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# MARS-PHOBOS SYSTEM DYNAMICS EXPLOITATION FOR MARTIAN EFFECTIVE CONSTELLATIONS DESIGN

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**Abstract**

Interest in Mars has been increasing for many years, as witnessed by the numerous robotic missions flown so far. Missions' main objective is not only to perform intense studies of the Mars environment but also to prepare the framework to support next decades manned and robotic expeditions. As long as interplanetary missions are considered, ground operations represent a significant portion of the overall technical and financial effort of a space mission, since the Earth link is still the baseline to answer the navigation needs of a planetary probe. Moreover, Phobos is considered a site of interest as an outpost to lighten the required effort for future missions. To cope with multiple scientific and technical demands and facilitate lighter, cheaper, easier to operate planetary spacecraft implementation, a versatile local infrastructure which takes care of communication relay and navigation services in martian environment would be greatly beneficial. The paper proposes a distributed space infrastructure to offer the Martian environment continuous spatial and temporal coverage and takes advantage of the multi-body dynamics environment offered by Mars and its moons to effectively design a proper constellation. Quasi Satellite Orbits (QSO) are considered to maximize the Martian moon's coverage while lightening the station keeping demand. Indeed, stability regions are observed for defined ranges of distances with respect to the moon. QSOs give the satellites the possibility to hover the moon, even if its gravitational pull is too weak to allow closed canonical orbits. These trajectories seem to be promising to enhance the Martian moon's scientific observations. The constellation coverage is increased by coupling the QSOs with triangular point orbits, such as Tadpoles and Horseshoes to serve the Martian equatorial regions too with a continuous communication relay service. Moreover, Phobos' proximity to the red planet's surface guarantees a higher data-rate compared to higher-altitude trajectories (such as Areostationary orbits). The non-Keplerian dynamics is well suited for supporting the navigation service to users with no need for ground-based observations. Indeed, the asymmetry of the gravitational field avoids state reconstruction ambiguity when only relative measures are available: relative measurements are enough to reconstruct the absolute state of all satellites in the constellation, which is a mandatory functionality to offer the users a calibrated reference for navigation. The paper explores the topic of Martian constellation design, focusing on the possible orbital architectures, and studying the advantages and disadvantages in terms of navigation performance, constellation maintenance, and communication with Martian users.

## 1. Introduction

Mars has become an appealing destination over the last decade for robotic missions. More precisely, scientific missions have the aim to better characterize the Martian environment, to support future manned and robotic expeditions. However, a significant portion of the technical and financial effort is represented by the ground operations, since the Earth link is the baseline for communication and navigation porpoises. Moreover, the need for establishing a direct link with Earth adds the constraint on the system to have a more powerful and heavier communication subsystem. These issues can be avoided by the definition of a dedicated planetary infrastructure that works as a communication relay between martian users and Earth. This role is already played by the scientific satellites orbiting the planet [1, 2]. Although these satellites provide complete coverage of the Martian surface, the temporal distribution of the communication windows can be quite sparse, leading to long visibility gaps, especially for equatorial users. Constellation concepts have been studied in literature to guarantee continuous coverage for interest regions on the surface [3]. Anyway, to guarantee coverage of most regions, the satellites are typically located at high altitudes, leading to a drastic reduction of the communication data-rate when CCSDS protocols are respected [4]. This work aims to assess the effects of new constellation concepts based on multi-body trajectories, designed by exploiting both the attraction of Mars and its moons: Phobos and Deimos. Such a system would allow locating satellites at lower altitudes (such as Phobos'), increasing the data-rate while keeping reasonable continuity of the equatorial band coverage. Moreover, distributed architectures exploiting multi-body orbital regimes can self-calibrate the satellites positions by means of relative range measurements only [5, 6]. This increases the autonomy of the system, reducing the Earth visibility constraints on the system.

