OPTIMISATION OF THE FUTURE ROUTINE ORBIT FOR MARS EXPRESS

Manuel Carranza
GMV S.A. at ESA/ESOC, OPS-GFI
E-mail: Manuel.Carranza@esa.int

Vicente Companys
ESA/ESOC, OPS-GFI
E-mail: Vicente.Companys@esa.int

ABSTRACT

Mars Express (MEX), the first planetary mission of the European Space Agency (ESA), reached Mars on December 25th 2003. Since then it is performing routine operations. Its operational phase had to cover one Martian year, with the possibility of an extension for a second Martian year (i.e. until November 2007).

The end of the mission extension is approaching but, given the good health of the payload instruments and the high science return of the mission, there is a strong will to achieve further extensions. Mars Express is also seen as an important asset, capable to provide relay functions for future Martian missions. The ESA Science Program Committee has recently approved a second extension of the MEX mission until May 2009 and even further extensions are possible.

Mars Express has an eccentric quasi-polar orbit with a period of approximately 6.72 hours and a pericentre height of about 300 km. Science observations are mainly performed at pericentre (but not only). In addition the orbit has a resonance of 11 revolutions per 3 Martian days. This means that ground tracks corresponding to orbits separated by 11 revolutions are adjacent, such that a given area can be covered by the on-board camera without leaving gaps.

The J2 effect of Mars causes a drift of both ascending node and argument of pericentre. The drift of argument of pericentre makes it possible to observe periodically all Mars latitudes from close distance. Illumination conditions at pericentre are influenced by both the drift of the argument of pericentre and the drift of ascending node, as well as by the rotation of Mars around the Sun.

The original MEX routine orbit was optimised for the duration of the nominal mission and extension, such that it produced a balanced share of day-side observations (for the optical instruments) and night-side observations (for the radar). The orbit was thus not optimised for the time beyond the assumed extension. Indeed, the evolution of the ascending node and argument of pericentre would cause in the following years a drift of the pericentre towards night-side observation conditions, hence uninteresting for the optical instruments.

In order to prevent this an optimisation process for the future routine orbit has taken place. The share between day-side and night-side observations can be controlled by adjusting the drift of argument of pericentre and ascending node.

This can in particular be achieved by changing the semi-major axis, eccentricity and/or inclination. A change of inclination is inefficient compared to a change in semi-major axis and eccentricity, and has therefore been discarded. An in-plane manoeuvre can be performed to change both semi-major axis and eccentricity, and thus the period of the orbit. Although an apocentre manoeuvre is cheaper in terms of ΔV, it would result in raising the pericentre height, which is unfavourable for close observations. Hence a pericentre manoeuvre is proposed, which will increase the apocentre height.

A repeat cycle is still required to allow mapping areas with adjacent ground tracks, so the change of semi-major axis must result in a new resonance. Resonances 18:5, 25:7 and 7:2 have been considered as potential candidates. The resulting long term evolution of the observation conditions has been analysed. Finally it has been decided to perform a change of orbit to reach the 18:5.

Another aspect of the optimisation process is the control of the ground track. The previous MEX reference trajectory included regular manoeuvres at every apocentre in order to adjust the orbital period, such that the separation of the ground tracks would be optimal, regardless of the latitude of pericentre. The implementation of the actual ΔVs on-board was done partly by optimising the attitude of reaction-wheel desaturation activities. Despite of it, this strategy has a significant propellant cost, because it prevents to

optimise reaction wheel de-saturation activities to minimize propellant consumption. Therefore, with the aim at preserving propellant resources for a long time extension it has been agreed to stop the ground-track control. This requires now a more accurate science operation planning, with improved attitude pointing control.

Finally, the approach to phase Mars Express to provide back-up relay functions for NASA Phoenix landing is explained.

In the context of the routine trajectory optimisation a new requirement for close fly-bys at Phobos, with different observation geometries, has been specified. The approach to fulfil this requirement is explained below.

