to calculate, even if heavier slew duration computations are introduced. It can therefore be calculated together with the finally chosen algorithm in order to have a reference point. It can also be used as a starting point in the second approach (direct assignment) for genetic and simulated annealing algorithms.

In Fig. 21, we present the average of the quality of the observation plans as a function of the number of landing candidate regions whose best slot is in conflict.

As expected, the average quality decreases with the number of conflicts on the best slot, which vary from 7 to 19 in this evaluation scenario. The genetic algorithms provide the best results in all cases.

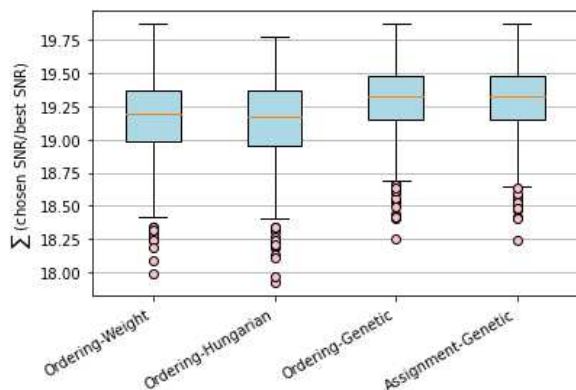


Fig. 21. Average of the quality of the observation plans as a function of the number of candidate landing regions with their best slot in conflict

A specificity of our problem allows a reduction of its cardinality. As the considered low-altitude QSOs are equatorial, candidate landing regions with close longitudes are in competition when they are observed with an average scanner angle of 0°. Conversely, regions separated by a sufficient longitude margin will not have any observation slots in conflict, and this can be used to reduce the cardinality of the problem: the 20 candidate landing regions can be divided into several subsets of conflicting regions, each one independent of the others.

6. The Essential role of Simulators

The simulators play a key role in the development of observation strategies in all phases of the project. At the start, they help to get an understanding of the main characteristics of the mission.

Then they allow a quick implementation of the envisaged strategies and algorithms that are, once proven, translated into specifications from which the operational libraries are implemented. An agile approach to this process allows a continuous improvement of the specifications with the feedback from the operational implementation. As algorithms and strategies are independently implemented both on the simulator and on the operational libraries, a cross-validation is carried out, ensuring the consistency of the performance figures.

Allied with visualization tools (for simulators that do not already embed such tools), the simulators provide synthetic and clear outputs that are shared among the project members to ensure mutual understanding.

During operations, especially on an interplanetary mission, it can occur that unforeseen categories of observations not directly supported by the operational

libraries have to be programmed. In that case, the simulators can but used for that purpose provided the option to import an externally-generated programming plan has been made available in the ground system: this mechanism is considered for MIRS, thanks to the original idea of the MicroCarb [11] mission observation team.

On MIRS, two different simulators are used:

- JASMINE: a Java simulator whose purpose is to use and validate the operational libraries for Line-of-Sight Guidance (based on the generic guidance Java library Polaris) and Observations Programming (using Flight Dynamics multimission Java library Patrius [9])
- Aurora: A multimission Guidance and Mission Programming simulator, implemented within the CNES Flight Dynamics subdirectorate [7], with the technical support of CS Group (Toulouse) which allows very efficient strategies implementation and 2D/3D visualization

The visualization tools used are VTS [6] for 3D/2D animations and PrestoPlot® [8] for timed data analysis. The latter allows very convenient analysis and processing of data, including among many others: derivation, integration and Fast Fourier transform.

Despite everything the simulators provide, we must keep in mind that they are only tools, whatever the level of automation or “artificial intelligence” they embed. They can help to improve the understanding of space missions and the responsiveness of analyses as long as they are used appropriately. The knowledge of their limitations, the clear description of the objectives, models, constraints and performance criteria, together with complementary analytical studies and the understanding of the underlying physical phenomena, are key to their meaningful and efficient use.

7. Conclusions

The typical process of observation strategies development, from early design to operations, has been presented, with the example of the MIRS instrument on the MMX mission, in its current D phase status.

Observation Strategies development requires the continuous refinement of the problem to be solved, together with an understanding of the underlying phenomena impacting performance, in order to determine the reachable optimum and identify the limiting factors.

