Quasi-Satellite Orbits around Deimos and Phobos motivated by the DePhine Mission Proposal

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DePhine - **De**imos and **Ph**obos **In**terior **E**xplorer - has been proposed to ESA as a medium-class mission by a scientific team led by the Institute of Planetary Research of DLR. Planned to begin its science mission in 2033, the spacecraft will fly in quasi-satellite orbits first around Deimos and then around Phobos while collecting remote-sensing data. Motivated by the DePhine proposal, this paper presents the results of a numerical analysis of some quasi-satellite orbits around the Martin moons. The orbits were studied in terms of their size and stability. At the same time, the feasibility of a global ground-track coverage was investigated.

Key Words: Quasi-satellite orbits, Deimos, Phobos

1. Introduction

In the framework of ESA's Cosmic Vision program, DePhine (**De**imos and **Ph**obos **In**terior **E**xplorer) has been proposed as an M-class mission by the Institute of Planetary Research of DLR and a study team from the scientific community and the space industry.[1)]

The mission is proposed to be launched in 2030 into a Mars transfer trajectory with 1.5 revolutions around the Sun. After arrival at Mars it would enter a quasi-satellite orbit around Deimos for collection of various remote-sensing data. Depending on the available resources, in the second mission phase, the spacecraft would either carry out multiple close flybys of Phobos, or, alternatively, the mission could be extended to include a quasi-satellite orbit around Phobos to perform similar remote sensing experiments as those for Deimos.

Motivated by this proposal and in collaboration with the Institute of Planetary Research, a study of feasible quasi-satellite orbits around Deimos and Phobos was performed at the German Space Operations Center of DLR.

A number of scientific studies on the subject of quasi-satellite orbits have already been carried out in literature, mostly with a focus on Phobos.[2, 3)] In particular, a dynamical model was developed by Wiesel[4)] including Mars gravity and oblateness, and the moon's orbital eccentricity. In Gil,[3)] a numerical search for stable quasi-satellite orbits around Phobos was conducted, and a sample 3D orbit was studied from a preliminary mission analysis point of view. In the book of Scheeres,[5)] an interested reader can find both numerical studies and analytical considerations.

In present research, a numerical analysis is performed to characterize quasi-satellite orbits around primarily Deimos and, secondary, Phobos in terms of their size and stability. Since the objective of DePhine is to cover as much of the surface of the moons as possible, highly-inclined orbits (as seen from the moon) are of great interest for this study, and are investigated in the present paper in terms of the covered ground-track.

The remaining of the paper is organized as follows. Section **2.** gives an introduction of the DePhine mission, its main scientific goals and key mission parameters. Section **3.** describes the objectives of the performed simulation, and the assumptions made for the present study. Section **4.** focuses on the results of a numerical analysis of quasi-satellite orbits around Deimos as the prime target of the mission. Section **5.** complements this with a comparable study of quasi-satellite orbits around Phobos. The conclusions are given in Section **6.**

2. DePhine Mission Profile

Up to the present day, the origins of Phobos and Deimos are controversial. According to the several prevailing theories, they may have formed in co-accretion with the main planet, as ejecta from Mars following large impacts; or, they may represent captured asteroids, for more information see the book of Oberst et al.[6)] and references therein. To obtain critical clues on whether the satellites originate from the same source and share the same formation scenario, the DePhine mission will perform comparative studies on the interior structures of the satellites.

The mission will first focus on Deimos, to obtain physical parameters (e.g. gravity field) and remote sensing data (e.g. multispectral image data) comparable to data assumed to be already available for Phobos by the time DePhine reaches its target. In particular, the properties of the Deimos soil will be studied to enable comparisons with Phobos samples, assumed to be available by then from the sample return missions (e.g. JAXA's Mars Moon Explorer planned for launch in 2024). The subsurfaces of Phobos and Deimos will be studied using a powerful high-frequency radar. The mission will attempt to understand the spatial distribution and layering of the regolith on both satellites and map the structure of impact craters including the Phobos grooves. Other experiments will be operated for monitoring the flux of dust particles in the Martian satellite system and for observing solar wind interaction with the surfaces of the bodies.

