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Orbit Design for Martian Moons Explorer

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The Martian Moons eXploration (MMX) mission is now under study in Japan Aerospace Exploration Agency. Its scope includes the world's-first landing on one of the Martian moons, collecting samples from the surface and return to the Earth. This paper describes orbit design for MMX.

Key Words: Mars, Exploration, Orbit, Sample Return, Phobos, Deimos

1. Introduction

Japan Aerospace Exploration Agency (JAXA) is now planning the Martian Moons eXploration (MMX) mission for launch in Early 2020's. This mission will make close-up remote sensing and in-situ observations of two Martian moons, Phobos and Deimos, and return samples from Phobos. The mission aims to elucidate the origin of the Martian moons by remote-sensing and sample-return. Revealing the origin will enable us to step further forward to constrain the behavior of small bodies and the evolution process of the early solar system. It includes also engineering challenges such as the world's first sample return from inside of the Martian system. In this article, we will describe the orbit and mission design for this MMX mission.

The spacecraft will be inserted into the Mars orbit, and then transfer to the Quasi-Satellite Orbit (QSO) of Phobos. This article will focus on the interplanetary trajectory and Mars orbit insertion/escape. The orbit design and mission design on QSO will be described in other articles. [1)]

2. Overview of Spacecraft

Table 1 shows an overview of spacecraft system specifications (proposed) derived from system requirements and investigations of the system configuration.

Table 1. System outline draft specification.

Item	Specification
Propulsion system configuration	Outgoing: chemical propulsion. Return: chemical propulsion
Spacecraft configuration	Propulsion Module/Exploration Module/Return Module
Launch	Rocket: H3-24L, Launch date: Summer 2024
Total mission lifetime	+5 years
Target mass	3,500 kg
Power consumption	Approx. 900 W
Orbital control	delta-V: Approx. 5 km/s (chemical propulsion)

3. Orbit Design

3.1. Launch Windows

The MMX mission aims the launch in 2020's. Launch opportunities which requires small energy and flight time are 2022, 2024, 2026 and 2028. Now we assume the nominal launch in 2024, and the backup in 2026. The arrival to Mars will be about 1 year after the launch. The Mars departure opportunities also come every two years, such as 2024, 2026, 2028 and 2030. The earliest departure opportunity after the Mars arrival in 2025 will be 2026. In this case, the phase around Mars will be less than 1 years and it is too short for the sufficient exploration. Thus we assumed 3-year stay around Mars, and departure in 2028. The return to Earth will be 2029.

3.2. Conditions for Launch Windows

We also considered the following conditions for launch windows:

- C_3 on Earth departure should be within 18 m^2/s^2 (TBD).
- Declination of launch asymptote (DLA) should be within ± 30 degrees constrained by the launch site (Tanegashima Space Center) and the vehicle capabilities.
- Time of flight should be within one Earth year.
- More than 2 weeks in succession should be available as the launch window.

3.3. Interplanetary Trajectory

Considering assessment results mentioned above, we assumed the nominal launch and return dates as 2024 and 2029, respectively, and designed trans-Mars orbits. Note that these are preliminary results presuming ballistic flights, not optimized, and no multibody dynamics, perturbations, trajectory correction maneuvers are regarded so far.

Table 2 and Figure 1, 2 show an interplanetary orbit and its properties.

3.4. Launch and Transfer to Mars

The spacecraft will be launched from Tanegashima Space Center by an H3 launch vehicle. The rocket will be launched toward the east with the azimuth angle of 90 degrees, and injected into a coasting orbit with the 300-km altitude after separation of the first stage. Either long or short coasting will be adopted considering the visible pass conditions. The spacecraft will be separated after the second engine ignition.

Table 2. Design results of interplanetary trajectories for MMX.

