Orbital Operations Strategy in the Vicinity of Phobos

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The Japan Aerospace Exploration Agency (JAXA) is currently studying the possibility of Martian moon exploration mission that surveys two Martian moons, and return samples from Phobos. As the nominal scientific orbit, Quasi-Satellite Orbit (QSO) is adopted in consideration of the dynamical environment characteristic of the Mars-Phobos system. Three-impulse method is known as an optimal transfer for fuel efficient, however the method consists of three impulses in the direction of along-track at periapsis and apoapsis and will only work if all maneuvers are carried out as planned. To overcome this situation, a swing QSO method that uses liberating stable QSO is proposed. This transfer method is relatively robust for delta-V error and enable a safer orbital transfer between different QSOs. In parallel with the trajectory analysis, orbit determination covariance analysis considering the dynamical model error (e.g., Phobos gravity, Phobos ephemeris, Mars gravity, Mars ephemeris, Solar radiation pressure) is conducted. According to the OD analysis, the error of Phobos gravity and ephemeris becomes dominant error sources and have a significant impact on the navigation accuracy and stable operation at low altitude. In order to improve the OD accuracy, we found that it is necessary to estimate the Phobos gravity and ephemeris using radiometric, optical, and altimetric measurements. This paper describes the results of trajectory analysis in terms of the terminal rendezvous, QSO insertion, transfer, and utilization of 3D-QSO are describes. The navigation strategy around Phobos is also discussed.

Key Words: Quasi-Satellite Orbit, 3-body problem, Phobos, Orbit Determination, Orbit Transfer

1. Introduction

There has been a growing interest in exploring the Martian moons Phobos and Deimos, with the view of not only the scientific purpose but also the potential destination for future human exploration. The Japan Aerospace Exploration Agency (JAXA) is currently studying the possibility of Martian moon exploration mission that surveys two Martian moons, and return samples from Phobos. The scientific objectives of the mission are to reveal the origin of the Martian moons, and further our understanding of planetary system formation and of primordial material transport around the border between the inner and the outer part of the early solar system.

Several previous missions have observed Phobos,[1)] for example, Mariners 9, Viking orbiters, Mars Global Surveyor (MGS), Mars Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Express (MEX). In addition, Mars rovers performed scientific observation of Phobos from Mars surface. As to the Phobos exploration mission, Phobos 88 and Phobos-Grunt mission are famous,[2)] however the both mission had a trouble and lost the mission. Ref. 1 summarized past Phobos missions. Among the previous mission, the MEX conducted the most detailed observations, and obtained relatively high resolution images. The three-dimensional shape model, gravity (mass), and ephemeris are also derived from the MEX mission.[3)] The previous missions aimed at scientific observation of Phobos and Deimos has not been realized, and the sampler return from the Mars region is the world's first and the scientific value of the mission is high.

Following the Earth-Mars transfer phase, the Mars Orbit Insertion (MOI) operation that consists of three large maneuvers, will be conducted to enter an orbit around Mars. After the MOI operation, the spacecraft (s/c) will be injected into the Phobos coplanar orbit and perform the terminal rendezvous for Phobos. As the nominal scientific orbit, Quasi-Satellite Orbit (QSO) is adopted in consideration of the characteristic dynamical environment of Mars-Phobos system.

The QSO is a periodic orbit in CR3BP and a type of Distant Retrograde Orbit (DRO).[4)] The sphere of influence (SOI) and Hill sphere are about 7.2 km and 16.6 km, respectively. Assuming that the shape of Phobos is a tri-axial ellipsoid (13.0km, 11.4km, 9.1km), the SOI exists inside Phobos. The distance between the surface and the Lagrange point is about 3.6 km. Unlike the Earth-Moon system, the Lagrange points is located very close to the Phobos surface. The several periodic orbits in the CR3BP (e.g., Lyapunov orbit, Halo orbit, Vertical orbit, Distant Retrograde orbit) has been planned as a trajectory for scientific observation for Phobos.[5)] In the case of ordinary planetary exploration missions, the polar orbits are often adopted to observed the entire planetary surface (e.g., mars orbiter, lunar orbiter). On the other hand, in the case of Phobos, the polar orbit is not stable and not suitable for nominal orbit, thus the QSO has been proposed, and the orbital characteristics have been discussed in previous studies.[6-8)]

In this paper, the results of trajectory analysis in terms of the terminal rendezvous, QSO insertion, orbital transfer between different size of QSOs, and utilization of 3D-QSO are described. The navigation strategy around Phobos is also discussed.

2. Overview of Proximity Operation

In order to make scientific observation of Phobos and to acquire the samples from Phobos' surface, several kinds of orbital operations will be performed. The classification of the operation scenario in the vicinity of Phobos is shown in Fig. 1. The operations are classified into eight types (2D-QSO, 3D-QSO, Descent, Landing, Ascent, Hovering, Transfer, and Orbit Control) based on the orbital characteristics and mission requirements.

The following sections describe characteristics of the s/c operations including terminal rendezvous operation, QSO insertion, and orbital transfer in the vicinity of Phobos.