According to the baseline scenario, DePhine will be launched in 2030 into a Mars transfer trajectory by the Ariane 6.2 launch vehicle. After reaching Mars, it will initially enter a quasi-satellite orbit around Deimos to carry out a comprehensive global mapping with various remote-sensing instruments. As a highlight of the mission, close flybys will be performed, dur-

Table 1. Characteristics of the Martian system.

	GM [km^3/s^2]	R [km]	a [km]	e [-]
Mars	42828.3756	3396.0	$228 \cdot 10^6$	0.0934
Phobos	0.00071524	11.1	9378	0.0151
Deimos	0.00009875	6.2	23459	0.0005

Table 2. DePhine spacecraft parameters.

Spacecraft mass	[kg]	1129.0
Cross-section SRP area	[m^2]	7.8
Reflectivity coefficient C_R	[-]	1.4

ing which radio tracking, stereo imaging, radar sounding, and observations of the magnetic field as well as the Gamma-Ray / Neutron flux will be carried out. A steerable antenna will allow simultaneous radio tracking and remote sensing observations. The close fly-bys at low relative velocities increase data integration times, enhancing the signal strength and data resolution. About 10 to 20 flyby sequences, including polar passes, will result in a dense global grid of observation tracks. The spacecraft orbit will then be changed into a Phobos resonance orbit (alternatively, into a Phobos quasi-satellite orbit in case of the mission upgrade scenario) and the spacecraft will carry out multiple close flybys and perform similar remote sensing experiments as those for Deimos for comparative studies.

The spacecraft will carry a suite of remote sensing instruments, including a camera system, a radio science experiment, a high-frequency radar, a magnetometer, and a Gamma Ray / Neutron spectrometer. Additional instrumentation, e.g. a dust detector, a solar wind sensor or a small landing package, will address secondary science goals of the mission.

3. Simulations of quasi-satellite orbits

With the strongly perturbing gravity of Mars and the masses of Deimos and Phobos being too small to capture a satellite, it is not possible to orbit the Martian moons in the usual sense. However, orbits of a special kind – generally referred to as distant retrograde orbits, a family of distant satellite orbits, also called quasi-satellite orbits – exist and can be sufficiently stable to allow many months of operations in the vicinity of the moon. While the spacecraft is still orbiting Mars, the perturbation exerted by the gravity of the moon prevents the spacecraft from drifting away from it. Thus, a coplanar orbit of this type can be described as a multitude of ellipsoidal trajectory segments with their centers moving back and forth in the along-track direction.

Following the common nomenclature used in scientific literature, each ellipsoidal segment of such an orbit will be referred to as an *epicycle*, whereas the entire manifold of drifting epicycles will be called in the following a *quasi-satellite orbit* (QSO).

The simulations of quasi-satellite orbits presented in this paper follow the numerical approach adopted by Gil,[3] with the main difference that the search performed in the work if Gil[3] assumed the spacecraft located initially on the V-bar of Phobos, whereas the present study focuses on the injection on the R-bar. The goal of the present study was to gain an understanding of the conditions required for a stable QSO around Deimos/Phobos, and to obtain experience in this type of problems. It was chosen to approach the problem numerically for the advantage of fast preliminary results and the possibility of including relevant perturbations in the stability analysis. Moreover, the numerical approach facilitates the investigation of the non-coplanar QSOs.

This study attempts to address the following issues:

- Initial conditions required for stable QSOs around Deimos/Phobos
- Sensitivity of the found QSOs to inaccuracies in initial injection velocity
- Size of QSOs in terms of the minimum/maximum altitude over Deimos/Phobos
- Maximum attained latitudes (in case of non-coplanar QSOs)
- Feasibility of a global ground-track coverage

The numerical integration of equations of motion was performed taking into account major forces including the Martian gravity field of degree and order 20 (from the JGMRO110C model available from Mars Reconnaissance Orbiter[7]), solar radiation pressure, and the Deimos/Phobos point-mass gravitational forces. Table 1 summarizes some properties of the Martian system (standard gravitational parameters and mean radii of the bodies, semi-major axis and eccentricity of the orbit of Mars around the Sun, and the orbits of Deimos/Phobos around Mars), while Tab. 2 provides a few key parameters of the spacecraft for solar radiation pressure modeling.