		Nominal		Backup	
		Earth-Mars	Mars-Earth	Earth-Mars	Mars-Earth
Departure	Date	2024/9/11	2028/8/6	2026/10/1	2030/9/10
	Vinf [km/s]	3.896	2.623	3.937	2.566
	RA [deg]	111.570	322.966	144.541	4.117
	DEC [deg]	13.277	-2.309	17.009	-13.512
Arrival	Date	2025/8/12	2029/7/12	2027/8/27	2031/8/23
	Vinf [km/s]	2.419	3.501	2.686	4.248
	RA [deg]	79.503	7.836	110.144	22.828
	DEC [deg]	7.831	22.287	-10.282	37.134
Time of Flight [days]		335	340	328	347
Inclination Change [deg]		10.359	2.928	12.938	17.423
MOI1/MOE3 DV [km/s]		0.653	0.750	0.781	0.722
MOI2/MOE2 DV [km/s]		0.075	0.070	0.078	0.069
MOI3/MOE1 DV [km/s]		0.786	0.786	0.786	0.786
DV Total [km/s]		1.514	1.605	1.645	1.593

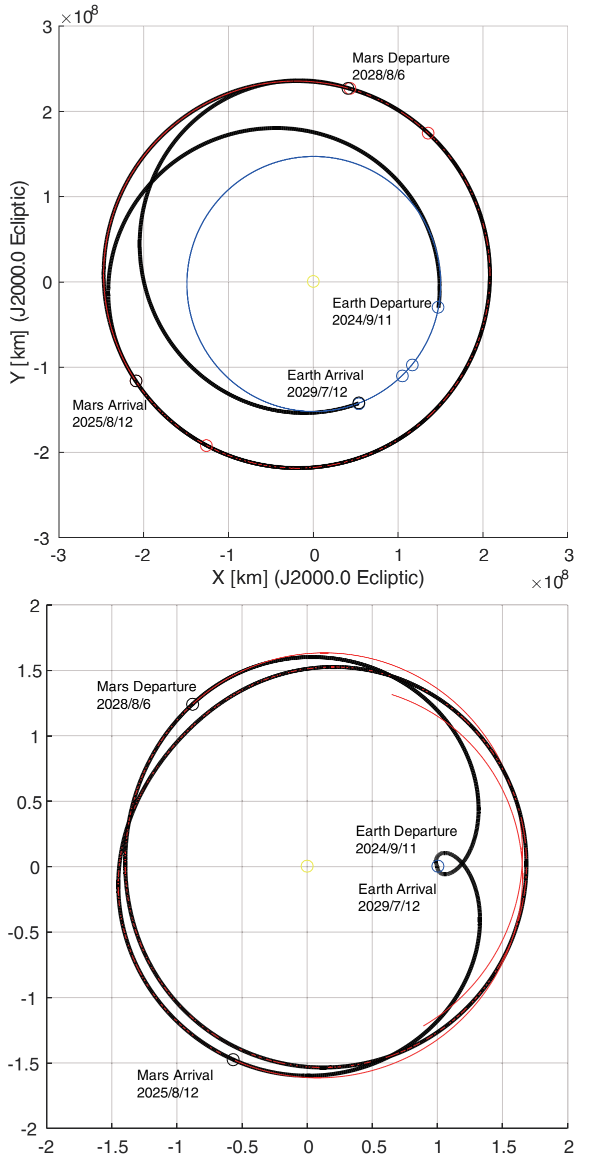

Fig. 1. An example for nominal interplanetary trajectories. Top: J2000 inertial frame. Bottom: Sun-Earth Fixed rotating frame.