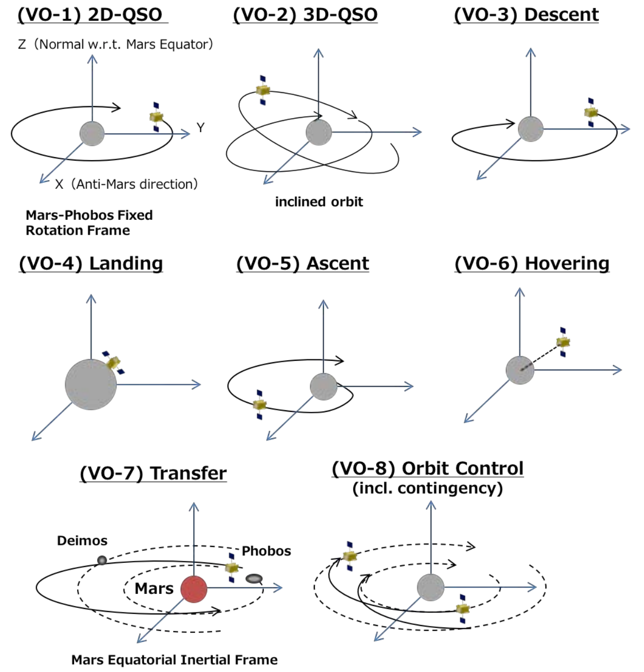

Fig. 1. Classification of Proximity Operation

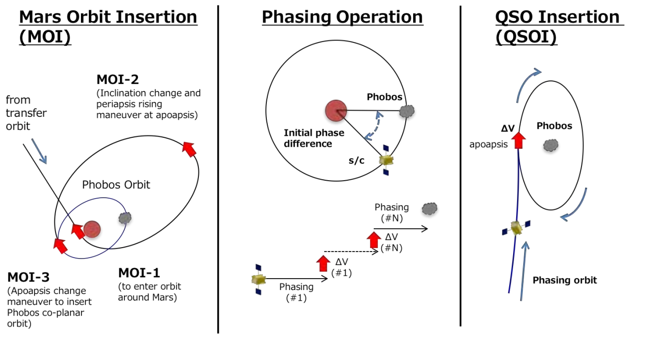

Fig. 2. Overview of Proximity Operation (from MOI to QSOI)

3. Rendezvous to Phobos

The operation scenario from MOI (Mars Orbit Insertion) to QSOI (QSO Insertion) is described in Fig. 2.

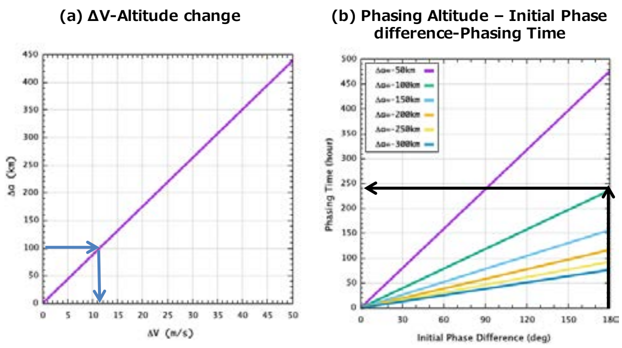

Fig. 3. Required ΔV(a) and Phasing Rate(b)

During the MOI operation, the s/c will be injected into Mars orbit by MOI-1, then inclination change and periapsis raising maneuver will be performed at apoapsis (MOI-2), after that the MOI-3 will be conducted at periapsis to insert the s/c into Phobos co-planer orbit.

A series of MOI maneuvers will place the s/c into Phobos co-planar orbit with some initial phase difference between Phobos and the s/c. In order to absorb the difference, the s/c will be entered into low or high altitude orbit with respect to the Phobos orbit. This phasing orbit may be divided into several segments in consideration of phasing rate, terminal rendezvous condition, navigation accuracy, and operational safety. During this phasing orbit, the s/c will perform the initial checkout operation not only for its bus system but also for its scientific instruments. Fig. 3(a) shows the ΔV required for altitude change. Insertion into the 100km altitude different orbit will take about 11 m/s. The relation between phasing altitude, initial phase difference, and phasing time is described in Fig. 3(b). Assuming the -100km phasing orbit, it takes about 240hours to absorb the 180deg phase difference.

4. Characteristic of QSO

A QSO is a periodic orbit in CR3BP and it is a kind of DRO. A coplanar in-plane orbit and out-of-plane orbit exist. In this analysis, they are referred to as 2D-QSO and 3D-QSO, respectively. Due to its orbital stability, a QSO is employed by several missions (e.g., Phobos-Grunt,[2]) PHOOTORINT,[9]) FASTMOPS[10])). A 2D-QSO is planned to be "Home Position" which is the nominal operation mode during the Phobos proximity phase. In general, the QSO such as around the ISS at near-Earth, the orbital dynamics can be expressed by Hill's equation without external forces, however, in the Phobos case, the Phobos' gravity affects the orbital dynamics of the s/c, and it is not negligible in terms of operation scheme and s/c configuration.

In order to roughly grasp the location of the QSOs, we studied a relationship between initial position (i.e. periapsis altitude) and initial velocity (along-track direction). Fig. 4(a) shows the schematic diagram for this evaluation. The search range for the altitude and velocity are from -100 km to -20 km and from -50 m/s to +50 m/s, respectively. Results are summarized in Fig. 4(b). The blue area is no impact and no escape region during 10 revolutions (where, one revolution