The reference frame used for the search of stable QSOs and for the presentation of the solutions is the orbital reference frame of Deimos/Phobos. The orbital or RTN reference frame is formed by the coordinate axes e_R pointing in the direction away from Mars (radial), e_N pointing in the direction of the angular momentum (normal), and the third axis e_T completing the orthogonal right-handed system, with the origin of the reference frame located at the center of Deimos/Phobos. The relative position and velocity vectors will be denoted in the remaining of the paper as (r_R, r_T, r_N) for position and (v_R, v_T, v_N) for velocity.

In the following, the typical simulation time interval is 30 days. If the altitude does not drop to zero (i.e. no crash occurs) within this timespan, and the maximum distance from Deimos/Phobos does not exceed 1000 km, the orbit is considered to be stable. Similar time and distance limits have been used in other literature.[3,4]

The assumption of the spherical shape of the bodies is made in the calculations of distances to the surface and the groundtracks (assumed mean radii are summarized in Tab. 1). Since the actual shape of Deimos and Phobos is irregular and, moreover, scientific observation require distances below 150-200 km, the limits used for the present study should be regarded as merely theoretical assumptions, rather than realistic constraints of an actual mission scenario. Especially in the case of near-QSOs, these preliminary results should be refined by taking into account the major characteristics of the actual shapes and the non-spherical gravity fields of Deimos/Phobos.

4. Deimos QSOs

To reduce the computational effort, the search for appropriate initial position and velocity was restricted to the variation of