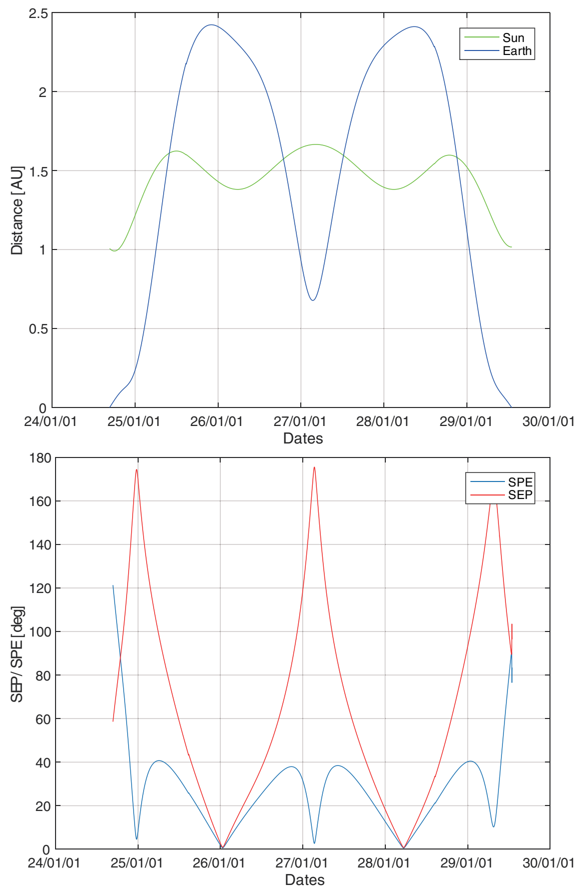

Fig. 2. Sun and Earth distance, Sun-Probe-Earth (SPE) angle, and Sun-Earth-Probe (SEP) angle (nominal).

The Mars Transfer Phase lasts from the end of the Early Orbit Phase until around 1 month prior to MOI. Regular health checks of the PI instruments will be planned. The interplanetary cruise will be a direct transfer orbit from Earth to Mars. No gravity assist is planned during this phase. The spacecraft will be guided toward the MOI targeting point around Mars by several trajectory correction maneuvers (TCMs) and precise orbit determination including ranging, two-way Doppler, and delta-differential one-way ranging (DDOR). The duration of the cruise phase will be approximately 11 months according to current candidate profiles. The nominal arrival time will be around July 2025.

3.5. Mars Orbit Insertion and Transfer to Phobos Co-Orbit

The final target orbit in the Martian system is the Phobos co-orbit. Because its inclination is around zero degrees, it is difficult to insert the spacecraft directly from the interplanetary space. We adopted three-staged Mars orbit insertion (MOI) where the spacecraft will be first injected into an ellipsoidal orbit, then into an intermediate orbit, and finally into the Phobos co-orbit.

In the first MOI (MOI1), the spacecraft will be injected into an ellipsoidal orbit with an apoapsis of 40 Rm (TBD, Rm is the Mars radius) and a periapsis altitude of 500 km (TBD). There is a degree of freedom for the B-plane phase angle in MOI1, which allows us to choose the inclination or the argument of periapsis of the first ellipsoidal orbit. If we set the argument of periapsis around 0 or 180 degrees, then the apoapsis will be placed within the equatorial plane. It means that we can change the inclination at the apoapsis in the following MOI2 and MOI3 maneuver sequences, leading to the drastic reduction of the fuel consumption. For example, in the case of launch in 2024, the B-plane phase angle should be about 7 degrees. An example of the geometry in MOI1 is shown in Figure 3. The spacecraft will approach from the dawn side of the Mars (blue line) and fly toward the dusk side. In this case we will not experience solar or Martian eclipses, but they can occur according to the injection conditions. The apoapsis altitude will be fixed later considering the ambiguity of the engine thrust, perturbation by Sun and Mars, the orbital period and operabillity.