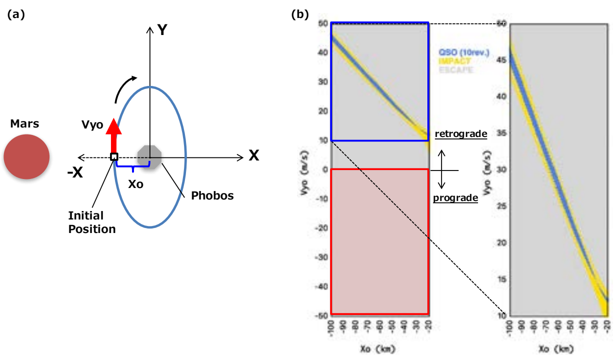

Fig. 4. The Existence Range of QSOs

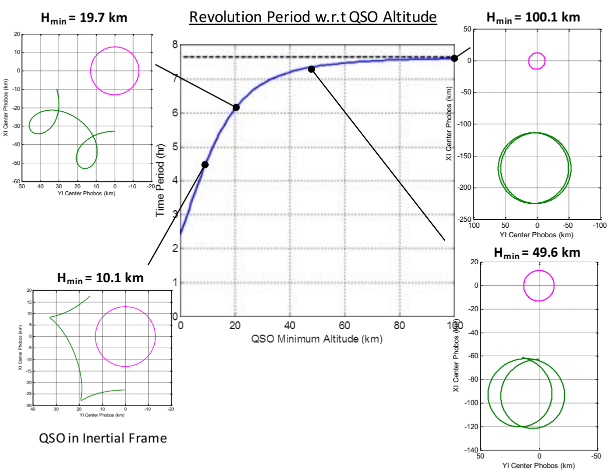

Fig. 5. Orbital Period of QSOs

means Phobos' orbital period), the yellow area is impact region to Phobos within 10 revolutions, the gray area is escape region within 10 revolutions. It indicates that the QSOs exist in a specific region and there is no stable prograde orbit. The velocity range satisfies stable QSO changes as a function of initial altitude.

An orbital revolution period of QSO becomes progressively shorter with decreasing altitude, due to the gravity effect (Fig. 5). The s/c motion in the inertial frame dynamically move around Phobos, the configuration of the High Gain Antenna (HGA), Solar Array Panel (SAP), and attitude operation must be decided taking into account for these constraints. In the present spacecraft configuration, the HGA and scientific instruments are fixed on the s/c body (oriented towards the +Z and –Z axis of the s/c, respectively), therefore, depending on the geometric condition, attitude orientation for the Earth-link and nadir pointing for Phobos observation may not be established at the same time. In order to avoid operational conflict between the HGA Earth-link communication and scientific observation, nominal operation time is divided into two categories; (1) command operation period and (2) scientific observation period. During the command operation period, the HGA communication between the s/c and ground station has a priority over the scientific observation, thus the s/c maintains Earth pointing attitude. On the other hand, during the scientific observation period, basically the s/c do not communicate with ground stations. The s/c changes its attitude toward the Phobos to perform scientific observation (e.g., nadir scan or particular area pointing).

5. QSO Insertion

This section describes a procedure for QSO insertion. We assume that the s/c transfers from the phasing orbit to 2D-QSO directly by means of a prograde maneuver at periapsis. A relation between an altitude of phasing orbit and a necessary increment ΔV is evaluated (Fig. 6(a)(b)). There are several characteristic distributions for impact region. The safety region around 30 km altitude is very narrow, and even 1 m/s ΔV error cannot be allowed. Considering the ΔV error, it is not realistic to enter low altitude QSO from a phasing orbit directly. There are about ±1.0 m/s safety region from -250 km to -80 km, therefore direct transfer from a phasing orbit to these regions seems reasonable, even though ΔV error is taken into account. From the point of view of s/c operational safety, it is better to insert a relatively higher altitude QSO at first, then lower its altitude gradually. Fig. 7(a)(b) show the 10rev stability and duration time (i.e. orbital lifetime), respectively.

Fig. 8 shows the cross-section view of Fig. 6(b), each branch of impact region has different duration time for impact to the Phobos. The orbital lifetime increases toward the center (i.e. stable QSO region), and the outmost branch collides with Phobos within one revolution. In terms of actual operation, it is necessary to avoid entering this region due to insufficient ΔV.