## 2. Constellation Design

The design of the constellation focuses on the selection of the most suitable trajectories and placement of the single agent, to improve the achievable performances. In particular, the present work explores two strategies, through single attractor (Mars) orbits, in a quasi-Keplerian dynamics context, and through multi-body environment orbits, leveraging the gravitational effect of the moons of the Martian system (Phobos and Deimos). Overall, three orbit types are explored:

- ◇ Trans-Areostationary Orbit (TASO) for the quasi-Keplerian strategy
- ◇ Quasi-Satellite Orbits (QSO) and Horseshoe Orbits (HS) for the multibody strategy

The *Trans-Areostationary Orbit* is a single-attractor (Mars) orbit, well approximated by the Keplerian dynamics. It is a circular trajectory, with a semi-major axis of $21\,000\,\mathrm{km}$, slightly above the *Areostationary*. This characteristics cause a relative shift of a spacecraft, on such orbit, with respect to Martian surface of about $15°$ per Martian sidereal day. Nevertheless, the preference of the Trans-Areostationary over the Areostationary orbit is justified by the improved stability when Mars's gravitational harmonics are considered. Two spacecrafts located in different points of the TASO, with their altitudes properly tuned with respect to the initial areographic longitude, can maintain a relative bounded motion thanks to the gravitational perturbations from Mars, without the need of any active station-keeping maneuver (as shown in Figure 1).

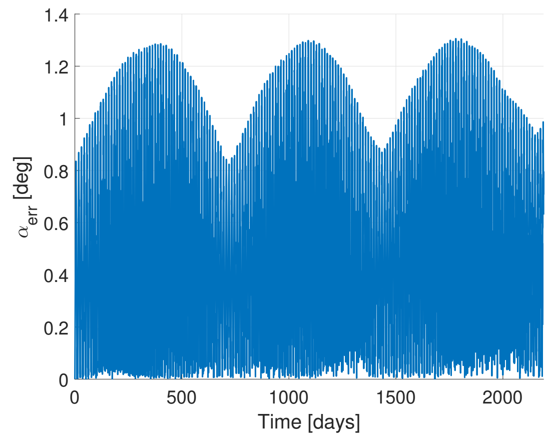
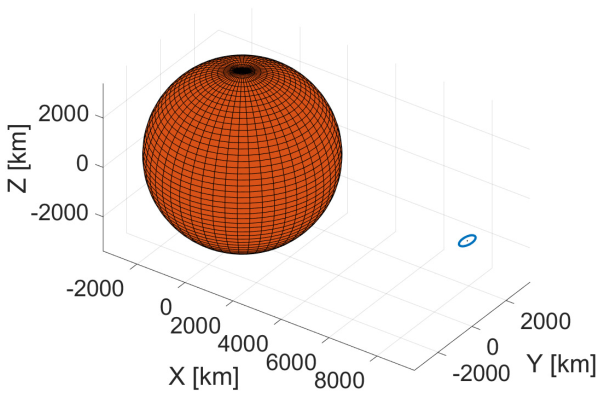



Fig. 1: Angle error between one spacecraft of the constellation, and its nominal location, exactly at $120°$ with respect to other spacecraft.

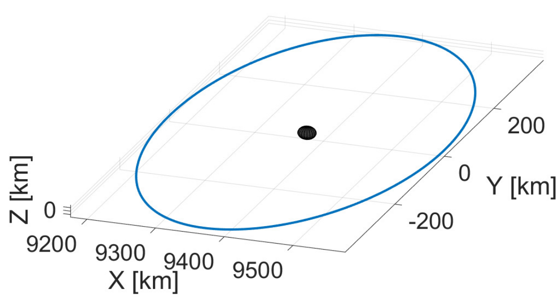
It has to be mentioned that the boundedness of the motion is strongly sensitive to errors in the initial altitude (as a function of the areographic longitude), therefore a high accuracy in the initialization of a TASO-based constellation is necessary.