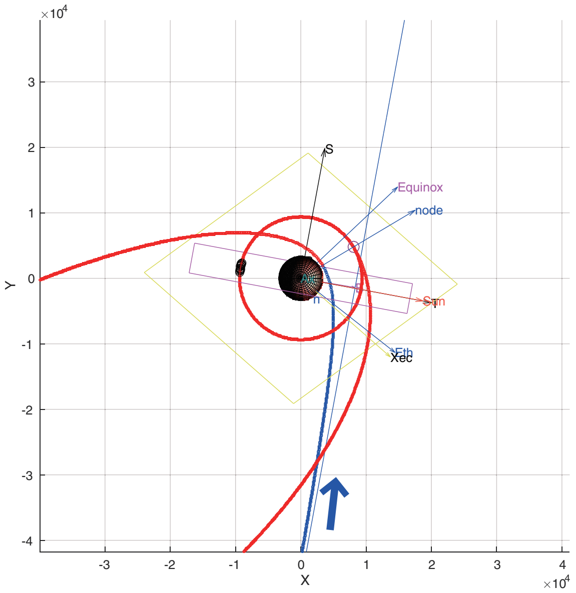

Fig. 3. An example of Mars orbit insertion (the X-Y plane: Mars equatorial plane, Z: Martian north).

After about 3.5 days (TBD), the second orbital maneuver (MOI2) will be executed at the apoapsis, so as to adjust the periapsis and inclination same as those of the Phobos co-orbit. According to the obit determination status, this maneuver may be after the second passing over the periapsis.

Then about 2.5 days later (TBD), the third orbital maneuver (MOI3) will be performed to lower the apoapsis to the Phobos co-orbit. Finally this places the spacecraft in the Phobos co-orbit. Actually, MOI3 will be divided into several maneuvers. During several MOI3 maneuvers, Propulsion Module will be jettisoned after the propellant is exhausted, and the remaining delta-V can be performed by RCSs in Return Module. The module(s) will be jettisoned in a sufficiently stable Mars orbit in order to avoid crashing on Mars to satisfy planetary protection requirements. The total duration of MOI1-3 will be approximately 2 weeks (TBD). Commissioning of some PI instruments will be performed after completion of MOI.

The total amount of delta-Vs for MOI1, 2 and 3 is about 2000 m/s at maximum.

For example, the orbit diagram for MOI1-3 for the case of 2024 launch is shown in Figure 4.

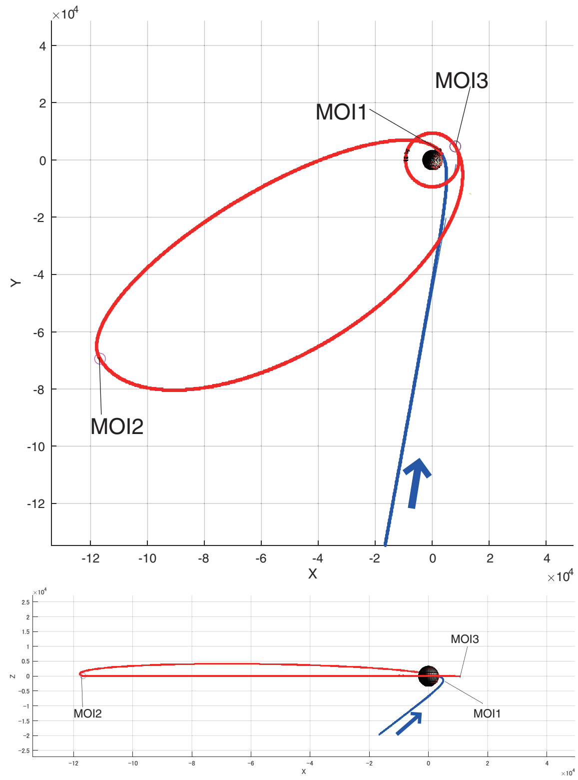

Fig. 4. Orbit diagram for MOI1-3.