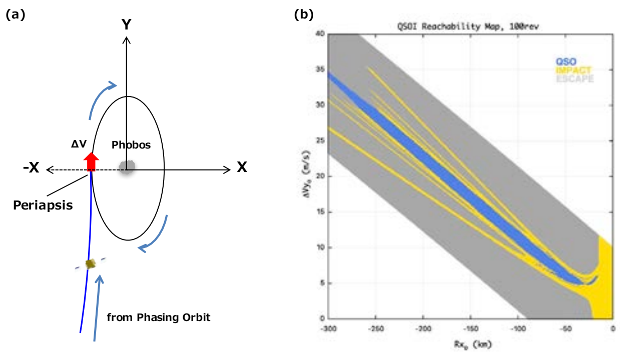

Fig. 6. QSO Insertion

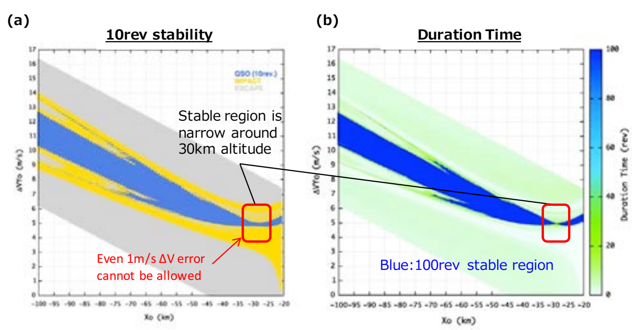

Fig. 7. Orbit Stability after QSOI

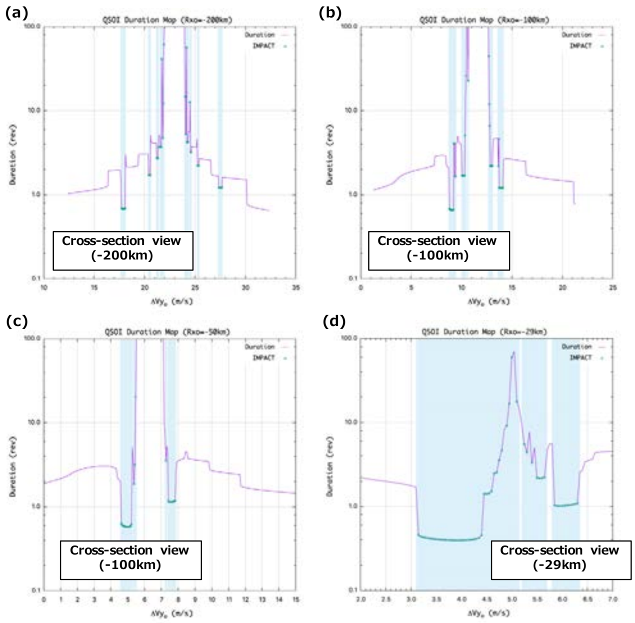

Fig. 8. Cross-section view of Reachability Map

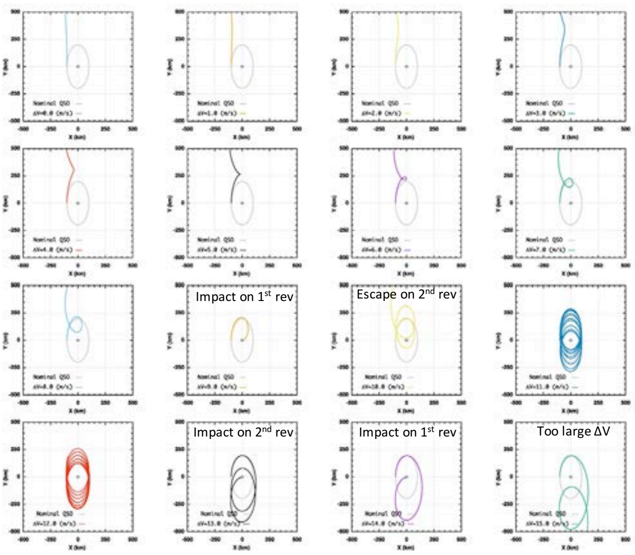

Fig. 9. Example Trajectories after QSOI

Fig. 9 shows some examples of the s/c trajectories after the QSOI ΔV. In this case, the s/c transfers from the phasing orbit to 100x200km QSO. If the ΔV is insufficient or exceeded, the s/c may collide with Phobos or escape from Phobos. The duration time from ΔV to collision varies depending on the ΔV performance.

5. Transfer between different QSOs

After the QSOI, to make scientific observation from an appropriate altitude, the s/c perform orbital transfer between different altitude QSOs in accordance with the operation plan. The orbital transfer operation in the vicinity of Phobos is one of the critical operations involving the possibilities of collision with Phobos. Although, the safety of the s/c is the top priority, from the point of view of fuel efficiency, the total ΔV for orbital transfer is expected to be suppressed as much as possible. Furthermore, it is also an important evaluation item to reduce the operation load as much as possible.

Regarding the relative orbit transfer problem, three impulse method is known to be an optimal solution for QSO altitude change without taking into account the Phobos gravity. [11] The directions of these 3-impulse maneuvers are all in the along-track direction. Fig. 10 show the ΔV required for orbital transfer without considering the effect of Phobos gravity by means of 2-impulse and 3-impulse method, respectively. Comparing 3-impulse and 2-impulse, it can be seen that the required ΔV is less than about half.

Two example trajectories of CR3BP case (i.e. the case of considering Phobos gravity) are described in Fig. 11. One is a transfer from 100 km to 60 km, the other is from 60 km to 40 km. In both cases, CR3BP requires more ΔV. Especially, when the altitude is low, the difference tends to be large. It is also characteristic that the control directions are not aligned with the along-track direction. These values are based on a preliminary analysis, and it is necessary to carry out further detailed analysis in the future.

In the case of optimal transfer method, ΔV execution points are apoapsis, periapsis, and apoapsis, and are all performed in the along-track direction. The transfer time can be adjusted by setting the control interval, and it is possible to make a transition within one rotation at the shortest. Because of the feedforward trajectory control, the influence of the ΔV error becomes large, but it has an advantage that the operation can be completed in a short time.