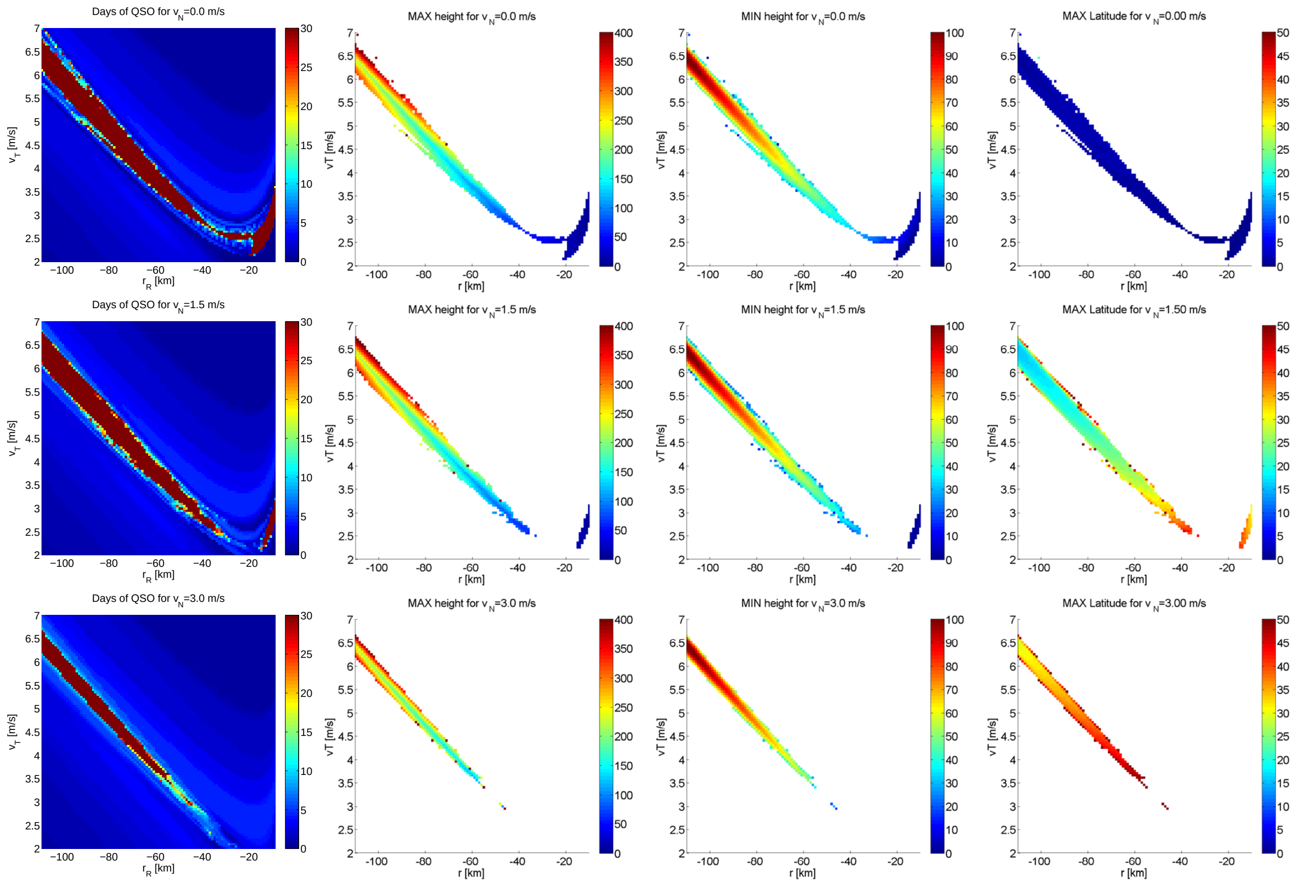

Fig. 1. 1st column: number of days of stability for QSOs around Deimos with initial conditions in the $r_R - v_T$ plane, and an increasing downwards out-of-plane initial relative velocity component v_N; 2nd column: maximum altitude [km] over mean surface of Deimos; 3rd column: minimum altitude [km] over mean surface of Deimos; 4th column: maximum achieved "latitude" [°]; simulation time interval: 30 days.

Table 3. Sample QSOs around Deimos.

	Initial conditions			*Altitude*		*Latitude*	*Stability*
	r_R	v_T	v_N	$h_{\max}$	$h_{\min}$	$\varphi_{\max}$	T
	[km]	[m/s]	[m/s]	[km]	[km]	[°]	[days]
QSO-1	-10	2.90	1.55	6.8	2.8	32.1	> 90
QSO-2	-14	2.30	1.50	14.5	1.0	40.2	> 90
QSO-3	-44	2.85	2.45	89.6	32.9	50.8	> 90
QSO-4	-49	3.05	4.00	126.4	29.2	64.8	≈ 30
QSO-5	-69	4.10	6.10	181.8	54.8	64.6	≈ 70
QSO-6	-69	4.05	7.75	192.1	49.4	71.1	≈ 35

relative initial position r_R in negative radial direction, and the variation of initial relative velocity v_T in positive tangential direction. Of course, such assumptions do not allow a complete systematic search of the phase space, and more simulations are required for a complete coverage of the possible QSOs. However, using this simplification we can get an idea on how often sufficiently stable solutions occur and gain an insight into the involved magnitudes of the initial relative position and velocity required for a stable trajectory.

In the second step, a variation of the out-of-plane component v_N of the initial relative velocity vector was added to estimate the corresponding sensitivity of the stability "areas" on the $r_R - v_T$ plane. This also allows to get an idea of the maximum apparent inclination that can be reached by non-coplanar QSOs.

The simulations showed that the influence of the position of Deimos along its eccentric orbit is not negligible when studying the "stable" regions of initial conditions in the $r_R - v_T$ plane. Thus, for convenience the simulations were initiated with Deimos at periapsis of its orbit around Mars.

4.1. Search results

Figure 1 shows the results of the conducted search for initial conditions leading to stable QSOs around Deimos. The leftmost plots show the number of days of stability, during which no crash occurs and the maximum distance from Deimos of 1000 km is not exceeded. The propagation time is restricted to 30 days. While the uppermost plots assume a zero out-of-plane component, the lower plots assume an increasing downwards non-zero v_N. The plots can be regarded as "slices" of the 3D stability area in the reduced phase space of r_R, v_T, v_N, with each "slice" corresponding to a particular value of v_N.