The *Quasi-Satellite Orbits* [7, 8, 9, 10] are generated from the simultaneous gravitational attraction of Mars and one of its moons, and are developed in the context of the *Circular Restricted Three-Body Problem* (CRTBP). Figure 2 depicts a QSO around Phobos. The QSO are characterized by a stable, retrograde motion with respect to the moon's orbit. Because of this, a spacecraft on a QSO displays a motion, with respect to Martian surface, which is closely comparable to the one of the moon itself. Furthermore, such orbits may be also leveraged to add scientific return to the constellation through the observation of moon's surface. Although generated in a simplified dynamics model, QSO provide excellent stability properties (within some distance range from the reference moon) which prevent the spacecraft from drifting away, as shown in Figure 3. Hence, as a first approximation, no active station-keeping is foreseen for this type of orbit.

The *Horseshoe Orbits* [11] share similar orbital parameters as the reference moon, but display a small variation in the semi-major axis, so that the spacecraft encounters the moon periodically. The moon flybys cause a relative acceleration and deceleration, which make the spacecraft move back and forth along the orbit, describing a trajectory as the one depicted in Figure 4. The propagation in the high-fidelity dynamics highlights higher frequency oscillations, which however do not dramatically affect the

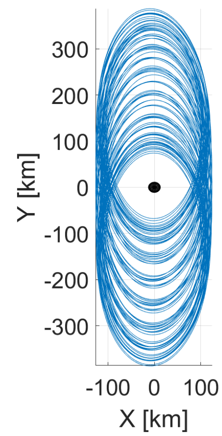



(a) Full Mars-Phobos system representation

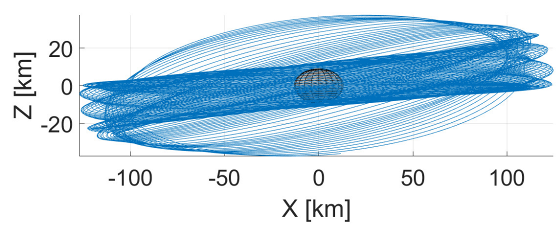



(b) Orbit detail (Phobos surroundings)

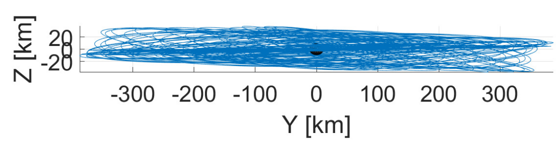
Fig. 2: Quasi Satellite Orbit around Phobos, in the CRTBP model




(a) X-Y view

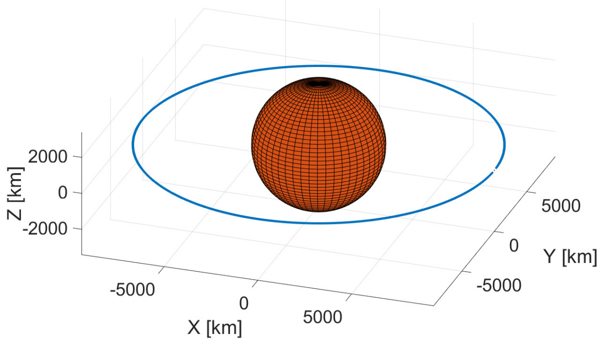



(b) X-Z view

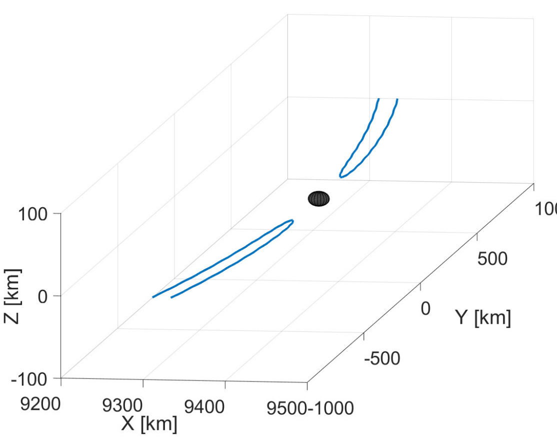



(c) Y-Z view

Fig. 3: Quasi Satellite Orbit (40 days propagation in high-fidelity model)




(a) Full Mars-Phobos system representation




(b) Orbit detail (Phobos surroundings)

Fig. 4: Horseshoe Orbit around Phobos, in the CRTBP model

properties of the orbit, nor its stability, as shown in Figure 5. It is important, for the design of the constellation, to