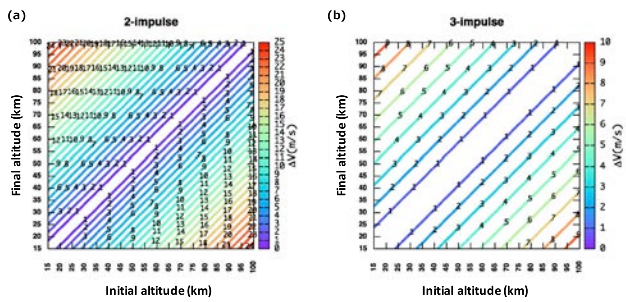

Fig. 10. Required ΔV for 2 and 3 Impulse Methods

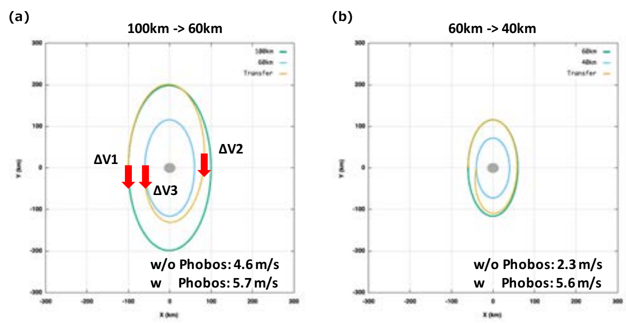

Fig. 11. Transfer Trajectories using 3 Impulse Method

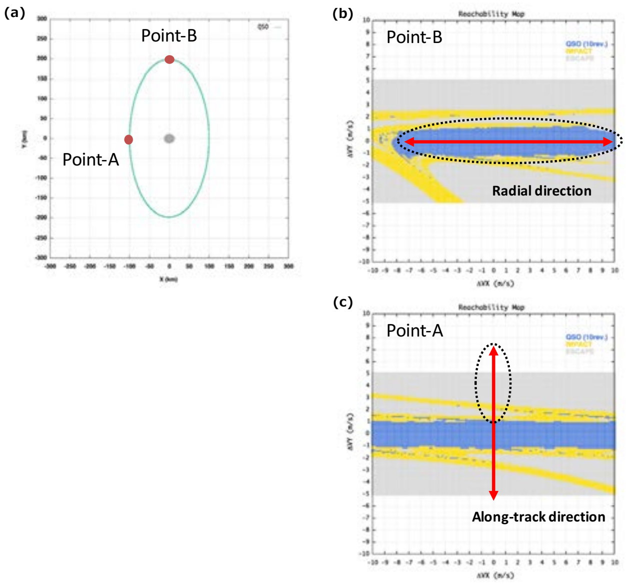

Fig. 12. Reachability Map of Orbital Transfer at Leading Point and Periapsis

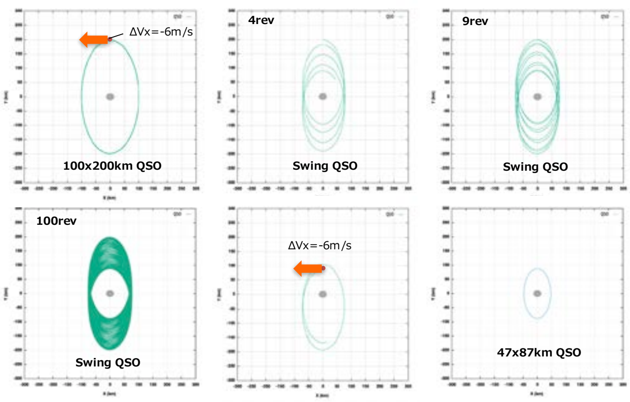

Fig. 13. Orbit Transfer using swing QSO

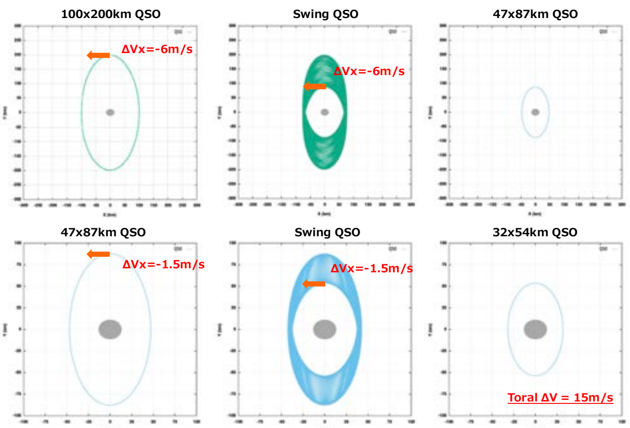

Fig. 14. Orbit Transfer from Higher QSO to Lower QSO

The reachability maps are created to evaluate the sensitivity of the ΔV direction for each control point. Assuming that the trajectory control is carried out while the s/c is orbiting the QSO, a sensitivity analysis chart is created when the ΔV executed at the periapsis (point A) or leading point (point B) (Fig. 12). The horizontal and vertical axes mean the radial direction ΔV and along-track direction ΔV, respectively. Each point shows the transition status in the case 10 revolution after execution of the orbit control. Blue indicates a region where the QSO can be maintained, yellow indicates a colliding region, and gray indicates an escape region. Allowable range of ΔV for radial direction is larger than that of along-track direction at both periapsis and leading point. In the case of 3-impulse method, ΔVs are executed at periapsis, apoapsis, and peiapsis with along-track direction, the transfer trajectory through the impact or escape region, if the magnitude of first ΔV is several m/s. In this situation, id the second ΔV are not implemented, it is necessary to perform additional trajectory control maneuver and abort from unsafe trajectory by the collision time.

Although, the 3-impulse method is optimal for fuel efficiency, its transfer trajectory through unsafe region, we proposed a method using Swing QSO as a relatively robust orbital transfer method considering operational safety. In this method, instead of using the most efficient ΔV in the along-track direction, the radial direction ΔV at leading or trailing point and change the trajectory by liberating the QSO. In the case of ΔV at point B, the ΔV in the radial direction is safe up to about 8 m/s. When creating a nominal QSO with CR3BP, after setting the minor axis radius, the initial speed on the X-axis is optimized so as to reduce fluctuation of the intersection point history with the Y-axis. On the other hand, Swing QSO is a trajectory that the intersection point with the Y-axis is not constant but vibrates in the along-track direction.