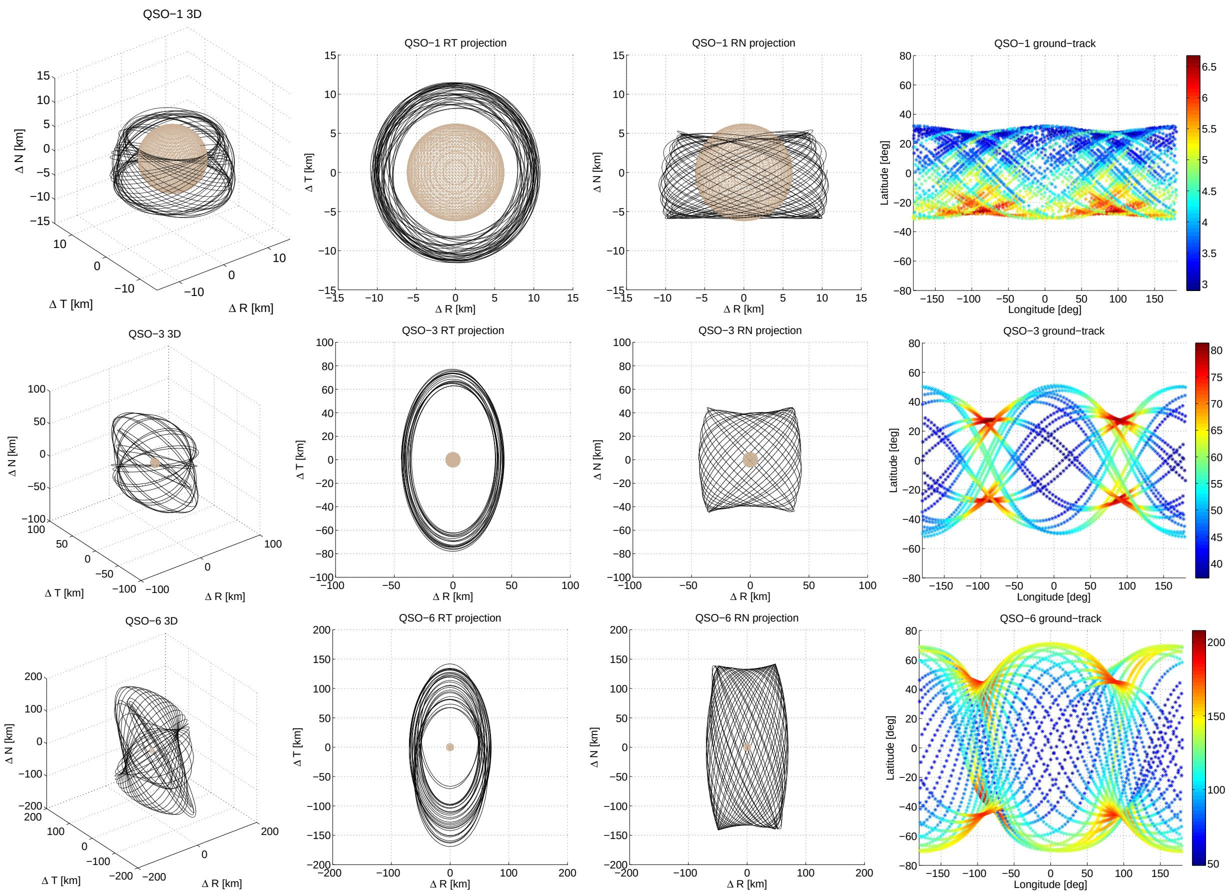

Fig. 2. Sample QSOs around Deimos: 3D trajectory (1st column), projection on the Deimos orbital plane (2nd column), projection on the cross-track plane (3rd column), ground-track (4th column) color-coded with instantaneous altitude [km] over mean surface of Deimos. Simulation time: 8 days for QSO-1, 20 days for QSO-3, 34 days for QSO-6.

The results show that there is quite a sharp transition between the "stable" area colored with dark red and the "unstable" area colored with dark blue. It seems that in case of unstable QSOs, the bounds are reached within a few days. On the other hand, longer propagation intervals demonstrate that if the orbit is stable for the selected simulation interval of 30 days, there is a good chance that it will be stable for a longer time period. Nonetheless, orbits with initial conditions at the border of the "stable" area might exceed the limits on distance shortly after the end of the simulation time interval of 30 days.

Looking closely at the plots for $v_N = 0$, a clear trend going through the stable region can be seen, which for any particular r_R defines the approximate v_T required for the stability of the solution together with an allowed interval of injection velocity error. The mean trend visible in the uppermost plots in Fig. 1 matches the curve of v_T as a function of r_R established by Wiesel[4] as a solution of the boundary value problem with dedicated equations of motion. It should be noted that the calculations in Wiesel[4] were performed assuming injection on mirrored axes, that is, with positive r_R and negative v_T. Three sub-regions of stability were found by Wiesel[4] when varying injection velocity errors in v_T (i.e. deviating from the ideal solution): the innermost region with $r_R \in [10, 20]$ km characterized by a quasi-Keplerian motion,[8] the middle region with $r_R \in [20, 35]$ km, and the outer region with $r_R > 35$ km. The same three sub-regions can as well be clearly recognized in the uppermost plots in Fig. 1.