1. MARS EXPRESS OPERATIONAL ORBIT CONCEPT

Mars Express was launched on June 2nd 2003 from Baikonur Cosmodrome in Kazakhstan on board a Soyuz-Fregat rocket. It arrived at Mars on December 25th 2003 and is performing routine operations since then.

The operational orbit of Mars Express has an average pericentre radius of 3,700 km, an apocentre radius of 13,500 km and an inclination of 86.7 deg. Science observations are mainly concentrated at the pericentre, the upper parts of the orbit being dedicated normally to communications.

Due to the effect of the flattening of Mars, the argument of pericentre drifts such that the pericentre flies over all northern and southern latitudes periodically. Also the ascending node changes due to the effect of the flattening of Mars. Figure 1 shows the evolution of the argument of pericentre.

Equations [EQ1] and [EQ2] show the dependency of the variation of argument of pericentre and right ascension of ascending node as functions of the orbital period, the orbit parameter and the inclination.

$$\dot{\omega} = \frac{3}{2} \cdot \frac{\pi}{T} \cdot J_2 \cdot \left(\frac{R_M}{p}\right)^2 \cdot \left[4 - 5 \cdot \sin^2(i)\right] \approx -\frac{2\pi}{574 \text{ days}} \qquad \text{[EQ1]}$$

$$\dot{\Omega} = -3 \cdot \frac{\pi}{T} \cdot J_2 \cdot \left(\frac{R_M}{p}\right)^2 \cdot \cos(i) \approx -\frac{2\pi}{5032 \text{ days}} \qquad \text{[EQ2]}$$

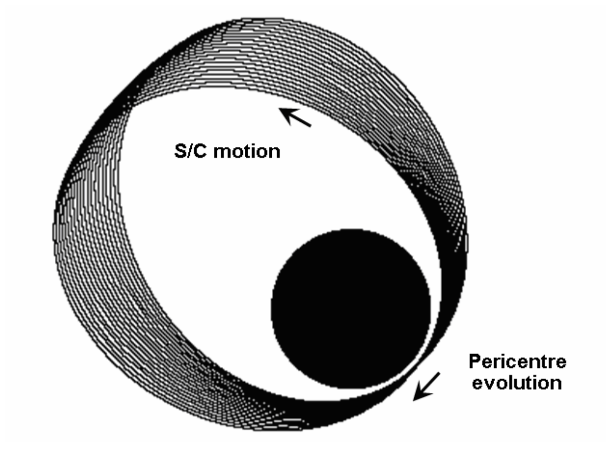

Figure 1: Evolution of the argument of pericentre.

The orbital period of Mars Express was selected to produce a repetition cycle of the ground-track. In particular, after eleven revolutions of the S/C, which corresponds to three rotations of Mars around its rotation axis, the S/C returns to the same original longitude, but with a small shift.

The main optical instruments of MEX work like line scanners, with the line perpendicular to the ground-track direction. Hence, by observing during consecutive passages through a longitude, the global mapping of an area of the surface can be achieved.

Figure 2 gives an overview of the scheme for ground-track repetition. The ground-track around pericentre of eleven consecutive revolutions is shown, during which the S/C visits eleven different longitudes. At the twelfth revolution (and following by multiples of eleven), the S/C returns to the original longitude slightly shifted, such that the spacing of the tracks is ideal for camera imaging. It can be appreciated that the adjacent ground tracks drift towards the West. It is also visible the drift of the argument of pericentre, which in this particular example shifts the pericentre towards the South Pole.

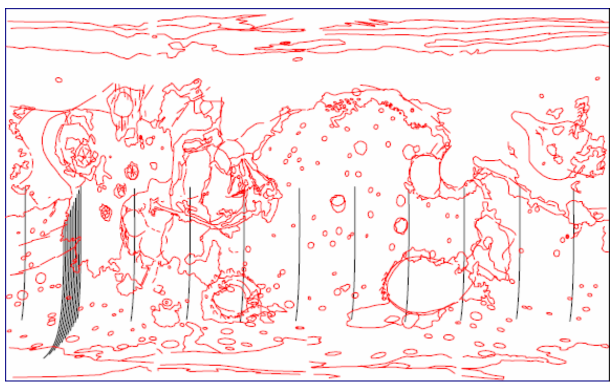

Figure 2: Ground track repetition pattern. Eleven different regions of Mars can be observed.