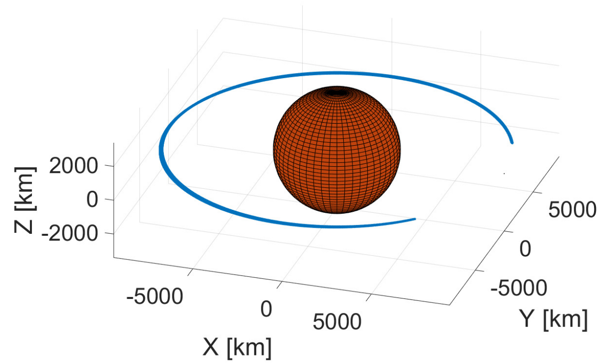



Fig. 5: Horseshoe Orbit around Phobos (6 years propagation in high-fidelity model)

keep a proper separation between the spacecrafts. In case one of the agents is placed around the moon (on a QSO), the satellite on the HS shall perform periodic maneuvers not to approach the moon. Nevertheless, HS around Martian moons show a very low-paced drift, and may need only few maneuvers, depending also on the maximum drift allowed.

The three trajectories are exploited to build different constellation architecture, with different numbers of agents:

- ◇ TASO constellation (3 satellites, $120°$ shifted)
- ◇ QSO+HS constellation (around Phobos or Deimos)
  - 2 satellites at $0°$ (QSO), and $180°$ (HS)
  - 3 satellites at $0°$ (QSO), $120°$ (HS), and $240°$ (HS)

Among the explored configurations, the TASO constellation represents the most balanced option. Being the TASO nearly synchronous with Martian surface, it does not consent a large surface coverage from a single spacecraft point of view. To provide a full coverage, at least at the equator, multiple agents must be dispatched along the orbit. Given the TASO altitude of about $17\,600\,\mathrm{km}$, a good coverage can be achieved through 3 satellites equally spaced along the trajectory (at $120°$ angular displacement among each other). Also, such distance consent to achieve moderate data rate and volume with users on Mars's surface.

The QSO+HS constellation around Phobos is characterized by a shorter distance from the surface ($\sim 5990\,\mathrm{km}$), which enables higher data rates with respect to the TASO scenario. The spacecraft revolve around Mars in $7\,\mathrm{h}\,40\,\mathrm{min}$ approximately, therefore a single agent performs multiple passages above the equatorial region within a Martian day. This enables to adopt a 2-satellite constellation (one on the QSO, and one on the HS, shifted of $180°$) with an increase of data-volume and reasonable visibility windows temporal distribution. Nevertheless, 3-satellite constellation is still studied to achieve continuous equatorial band coverage.

The QSO+HS constellation around Deimos displays opposite performances with respect to the Phobos case. Deimos's orbit is higher than the TASO of about $2460\,\mathrm{km}$ and has a period of approximately $30\,\mathrm{h}$; however, the difference from TASO is moderate, and similar performances are expected. In particular, slightly lower data rates, and larger covered surfaces are foreseen for the Deimos constellation. As for TASO scenario, 3-satellite constellation appears to be the best option, but a 2-satellite constellation will be analyzed for sake of completeness.

## 3. Transfer strategies

The transfer strategy takes into account different departure possibilities in order to try to reduce the cost of the launch itself. In particular, the departure strategies analyzed allow the possibility to share the launch with other spacecrafts, reducing the costs.

### *3.1 Interplanetary trajectory*

The interplanetary trajectory is designed following the patched conics approach, and considering impulsive manoeuvres only. In order to take the Gravity Losses into account, dedicated Finite Thrust analysis have been performed for the escape and capture phases. In order to be compliant with the ECSS requirement [12], a minimum launch windows of 21 days was considered. Figure 6 and Figure 7 show respectively the $C3$ and the asymptote declination at the Earth departure and Mars arrival.