The second and third columns of plots in Fig. 1 show the maximum and minimum height over the mean surface of Deimos achieved within the simulation time interval of 30 days. The colormaps were kept constant throughout the different values of v_N to facilitate the assessment of the evolution of the parameters. It can be concluded, that although the stable area is shrinking with increasing out-of-plane component of the initial relative velocity vector, this does not seem to have a significant influence on the size of the corresponding stable QSOs. In other words, for any particular pair (r_R, v_T) well inside the stable region, the minimum and maximum distance to Deimos seems to stay more or less constant with varying v_N. The orbits starting at 70 km and less of radial distance from Deimos seem to show the lowest values both in the minimum and the maximum altitude, with the latter being restricted in this region to 250 km.

The rightmost column of plots shows the evolution of the maximum latitudes corresponding to the stable QSOs. As this series of plots shows, relatively high inclinations of up to 45° can be reached in orbits starting at injection radius -10 km $\leq r_R \leq -70$ km from Deimos. In general, it seems that the inclination of 45° represents a kind of threshold, meaning that the orbits with significantly higher inclinations rarely remain stable over periods much longer than 30 days.

The requirement on the accuracy of the injection speed is probably going to be the biggest challenge when placing the spacecraft in a highly-inclined QSO with inclination over 45°. The simulations show that in this case the maximum allowed error in the injection speed can be as small as 5-10 cm/s. It might be possible to overcome this challenge by placing the spacecraft in a less inclined, “safer”, orbit first, and increase the inclination with a series of small maneuvers based on a series of orbit determination sessions. For the case of inclinations of up to 30°, the requirement on the accuracy of injection velocity is less tight, depending on the sub-region of the stable area. For instance, for the near-QSOs with -10 km $\leq r_R \leq -20$ km, the limits on the injection velocity are much broader: up to 0.5 m/s in υ_T, and up to 1.5 m/s in υ_N.

4.2. Sample stable orbits

To illustrate some generic cases, the first two orbits listed in Tab. 3 represent near-QSOs which remain stable for at least three months reaching instantaneous inclinations greater than 30° and 40°, respectively. It seems to be difficult to reach significantly higher inclinations starting from -10 km $\leq r_R \leq -20$ km. However, it is apparently possible to achieve inclinations over 50° and higher in more distant QSOs. As an example of that, Tab. 3 includes an orbit denoted “QSO-3”, which is stable over at least three months with altitude varying between 33 km and 90 km while reaching inclination over 50°.

Starting with larger out-of-plane components it seems to be feasible to achieve even higher inclinations, however, at the cost of increasing instability and/or distance to Deimos. In this manner, starting from a similar radial distance of -49 km away from Deimos but increasing the initial out-of-plane relative velocity component υ_N to 4 m/s, it is feasible to achieve instantaneous inclinations of almost 65°. However, the simulations show that this orbit – denoted by “QSO-4” in Tab. 3 – would be stable only a little longer than 30 days. Thus, orbit correction maneuvers, albeit small in magnitude, might be necessary once a month to maintain the spacecraft in this orbit, which might pose additional challenges from satellite operations point of view. Interestingly, this orbit demonstrates a higher amplitude of the altitude variation as compared to QSO-3.

A similar inclination can be achieved in an even more distant orbit starting from radial distance of -69 km from Deimos. The orbit QSO-5 from Tab. 3 is characterized with a longer stability period (over 70 days), and the altitude varying between 55 km and 182 km.

Starting from the same radial distance, even higher inclination (over 70°) can apparently be achieved when increasing the initial out-of-plane relative velocity component to almost 8 m/s. Again, this orbit – QSO-6 in Tab. 3 – exhibits higher amplitude of altitude variation compared to the previous orbit starting from a similar (r_R, υ_T) pair, and is only stable for a little longer than one month.

While the orbits mentioned above represent only a few interesting samples that could be identified within this study, a much more extensive trade-off analysis will be required in a preliminary mission analysis to define one or more QSOs appropriate for a real mission taking into account all the major factors from mission science goals to adequate operational complexity.