2. ORBIT LONG TERM EVOLUTION

As given by [EQ1] the pericentre of Mars Express performs a full revolution around Mars within 574 days approximately.

As given by [EQ2] the ascending node of Mars Express performs a full revolution around the Mars polar axis within 5032 days approximately.

Mars performs a revolution around the Sun in 687 days, (or alternatively, seen from Mars, the Sun performs a full revolution around Mars in 687 days).

Approximately each orbital revolution of Mars, the Sun crosses twice the Mars Express orbital plane (once around ascending node and once at descending node). Due to the regression of the Mars Express orbit node, the period between two crosses of the orbital plane by the Sun on the side of the ascending node is not exactly the period of Mars around the Sun, but smaller. For the current node regression of Mars Express this period (which we call period of the Sun around the Mars Express orbital plane) is around 606 days.

The orientation of the Sun with respect to the orbital plane drives the illumination conditions for science operations. For instance, if the Sun direction is close to the pericentre direction, the pericentre areas are illuminated by Sun light and optical measurements are possible. In the reverse case, if the Sun direction is far from pericentre, the pericentre areas are dark, and radar observations can be performed.

If the period of the argument of pericentre and the period of the Sun around the orbital plane were the same, the illumination conditions would just evolve periodically. E.g. the illumination conditions at pericentre would evolve periodically, following the periodical evolution of the pericentre latitude.

As these two periods are quite similar, the resulting illumination conditions do not stay periodic, but rather vary slowly.

The original orbital parameters of the Mars Express operational orbit were selected to produce a balanced share between day-side observations (for optical instruments) and night-side observations (for the radar) at pericentre. This share was optimised for the duration of the nominal mission plus the first mission extension, up to November 2007.

Due to the good performance of the S/C and the instruments, and due to the sustained interest on continuing science operations, the Mars Express mission has got a second extension (until May 2009), and it is very likely that further extensions will follow.

However, with the current orbit the share between day-side and night-side observations gets more and more biased towards the night side. End of 2009 the S/C will enter a long season in which no day-side observations at all will be possible at pericentre. To illustrate this, Figure 3 shows the evolution of the Sun elevation for the sub-satellite point at pericentre.

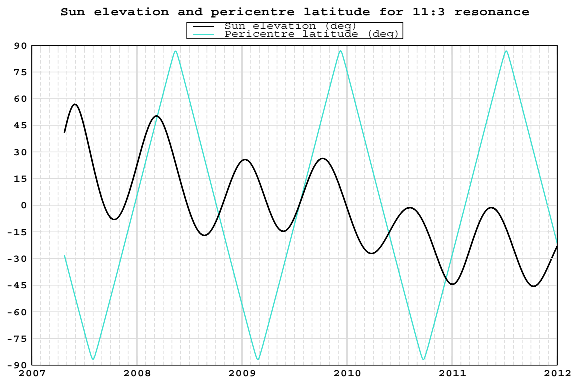

Figure 3: Sun elevation at pericentre for 11:3 resonance.

3. FUTURE ORBIT STRATEGIES

With the characteristics of the current orbit shown before, it is clear that beyond 2009 there will be no possibility for optical instruments observations for a long period. This is not acceptable if the mission is extended beyond 2009 (or, in other words, the mission will not be extended under these conditions).

It is possible to slow down the trend of the pericentre to night side by changing the orbit characteristics. In simple words, the aim is to achieve a period of the argument of pericentre closer to the period of the Sun around the orbital plane. I.e. the drift of the argument of pericentre shown in [EQ1] has to become smaller.

This can be done either by an in-plane manoeuvre essentially increasing the period and the parameter of the orbit, or by an out-of-plane manoeuvre decreasing the inclination. The first option is more efficient in terms of fuel consumption. Inclination change manoeuvres can only be implemented efficiently when the apocentre crosses the equator. Anyway, the effect achieved by an in-plane manoeuvre is stronger than that of an inclination manoeuvre of the same size. Therefore, only in-plane manoeuvres are considered.