An example of orbital transfer between different altitude QSOs by using swing QSO is described in Fig. 13, where the initial QSO size is 100x200 km and final is 47x87 km. First, a -6.0 m/s ΔV is performed at leading point, and transfer the swing QSO. This ΔV was selected within the stable region on the reachability map. In the case of the swing QSO in Fig. 13, the s/c returns to almost the same point at 9 rev and the trajectory does not collide with Phobos even when propagating 100 rev. After the swing QSO transition, when the target altitude is reached, the deceleration maneuver is executed again to make transition to the lower altitude QSO. Even when some trouble occurs and ΔV operation is not implemented, s/c will remain in a stable orbit.

An example for orbital transfer from higher altitude QSO to lower altitude QSO is described in Fig. 14. The period required for the orbit transfer depends on the length of stay at swing QSO and can be selected by a operational design side. Although the orbital altitude at every orbit is different, scientific observation of Phobos surface can be carried out like ordinary QSO, and there is also the advantage that it can observe from as a result. Furthermore, since the altitude across the Y-axis is lower than the usual QSO, the Phobos surface can be observed from a lower altitude overall. Since the trajectory control is not continuous within a short period, it is also safer in terms of operational aspect that it is possible to perform orbit determination with sufficient time after the orbital control.

6. Effect of Navigation Error

Ideally, it is preferable to perform trajectory control with no navigation error. However, in actual operation, ΔV is performed with the navigation error accumulated due to OD error and orbit prediction error. In addition, ΔV error also affect the orbital transfer. The effect of navigation error is evaluated using sensitivity analysis. As to the navigation error, 100 m and 1 km for the s/c position are considered. The contour diagram shows ΔV amount that can remain in the QSO without colliding with nor escaping from Phobos when ΔV is injected at ±100 m and ±1km in the X and Y direction respectively away from nominal position. Dot in Green and yellow represent the safety ΔV amount region in the case there is a navigation error of ± 100m and ± 1km, respectively. As to the ΔV error, the magnitude (5%, 3σ) and the direction (0.1deg 3σ) error are taken into account.

The reachability maps for several orbit transfer cases are described in Fig. 15. The purple, green, and yellow area means safety region without error, with 100 m error, and with 1 km error, respectively. Dot in black indicates the range of ΔV error. The safety region decreases as the altitude decreases. The safety region is relatively wide in the +ΔVx direction, which means the QSO size will be increased by performing the prograde maneuver, and possibility of collision decreases as the Phobos distance increases. Conversely, as the transition to the lower altitude, the safety region in the –ΔVx direction decreases, it means that the reduction of the QSO size by retrograde maneuver at a lower altitude increases the possibility of collision. Therefore, trajectory control is necessary to keep within safety region and achieve stable s/c operation. Focusing on the error component, it is found that the influence of the position error in the X direction is dominant and the influence of the position error in the Y direction is small. Although the navigation error of 100 m does not change greatly with respect to the nominal case, in the case where there is a navigation error of 1 km, the safety area has drastically decreased, especially when transfer to the low altitude QSO (32x54 km) from swing QSO, the ΔV=-1.5 m/s which is necessary for orbit transfer is not included in the safe area.

Fig. 16 shows the reachability map with navigation error, blue, purple, and green area means safety region without error, with 100 m error, and with 200 m error, respectively. The duration time is 10 rev and, yellow means impact to Phobos, gray means escape region. The ΔV in the Y axis direction is allowed to some extent at the higher altitude, but as the altitude decreases, the allowable region in the Y axis direction decreases along with the safe region for -X axis direction. At around 30 km the safety area is extremely narrow and the shape is very characteristic. When the distance reaches around 20 km, the allowable range in the Y axis direction slightly increases. Since Fig.17 plots the region where the QSO can be maintained for one revolution, it implies that active abort is necessary as soon as it exists in the yellow region after some trajectory control has been performed.