### *3.2 Earth departure*

In this phase the spacecraft shall escape from earth gravity field, matching the boundary conditions (mainly C3 and asymptote declination) required by the interplanetary trajectory. Different strategies have been considered:

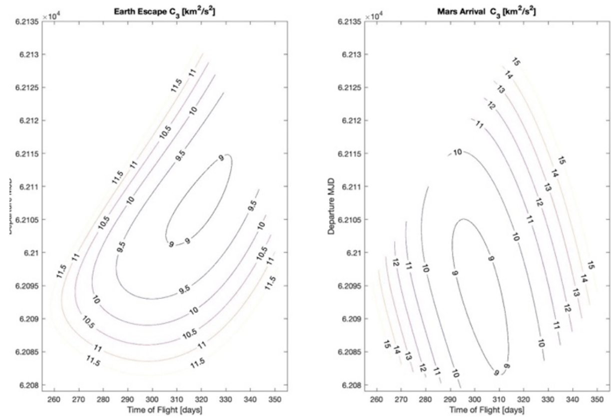


Fig. 6: $C3$ at Earth departure and Mars Arrival

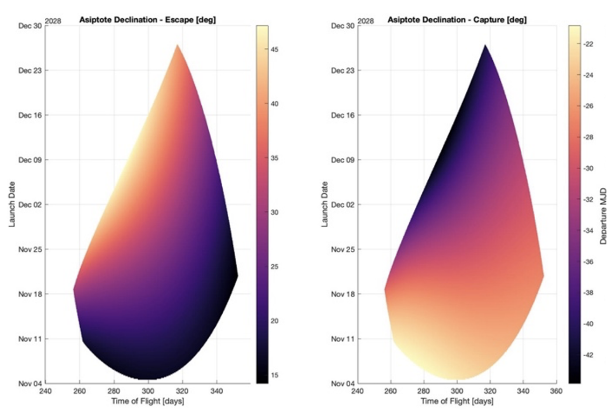


Fig. 7: Asymptote declination at Earth departure and Mars Arrival

- ◇ **Direct Hyperbolic Escape:** Represents the easiest way to reach Mars, in which the launcher injects the spacecraft directly in the correct escape trajectory. The spacecraft shall perform only small correction manoeuvres, therefore the nominal $\Delta V$ for this strategy is close to zero. The drawback is that the cost of the launch is higher and the launchable mass is significantly lower with respect to the other scenarios.
- ◇ **HEO departure:** In this strategy the spacecraft is injected by the launcher in a High Elliptical Orbit (900000km x 250km) around Earth with a 6° inclination. The spacecraft shall perform a change plane (that, due to the altitude of the apocenter, is cheap) and a pericentre manoeuvre to reach the desired energy.
- ◇ **GTO departure – unconstrained perigee:** Represents the most flexible strategy, since launches in the GTO orbits are extremely frequent and are cheaper with respect to HEO and Direct escape launches. Moreover, the possibility to find a shared launch is high. Unfortunately, the departure cost from this orbit is quite elevate, even if a three manoeuvres strategy is applied (basically an intermediate HEO orbit is

reached to reduce the cost of the plane change). In this scenario, the Local Time of the perigee is free.

- ◇ **GTO departure – Local Time of perigee constrained:** This scenario is similar to the previous one, but the Local Time of the perigee is forced to be midnight in order to increase the possibility to have a shared launch.
- ◇ **GTO departure with Moon-Earth Gravity Assists:** This strategy mitigates some drawbacks of the GTO departure. It includes a Gravity Assist of the Moon to perform naturally the change of plane (and partially to increase the energy). The drawback is an increased complexity for the operations and the necessity to wait on the GTO until a correct phasing with the Moon is reached.

### *3.3 Mars capture*

The spacecraft shall close the trajectory around Mars and reach the correct operational orbit, matching the boundary conditions (mainly C3 and asymptote declination) required by the interplanetary trajectory. The adopted approach is identical for all the Martian scenarios: a three burn strategy to close the orbit at the desired altitude and on the correct plane. The possibility to include aerobraking was initially considered, but finally discharged due to the increase in the complexity of the operations.