Figure 2 illustrates some of the potentially interesting orbits from Tab. 3 in terms of the trajectory in the Deimos orbital RTN reference frame, the trajectory projections on the Deimos orbital plane and the cross-track plane. The corresponding ground-tracks are shown in the rightmost column of the plots color-coded with the instantaneous distance to the mean surface of Deimos. The simulation time period of 30 days was adopted for this illustration, and two stable orbits QSO-1 and QSO-3, and a somewhat less stable orbit QSO-6 were selected as they represent quite a wide range of possible inclinations. From the plots in Fig. 2, the dimensions of the orbits can be inferred, as well as the distribution of altitudes along the ground-track. It appears that not all the “longitudes” receive the same coverage of the “latitudes”. Thus, the covered “latitude” is at minimum at “longitudes” close to 90°, which correspond to the along-track direction of Deimos on its path around Mars. In combination with the generally higher altitudes in this regions of Deimos, the observations of the sides of Deimos facing the along-track direction (and the opposite) will be performed under less beneficial conditions, than the observations of the sides facing the radial direction. For the orbits QSO-3 and QSO-6 this is an obvious consequence of the general “ellipsoidal” shape of the epicycles with the “semi-major axis” extended along the tangential direction. This effect, however, is less noticeable for the closer QSO-1, where the distribution of the “latitude” coverage is more smooth, and the areas color-coded with high altitudes are “wandering” from north to south, which at some particular times allows observations at short distances of both the norther and southern areas of the sides facing the along-track direction and the opposite to it.

5. Phobos QSOs

To complement the results of the study on QSOs around Deimos, a similar phase space search was performed for the orbits around Phobos – the secondary mission target of DePhine. The trajectory search was conducted under the same baseline assumptions of beginning the trajectory on the negative radial axis with the non-zero υ_T and υ_N components of the relative velocity vector, at an epoch when Phobos is located at periapsis. Also, the same force model was applied including Mars gravity field of degree and order 20, solar radiation pressure, and the point-mass gravity field of Phobos.

Figure 3 shows the results of the (r_R, υ_T) phase space search for three different values of the initial out-of-plane relative velocity component υ_N. A similar behavior of the stability area can be observed as in the case of QSOs around Deimos, with the main difference that on the same interval of r_R, much higher υ_T values are required for the stability of the resulting trajectories. In the upper plots corresponding to the case of coplanar orbits, two sub-regions can be identified characterized by varying distribution of the allowed injection velocity errors in initial υ_T. The shape of the mean curve characterizing the stable area is in accordance with the result of Wiesel,[4)] including the two sub-regions separated at injection radius of about 28 km. As opposed to Deimos, no region of quasi-Keplerian motion exists around Phobos.[4)]

Regarding the feasibility of a global ground track coverage, the situation seems to be similar to the case of QSOs around Deimos. Thus, “latitudes” of up to 45° seem to be relatively easy to achieve, while orbits with even higher inclination are more rare and less stable. Additionally, as the stable region is shrinking with increasing initial υ_N, the requirement of the injection velocity accuracy in υ_T becomes more stringent.