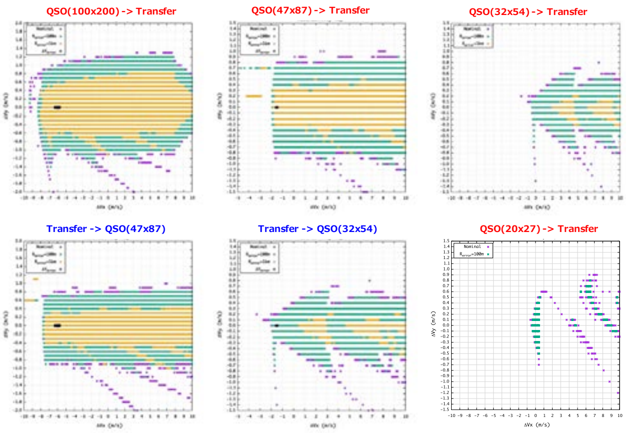

Fig. 15. Reachability Map Considering Navigation Error

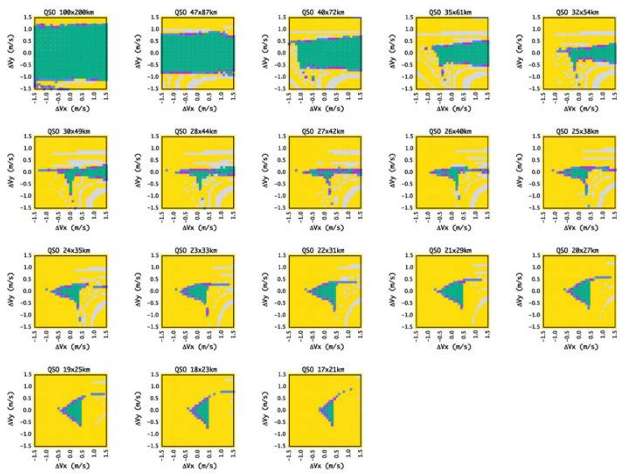

Fig. 16. Safety Map for 10 Revolution

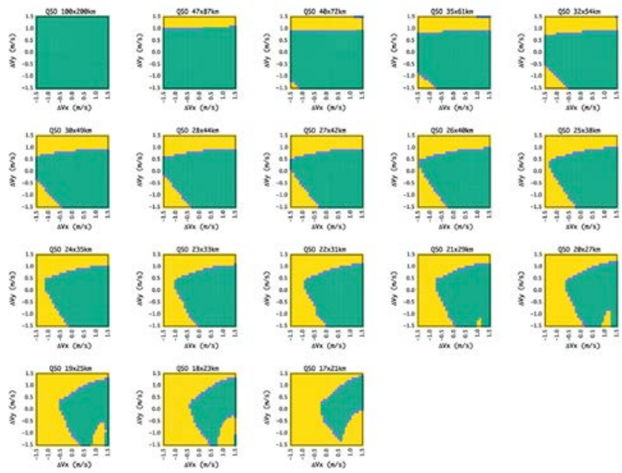

Fig. 17. Safety Map for 1 Revolution

7. 3D-QSO

In order to make scientific observation on Phobos' high latitude area, the s/c is necessary to be injected into 3D-QSO. There are still many problems to be solved to achieve stable 3D-QSO operation (e.g., orbital transfer from/to 2D-QSO, orbit maintenance, and attitude control for pointing observation).

We evaluate a reachability assuming that the transfer operation is executed at leading point. Fig. 18 show the reachability maps for 3D-QSO, where the X-axis mean the ΔV of radial direction and the Y-axis means the ΔV of normal direction. Although, the allowable out-of-plane maneuver is large at higher altitude QSO, the safety area reduce with decreasing altitude and large maneuver cannot be performed in normal direction at lower altitude QSO. As a result of this evaluation, the active and relatively frequent orbit maintenance maneuvers are necessary to realize stable 3D-QSO with a high inclination angle at lower altitude QSO. Fig. 19 shows an example for middle altitude 3D-QSO (50x100x60km). These footprints indicate that the latitude within ±50 deg are observable.

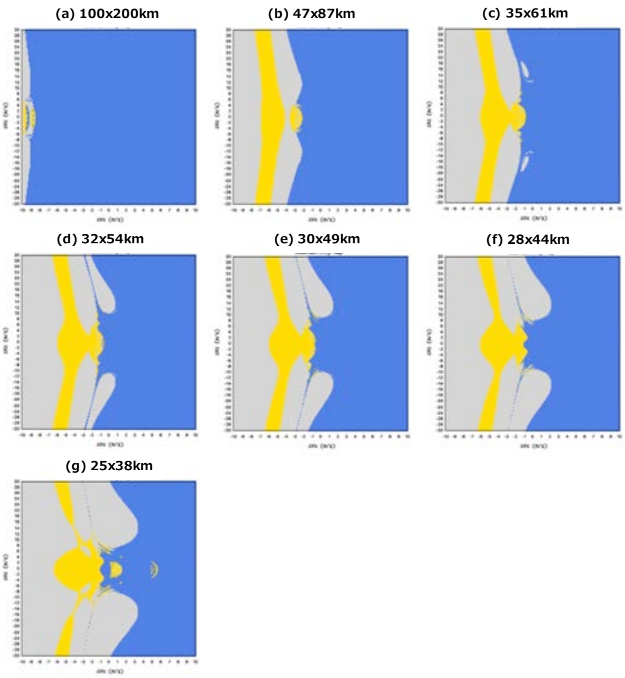

Fig. 18. Reachability Map of 3D-QSO

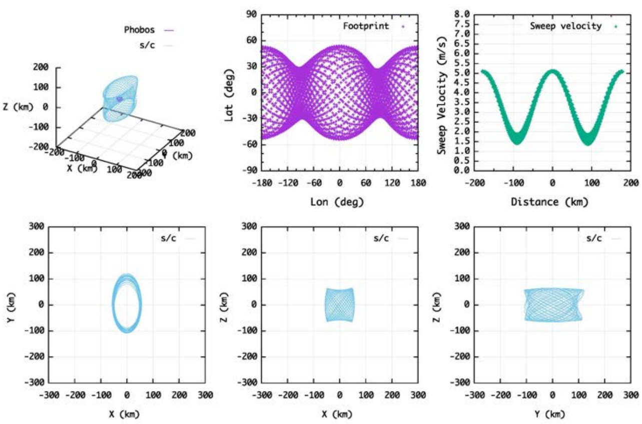

Fig. 19. Example Trajectory of 3D-QSO

The sweep velocity on the Phobos surface varies from about 1.4 m/s to 5.1 m/s. The stable and easy to operate 3D-QSO will be designed and evaluated. The lower altitude 3D-QSO contributes to the gravity estimation, and it is also expected from the aspect of science operation. We plan to investigate to realize lower altitude 3D-QSO with high inclination angle as far as possible with securing the safety of the spacecraft.