3.6. Mars Orbit Escape

For Mars Orbit Escape (MOE) before way back the Earth, we assume a simply reversed sequence of MOI. MOE consists of three orbit control maneuvers: MOE1, MOE2, and MOE3. Prior to MOE maneuvers, the spacecraft is around the Phobos or Deimos co-orbit. In MOE1, the apoapsis will be raised up to around 40 Mars radii (TBD). At apoapsis, the subsequent MOE2 maneuver will change the orbit inclination in preparation for escape taking the escape declination into account, and lower the periapsis altitude to 500 km (TBD). Then the MOE3 burn at periapsis will finally insert the spacecraft into an interplanetary trajectory, escaping Mars. The total duration of MOE1-3 will be approximately 2 weeks (TBD). The exploration module may be jettisoned after final scientific observation and before MOE1; it depends on the module configuration. The module(s) will be jettisoned in a sufficiently stable Mars orbit in order to avoid crashing on Mars to satisfy planetary protection requirements. The detailed timing of jettison will be

TBD. The total amount of delta-Vs for MOE1, 2 and 3 is about 2000 m/s at maximum.

3.7. Options for Rendezvous or Flyby of Deimos

After completion of Phobos observation and sampling, several flybys around Deimos or rendezvous with Deimos will be planned. Actual decisions will depend on remaining fuel.

In the case of a rendezvous, a Hohman transfer will insert the spacecraft into Deimos-revolution orbit. It requires about 800-m/s delta-V at the apoapsis and the periapsis. However, the MOE delta-V from the Deimos QSO is about 300 m/s lower than that from the Phobos QSO. Thus the balance is about 500 m/s excess compared to the Deimos flyby.

In the case of a flyby, the apoapsis will be raised up to or beyond the Deimos orbit so that the spacecraft intersects the Deimos orbit, and orbital resonance will be achieved between the spacecraft and Deimos. The spacecraft will encounter Deimos several times in the flyby orbit. The duration of Deimos flybys or rendezvous will be TBD.

3.8. Deimos Flyby Option

The spacecraft will be placed in the ellipsoidal orbit with 40-Rm apoapsis after MOI2 and before MOE2, which will provide opportunities of Deimos flyby at intercept points with the Deimos orbit. Moreover, if the transfer between this ellipsoidal orbit and the Phobos co-orbit is divided into two-stage transfers via an orbit with an intermediate apoapsis, almost no additional delta-V is needed for adjustment of encounter conditions with Deimos.

Encounter period and the relative velocity are the two major parameters in Deimos flyby. In order to encounter Deimos periodically, ratio of their orbital periods should be a simple rational number. Relative velocity will be an input for scientific instrument. These parameters are determined by the apoapsis altitude.

Figure 5 shows the relationship among the apoapsis altitude, orbital period and relative velocity in Deimos flyby. The upper limit of the orbital period and the relative velocity is derived at just after MOI1. The lower limit appears when the apoapsis reaches the Deimos co-orbit.

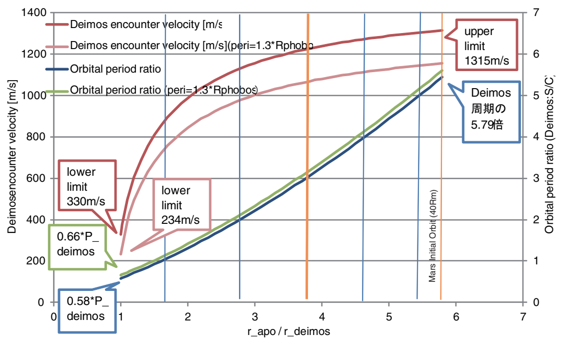

Fig. 5. Apoapsis altitude, orbital period and relative velocity in Deimos flyby.

3.9. Return to Earth

The Earth Transfer Phase lasts from the end of MOE until around 1 month prior to capsule re-entry to Earth. The interplanetary cruise will be a direct transfer orbit from Mars to Earth. No gravity assist is planned during this phase. The spacecraft will be guided toward the capsule separation targeting point around Earth by several TCMs and precise orbit determination, including ranging, two-way Doppler, and DDOR. The duration of the cruise phase will be approximately 11 months, according to candidate profiles.