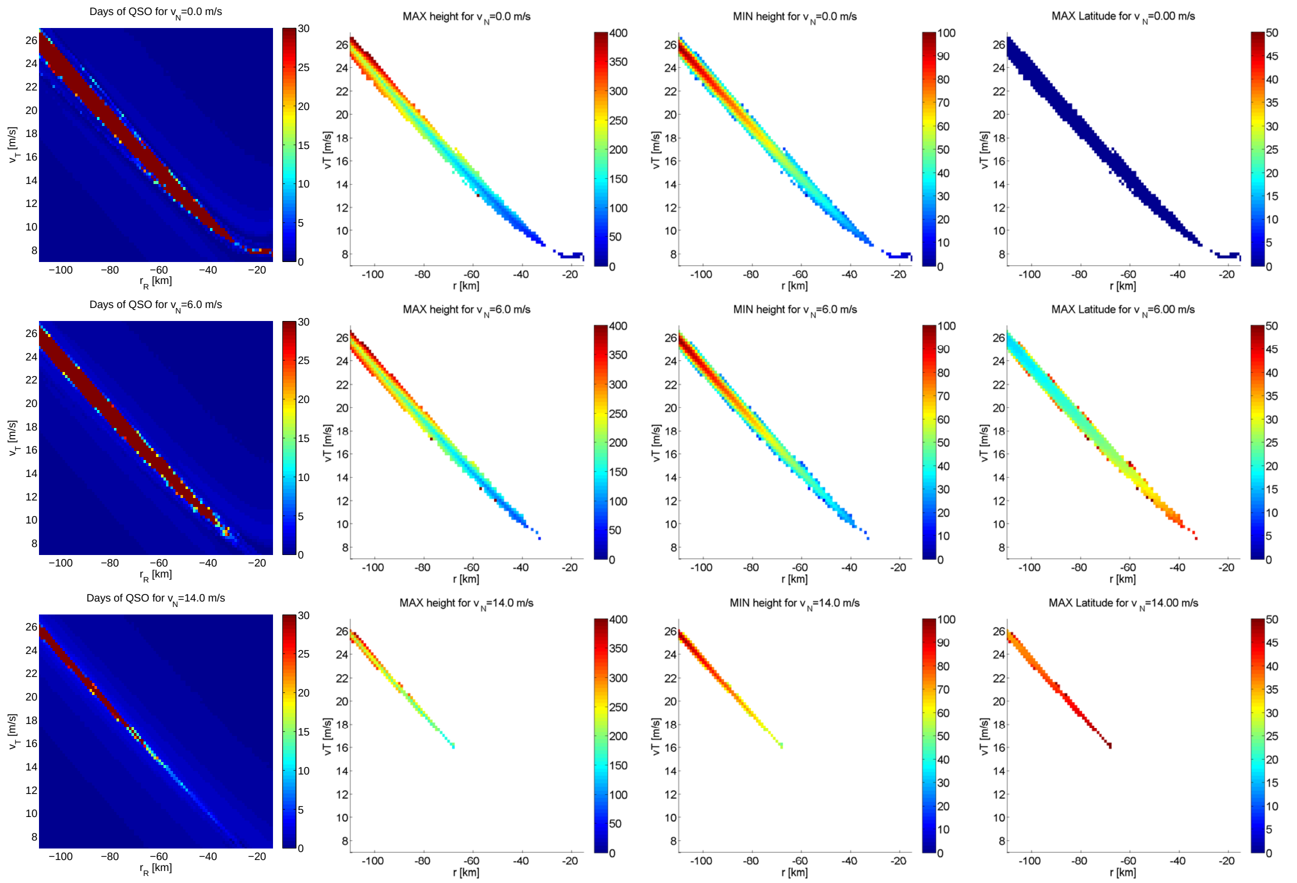

Fig. 3. 1st column: number of days of stability for QSOs around Phobos with initial conditions in the $r_R - v_T$ plane, and an increasing downwards out-of-plane initial relative velocity component v_N; 2nd column: maximum altitude [km] over mean surface of Phobos; 3rd column: minimum altitude [km] over mean surface of Phobos; 4th column: maximum achieved "latitude" [°]; simulation time interval: 30 days.

6. Conclusion

This paper presents the results of a numerical search for stable quasi-satellite orbits around Deimos and Phobos. This research was motivated by the DePhine mission proposal, and, in general, driven by the mission requirements. Thus, the feasibility of a global ground-track coverage from highly-inclined QSO was investigated. It was established, that inclinations of up to 40° are feasible in the vicinity of Deimos with injection radius of less than 20 km. An injection in such an orbit seems to be possible as the limits on the required velocity accuracy are relatively broad (in the order of 0.5 m/s). Orbits with higher ground-track coverage (inclinations up to 70°) might also be possible at the cost of a larger injection radius in the order of 50-70 km, however, reaching these orbits would require stringent injection velocity control, and more analysis will be needed to establish the practicability of placing a real spacecraft in such an orbit.

Similar findings were identified for QSOs around Phobos. Near-QSOs attaining "latitudes" of up to 30° seem to be feasible, assuming that the control of the injection velocity errors in the order of 0.2-0.3 m/s is possible. Higher inclinations appear to be reachable for larger injection radii with somewhat less tight injection velocity requirements.

For a preliminary assessment of QSOs around Deimos and Phobos motivated by the DePhine proposal, some strong assumptions were made to simplify the problem for the present study. A much more extensive analysis on the influence of the omitted factors (eccentricity of the moon's orbit, eccentricity of Mars orbit, moon's non-spherical gravity field and shape, etc.) will be needed when the mission enters the next project phase.

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