8. Navigation Strategy around Phobos

The operational requirements for orbit determination depend on the orbit phase (e.g., Earth-Mars transfer, MOI, Phasing and terminal rendezvous, QSOI, QSO transfer, Descent and Landing, Ascending), therefore the OD accuracy should be evaluated considering the availability and accuracy of measurements (e.g., Doppler, range, NAC, WAC, altimeter). In general, to improve the navigation accuracy, the errors of dynamical models have to be removed as much as possible. In the case of Phobos proximity operation, unlike ordinary Mars orbiting spacecraft, the uncertainty of Phobos gravity and ephemeris have a great influence on OD accuracy. In fact, during the high altitude QSO phase, these parameters will be updated by using s/c tracking data and relative observation data to reduce the navigation error. The gravity field model and the rotational motion model give constraints on the internal structure of Phobos and are important not only from an engineering point of view but also scientific point of view. In this preliminary analysis, OD covariance analysis is performed assuming a high altitude QSO and a low altitude QSO cases.

8.1. Error of acceleration model

Estimating the error of acceleration model in the proximity of Phobos, according to the results of Ref. 12, the gravity error is calculated as on the order of 10E-10 km/s^2 and 10E-9 km/s^2 at high altitude QSO and at low altitude QSO, respectively. If the Phobos ephemeris error is 200 m, the acceleration error is on the order of 10E-10 km/s^2 and 10E-8 km/s^2 at high altitude QSO and at low altitude QSO, respectively. In addition, the error of Mars gravity (10E-12 km/s^2) and the error of solar radiation pressure model (10E-12 km/s^2) also exist. The Phobos rotational model is calculated from IAU model and used as fixed value (i.e., not estimated parameters). In the future, it is also necessary to consider the rotational motion model error of Phobos.

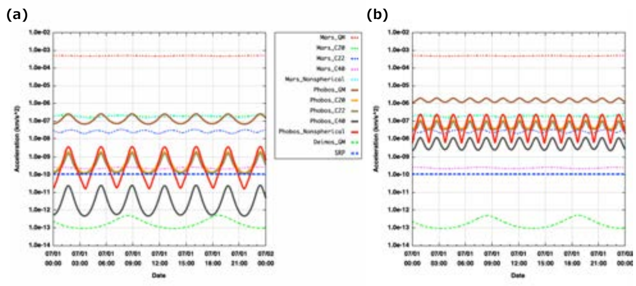

Fig. 20. Acceleration Histories at Higher Altitude QSO and Lower Altitude QSO

The examples of acceleration histories at higher altitude QSO (50x100 km) and lower altitude QSO (19x24 km) are described in Fig. 20. Duration time is one week, there is no orbit maintenance maneuver in this period. The solar radiation pressure term is smaller than Phobos GM. Phobos C_{20} and C_{22} terms are 10 times as large as SRP. Phobos C_{40} term is 10-100 times as small as SRP.

8.2. Covariance Analysis

As to the measurements for OD, the X-band 2way RARR (i.e., Doppler and range), optical navigation information (NAC/centroid), and laser altimeter are used. Although, during the Earth-Mars and Mars-Earth transfer phase, the ΔDOR (Delta Differential One-way Range) is extremely effective for OD in the celestial reference coordinate frame, the OD arc setting used in this analysis is relatively short (the same as the Phobos revolution period) and the target is Mars orbiting spacecraft, therefore ΔDOR measurement is not included in the OD process. The landmark information on the Phobos will also be used in actual operation, detailed analysis is underway and is not included in this paper.

Setting for OD covariance analysis are summarized in Table 1. The estimated accuracy from OD covariance analysis is summarized in Table 2. As a result of OD covariance analysis, it was found that Phobos gravity model error and ephemeris model error are dominant error sources for OD, and to improve the OD accuracy we must estimate the Phobos gravity and ephemeris using the s/c radiometric tracking and relative observation data (e.g., RARR, WAC, NAC, altimeter). In particular, these acceleration models error have a significant impact on the navigation accuracy and stable s/c operation at low altitude QSO phase. As a flow of actual operation, at first, during the high altitude QSO phase, the gravity and ephemeris information will be updated to improve the navigation accuracy; then, gradually improve the accuracy by decreasing the QSO altitude. Finally, precise gravity model will be estimated using the data acquired at low altitude QSO phase.

9. Conclusion

The rough operation scenario for phasing, QSOI, QSO transfer are evaluated. The orbital transfer between the different size of QSOs with navigation error is investigated to propose a relatively robust and safer swing QSO transfer method. The navigation accuracy is estimated by means of OD covariance analysis and the results indicate that the error of gravity and ephemeris model have a great influence for navigation, and in order to improve the OD accuracy, these parameters have to be estimated before starting operation in the lower altitude region.

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Table 1. Simulation Setting for OD Covariance Analysis

Item		Setting
Measurements	2way X-band Doppler	0.2 mm/s
	2way X-band range	50 m -> 100 m
	Optical Navigation	0.1 deg (Phobos centroid)
	Laser Altimeter (LIDAR)	20 m (include shape model error)
Tracking	OD arc	1pass：12hour (UDSC) 2pass：24hour (UDSC+DSN)
	Doppler obs rate	1data / 60sec
	range obs rate	1data / 60sec (only high elevation period)
	EL cut angle	15deg
Acceleration model error	Phobos gravity	・1.0×10^{-7} to 1.0×10^{-10} km/s^2 per axis(x,y,z) ・Consider parameter
	Phobos Ephemeris	
	Mars gravity	
	Solar radiation pressure	
	Other model error	

Table 2. Summary of OD Covariance Analysis

Phase	Acceleration model error (km/s^2)	Position error	Velocity error
High altitude QSO	1.0×10^{-9}	A few m ～ 10m	1 cm/s ～
	1.0×10^{-10}	1m ～	1 mm/s ～
Low altitude QSO	1.0×10^{-9}	A few 10m ～	A few cm/s ～
	1.0×10^{-10}	A few m ～	A few mm/s ～

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