### *3.4 Transfer cost summary*

Table 1 shows the summary of the whole $\Delta V$ for the interplanetary transfer, including Margins and Gravity losses as in the ECSS [12]. To find the optimal trade-off between the cost of the launch and the $\Delta V$ budget, a launch in HEO orbit was selected as baseline.

| **Scenario** | **GTO** | **GTO con.** | **GTO + GA** | **HEO** | **Direct** |
|---|---|---|---|---|---|
| **TASO** | 3,372 | 3,854 | 3,494 | 2,561 | 1,810 |
| **Phobos** | 3,655 | 4.137 | 3.777 | 2.844 | 2,093 |
| **Deimos** | 3,351 | 3,833 | 3,473 | 2,54 | 1,789 |

Table 1: $\Delta V$ summary for the orbital transfer [km/s]

## 4. Constellation performances

In this section, the main results in terms of data-rate, coverage and $\Delta V$ budget are reported for all the previously mentioned constellation architectures.

### *4.1 Data-rate and coverage*

For Deimos architectures, the results are reported in Table 2, compared to TASO.

| Architecture | $t_W$ | $t_V$ | $t_G$ | $D$ |
|---|---|---|---|---|
| *TASO* | | | | |
| 3 sat | 24h | 24h | 0h | 259.2 Mb/day |
| *Deimos* | | | | |
| 2 sat | 33h | 33h | 33h | 86.4 Mb/day |
| 3 sat | 33h | 33h | 9h | 204.12 Mb/day |

Table 2: Deimos architectures performances compared to TASO.

The results are computed for a test user at the equator. $t_W$ is the duration of a single communication window between the user and the satellite. $t_V$ is the visibility time per day, that can be seen as the sum of the single user-satellite windows' duration. The visibility gap $t_G$ is instead the amount of time between two consecutive visibility windows. As can be seen, the visibility window for a single satellite located in a QSO or HS orbit in the Mars-Deimos environment lasts up to $33h$. Indeed, Deimos' altitude is close to the TASO range, leading to a slow relative drift with respect to Mars surface. This is also the reason behind the long duration of the gap between two successive windows ($33h$ for the 2 satellite configuration and $9h$ for the 3 satellites). The increase of the distance between the user and satellite leads to a reduction of the data-volume $D$ with respect to TASO (up to $204.12$ Mb/day for the 3 satellites configuration versus $259.2$ Mb/day for TASO), as expected by the data-rate reduction.

Analogously, the performances of Mars Phobos architectures are reported in Table 3.

| Architecture | $t_W$ | $t_V$ | $t_G$ | $D$ |
|---|---|---|---|---|
| *TASO* | | | | |
| 3 sat | 24h | 24h | 0h | 259.2 Mb/day |
| *Phobos* | | | | |
| 2 sat | 4h | 20h | 1h-6h | 628 Mb/day |
| 3 sat | 4h | 24h | 0h | 942 Mb/day |

Table 3: Phobos architectures performances compared to TASO.

For Phobos architectures, the window duration $t_W$ is reduced to 4h. Anyway, the relative drift of the satellite with respect to the surface is increased with respect to TASO due to the lower altitude of Phobos orbit. This leads to a higher frequency of the windows, reducing the gap duration $t_G$ up to 1h to 6h, depending on the position of the satellite on the HS trajectories. Hence, using two satellites it is possible to reach 20h of visibility per day, that increases to 24h in the 3 satellites configuration. The increase of visibility time and data-rate leads to an increase of the daily data-volume $D$ with respect to TASO, up to 942 Mb/day for the 3 satellites configuration.

For these last configurations, the data-rate over time is reported in Figure 8 and Figure 9.

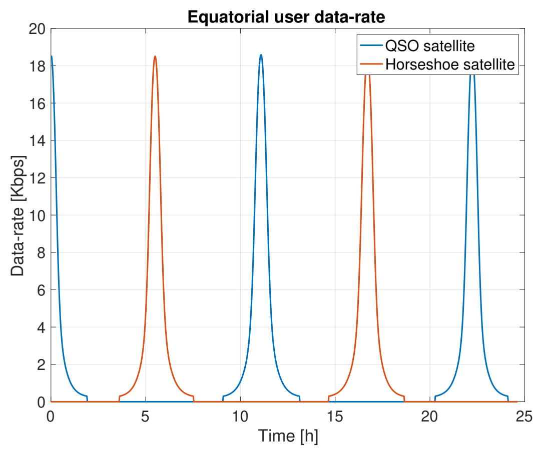



Fig. 8: Data-rate evolution for the Mars-Phobos 2 satellites architecture, considering an equatorial user.