It also requires frequent and efficient communication with all the teams of the various space systems: reformulation, cross-validation and exchange of figures, illustrations and videos are crucial to improve mutual understanding.

For each space mission, and particularly for MMX, it is a fantastically motivating challenge.

Acknowledgements

MMX is developed and built by JAXA, with contributions from CNES, DLR, ESA and NASA. We thank the MMX JAXA teams for their efforts in defining and building the mission.

All activities described in this paper address the observation strategies and involve several teams. For the sake of simplicity, they have not been exhaustively mentioned, although they are obviously all essential.

Focus has been made on MIRS observations. At a higher level, the long-term preparation of multi-instrument observation is coordinated by the Mission Operation Working Team led by Nakamura-san (see [2]), taking as input the mono-instrument observation strategies. The understanding of the entire system and the search for the best scientific return by each instrument team contribute to the pertinence of the discussions, the optimality of the multi-instrument solutions and international cross-validation.

Appendix A Geometric formula for observation conditions

For observation modes, we can choose to break down the $MMXtoSUN_{direction}$ expression in Satellite Frame (SAT) in Elevation and Azimuth components with respect to the plane normal to $Y_{SATELLITE}$ axis:

$$(1) MMXtoSun_{direction}|_{SAT} = \begin{pmatrix} \cos(Sun^{Elevation})\sin(Sun^{Azimuth}) \\ \sin(Sun^{Elevation}) \\ \cos(Sun^{Elevation})\cos(Sun^{Azimuth}) \end{pmatrix}$$

With this definition, $Sun^{Azimuth}=0^\circ$ when $Z_{SATELLITE}$, $MMXtoSUN_{direction}$ and $Y_{SATELLITE}$, are in the same plane and scalar product of $MMXtoSUN_{direction}$ and $Z_{SATELLITE}$ is positive. In order to observe high/low latitudes of Mars and Phobos, a roll rotation around $X_{SATELLITE}$ can be performed.

If we consider the SAT' frame, the result of a roll rotation applied to SAT frame, the transformation matrix from SAT frame to the SAT' frame is the following:

$$(2) SATtoSAT' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & \cos(roll) \end{pmatrix}$$

With (1) and (2) we can deduce the expression of $MMXtoSun_{direction}$ in the SAT' frame:

$$(3) MMXtoSun_{direction}|_{SAT'} = \begin{pmatrix} \cos(Sun^{Elevation})\sin(Sun^{Azimuth}) \\ \sin(Sun^{Elevation})\cos(roll) + \cos(Sun^{Elevation})\cos(Sun^{Azimuth})\sin(roll) \\ -\sin(Sun^{Elevation})\sin(roll) + \cos(Sun^{Elevation})\cos(Sun^{Azimuth})\cos(roll) \end{pmatrix}$$

To ensure that the angle between $MMXtoSUN_{direction}$ and $-Z_{SATELLITE}$ is equal to or above 90° , the third

component of $MMXtoSun_{direction}|_{SAT'}$ has to be greater than or equal to 0. As we know that $Sun^{Elevation}$ and roll are both below 90° , we can deduce that the condition is equivalent to

$$(4) Sun^{Azimuth} \leq \cos^{-1}(\tan(Sun^{Elevation})\tan(roll))$$

When roll is equal to 0° , this condition becomes

$$(5) Sun^{Azimuth} \leq 90^\circ$$

Relatively to the Celestial-Body-to-Sun distance, the distance between MMX and the observed Celestial Body is negligible, consequently we can consider that the Celestial-Body-to-Sun direction and $MMXtoSun_{direction}$ are equivalent. In observation modes, the Celestial-Body-to-MMX direction in the SAT frame is equal to (0 0 1) when roll = 0° . With (1) we can deduce that the angle between the Celestial-Body-to-Sun direction and the Celestial-Body-to-MMX direction is equal to:

$$(6) (\widehat{CelestialBodytoSun, CelestialBodytoMMX}) = \cos^{-1}(\cos(Sun^{Elevation})\cos(Sun^{Azimuth}))$$

If this angle is below or equal to 90° then condition (5) is met. However, it does not guarantee that condition (4) is met when the roll angle different from 0° .

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