Near Earth, the spacecraft will target the re-entry interface point. Separation of the capsule from the spacecraft will be performed several hours prior to Earth atmosphere re-entry. The capsule will re-enter the Earth atmosphere, descend using a parachute, land on the ground, and be recovered immediately. After capsule separation, the spacecraft will de-orbit from the trajectory targeting the interface point using the chemical propulsion system to escape from Earth gravity to interplanetary space.

Table 3. An example of the trajectory for robust MOI.

		Earth-Mars	Mars-Mars
Departure	Date	2024/9/11	2028/8/6
	Vinf [km/s]	3.895	2.623
	RA [deg]	111.294	322.966
	DEC [deg]	12.753	-2.309
Arrival	Date	2025/8/10	2029/7/12
	Vinf [km/s]	2.420	3.501
	RA [deg]	80.307	7.836
	DEC [deg]	7.968	22.287

4. Robust MOI

MOI is one of the most critical events in this mission. If the main thruster produces no or insufficient thrust during MOI, the spacecraft cannot be injected into the Mars orbit and will be fly away from the Martian system to the interplanetary space again. In the MOI sequence of MMX, over 90 percent of the planned thrust is required to be captured by the Mars gravity. Akatsuki, the Venus climate orbiter, tells us difficulty of orbit insertion and re-encounter with the target after insertion failure.

In MMX, we propose utilization of Mars evolution synchronous orbit (one of the free return orbit and also called as an interplanetary parking orbit) to reduce the difficulty of re-encounter. In this scheme, the targeting point on the MOI B-plane is chosen so as to connect to the Mars evolution synchronous orbit in the case of the thrust failure. If the MOI is successful, the spacecraft will be injected into the planned orbit as a nominal sequence. Even if the thruster does not work at all, the spacecraft will go away but then come back to Mars. It will enhance the robustness of the mission drastically. Especially, Mars evolution synchronous orbits with the period of one Martian year has a degree of freedom for the escape direction from Mars, [2] which makes it easy to satisfy orbital conditions for both success and failure. This scheme is hereinafter referred to as “robust MOI.” [3]

We show an design example of the robust MOI in Table 3 and Figure 6. In this example, the spacecraft tries MOI at 10 August 2025 and flies-by Mars at the altitude of 540 km, but re-encounters Mars after 1 Martian year.

This robust MOI orbit shown above is designed so as to match the case with no MOI thrust. If the thrust is non-zero but not sufficient for MOI, then the escape direction will be changed and the spacecraft will not re-encounter Mars. However, an additional deep space maneuver of about several hundred m/s can

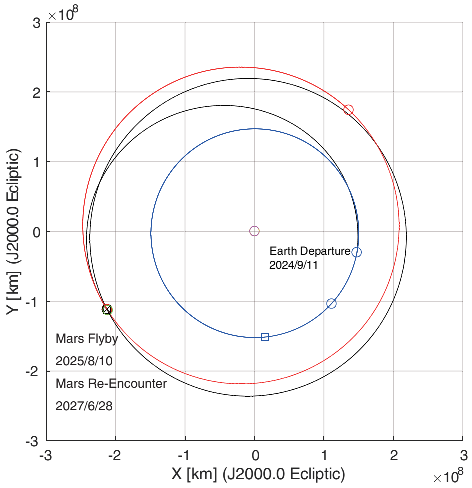

Fig. 6. An example for the trajectory of the robust MOI.

force the spacecraft to re-encounter, even if the MOI thrust is 0-90 percent of the planned value. We confirmed that each day in the 2-week launch window has a robust MOI solution.

5. Summary

We described a preliminary trajectory plan for the MMX mission. Feasible interplanetary transfer trajectories and orbit insertion including robust MOI methods were proposed considering mission requirements. In future works, the operation analysis, consideration of planetary protection, contingency and backup plans are to be discussed.

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