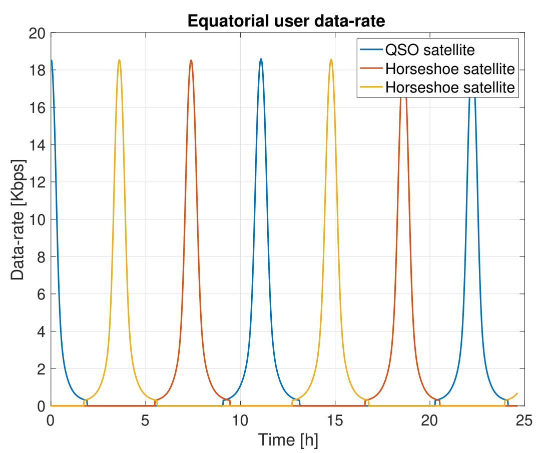



Fig. 9: Data-rate evolution for the Mars-Phobos 3 satellites architecture, considering an equatorial user.

For the 2 satellites configuration it can be seen that the data-rate over time spans 2.5 windows of 4h duration per satellite. The gap between the windows can be adjusted by changing the control strategy of the HS satellite. For the 3 satellites configuration the visibility windows overlap, leading to a 0h gap and a continuous coverage of the equatorial band.

Regarding the performance for higher latitude users, the maximum data-rate achievable depending on the user latitude is reported in Figure 10.

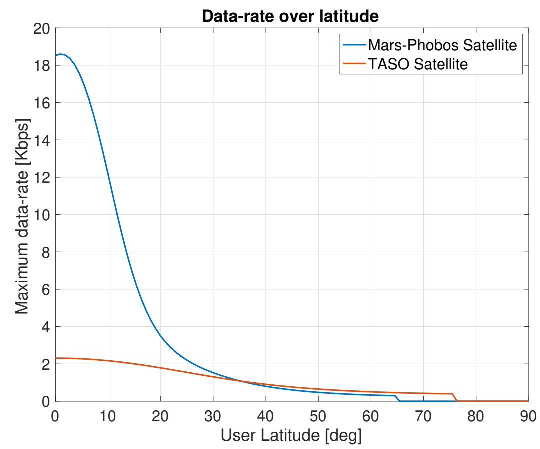



Fig. 10: Maximum data-rate of the satellite-user link depending on the user latitude.

As expected, the maximum data-rate achievable is reached at the equatorial region, decreasing when the user latitude increases. The maximum data-rate reached is higher for the Mars-Phobos architecture with respect to TASO satellites, and reaches similar values for latitudes higher than 35°. Moreover, the maximum latitude reachable is higher for the Mars-Phobos architecture (up to 76°) with respect to TASO satellites (65° maximum).

To compute the data-rate, a dynamical link budget analysis has been performed taking into account the user-satellite distance and standard hardware parameters compatible with Elektra-Lite communication protocols [13] on a small-satellite class. A summary of all the parameters used is reported in Table 4.

### *4.2 $\Delta V$ budget*

In Table 5, the phasing and station keeping $\Delta V$ are reported for the single satellites composing the different architectures. Phasing maneuvers are computed as bi-impulsive transfers to reach the correct relative angle from one of the spacecraft of the constellation. For this reason, such cost is evaluated for two satellites only, in the 3 satellites constellations, and for a single satellite in the 2 satellites constellation. Station keeping cost apply to HS and TASO only, as QSO show a stable motion. In

| Parameter | Unit | Value |
|---|---|---|
| Frequency | MHz | 400 |
| Tx Power | W | 4 |
| Tx Antenna Gain | dBi | -3.15 |
| Tx Losses | dB | 1 |
| Atmosphere Losses | dB | 5 |
| Rx Polarization Losses | dB | 0.8 |
| Rx G/T | dBK | -25.23 |
| Demodulation Losses | dB | 1 |
| Modulation Losses | dB | 0 |
| Minimum $E_b/N_0$ margin | dB | 3 |

Table 4: Link budget hardware parameters.

particular, bi-impulsive maneuvers are introduced after a phase error threshold is reached: for TASO and Deimos constellations, the nearly stationary motion with respect to Mars's surface imposes a narrow error range, and $\pm 2°$ are considered as trigger value for the maneuver; vice versa, frequent passages of the Phobos constellation allow a looser constraint, hence a relative drift of $\pm 10°$ is considered.

| | $\alpha$ | $\Delta V_{PH}$ | $\Delta V_{SK}$ | $\Delta V_{TOT}$ |
|---|---|---|---|---|
| TASO | 120°/240° | 21.2 m/s | 0 m/s | 21.2 m/s |
| *Phobos* | | | | |
| QSO | 0° | 0 m/s | 0 m/s | 0m/s |
| HS | 120°/240° | 15 m/s | 4 m/s | 19 m/s |
| | 180° | 17.5 m/s | 4 m/s | 21.5 m/s |
| *Deimos* | | | | |
| QSO | 0° | 0 m/s | 0 m/s | 0m/s |
| HS | 120°/240° | 22.6 m/s | 25.8 m/s | 48.4 m/s |
| | 180° | 28.8 m/s | 25.8 m/s | 54.6 m/s |

Table 5: $\Delta V$ budget for phasing and station keeping for the single satellites.

$\alpha$ is the target phase angle, $\Delta V_{PH}$ is the phasing maneuver cost, $\Delta V_{SK}$ is the one related to station keeping and $\Delta V_{TOT}$ is the total needed to reach and maintain the corresponding orbit. The budget is computed by considering a mission operative phase of six years.

In Table 6, the total $\Delta V$ budget is reported, for all the configurations, comprehending the transfer cost to reach the desired altitude, reported in Table 1.

Note that the selected transfer strategy is HEO, and the $\Delta V_{CONST}$ is obtained by multiplying the values reported in Table 5 by the number of satellites of the constellation, considering that the arrival is performed at phase $\alpha = 0°$.

| | $\Delta V_{TR}$ | $\Delta V_{CONST}$ |
|---|---|---|
| TASO | 2.561 km/s | 42.4 m/s |
| *Phobos* | | |
| 2 satellites | 2.844 km/s | 21.5 m/s |
| 3 satellites | 2.844 km/s | 38 m/s |
| *Deimos* | | |
| 2 satellites | 2.844 km/s | 54.6 m/s |
| 3 satellites | 2.54 km/s | 96.8 m/s |

Table 6: $\Delta V$ budget for constellation architecture and transfer.

## 5. Conclusions

Concluding, three main results can be extracted by the performed analyses:

- The station keeping and phasing $\Delta V$ required is the lowest for Phobos architectures and increases when moving to TASO and Deimos constellations; however, TASO and Deimos constellations provide lower insertion cost. Hence, less propellant mass budget is needed by single spacecrafts in the Phobos architectures, while the propellant needed for possible carrying modules increases;
- The visibility windows for a single satellite of the Phobos constellation are shorter (4h) with respect to TASO, due to lower distance. They are longer for Deimos satellites (33h), but with a drastic increase of duration of the gap between to consecutive windows (up to 33h). Moreover, it is not possible to achieve continuous visibility for Deimos architectures, while it can be done with TASO and Phobos 3 satellites;
- Although visibility is reduced, higher data-volume is obtained by Phobos architectures (up to 942Mb versus 259.2Mb of TASO) and lower for Deimos (up to 204.12Mb), due to data-rate variations.

Depending on the mission constraints (cost, required data-volume and visibility) Phobos and TASO architectures are both suitable options for a communication constellation. However, Deimos architectures revealed to be an inconvenient solution for all the aspects.

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