In-plane manoeuvres can be performed at any true anomaly. It can be seen that the effect achieved by a manoeuvre performed at apocentre is largest (for a given size of manoeuvre). However, this raises the pericentre altitude, which is undesirable as it has an adverse impact in the resolution of the optical instruments.

Hence the selected approach to slow down the trend of the pericentre towards the night side is to perform a manoeuvre at pericentre in the direction of the velocity, thus increasing the period of the orbit.

An important requirement of the future orbit is to achieve a repeat cycle in order to allow mapping areas of the Martian surface with adjacent ground tracks (i.e. repeat of ground track after a certain number of revolutions). For the current orbit this corresponds to a resonance 11:3 (i.e. 11 orbital revolutions for 3 Mars revolutions). The manoeuvre aimed at changing the evolution of the illumination conditions shall hence achieve a resonance between the orbit period and the Mars rotation. Several resonances close to the current 11:3 have been analyzed as potential candidates for the resulting target orbit, namely resonances 18:5, 25:7 and 7:2, which are summarized in Table 1.

Target Resonance	Orbits per Mars revolution	Orbital period (hours)	ΔV Pericentre (m/s)
11:3	3.666	6.72	-
18:5	3.600	6.84	7.06
25:7	3.571	6.90	10.05
7:2	3.500	7.04	18.16

Table 1: Comparison of target resonances.

The target resonances are ordered by increasing orbital period. It is obvious that the bigger the target period, the more expensive the manoeuvre at pericentre necessary to change the orbit, but also the stronger the effect of improving the day side observation conditions of the target orbit.

It is also obvious that the earlier the change of orbit is done, the earlier the drift towards the night side is slowed down and thus the better the future observation conditions for day-side instruments.

For comparison purposes a manoeuvre was assumed in April 2007 (actual change of orbit is currently delayed to November/December 2007). The 7:2 resonance would allow having good illumination conditions at pericentre for most of the mission duration up to end 2011. The 25:7 resonance would have a balanced share between day-side and night-side observations, thus allowing observations of both the optical instruments and the MARSIS radar. The lesser effect is obtained with the 18:5 resonance, for which there is still a significant bias towards night observations.

Table 2 summarizes the number of days per year with the Sun above the local horizon of the sub-satellite point for all the cases considered. The maximum and minimum elevations for 2010 and 2011 are also shown.

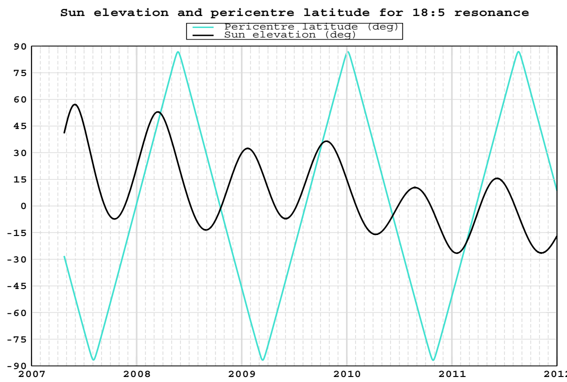

Figure 4: Sun elevation at pericentre for 18:5 resonance.

Figure 4 shows the evolution of the Sun elevation for the sub-satellite point at pericentre for the 18:5 resonance. In this case, the illumination conditions are much better than for the original 11:3 resonance, but rather worse than for resonances 25:7 and 7:2.

A change of orbit to one of the aforementioned resonances has an impact not only on the observation conditions and the remaining fuel available for operations, but also on the duration of the eclipses. These are most critical when Mars is at its aphelion, as the batteries on board Mars Express have less time to recharge. Besides, both batteries and solar panels degrade with time, so future eclipse seasons become more and more critical. Figure 5 illustrates the duration of the eclipse seasons up to end 2011 for the current

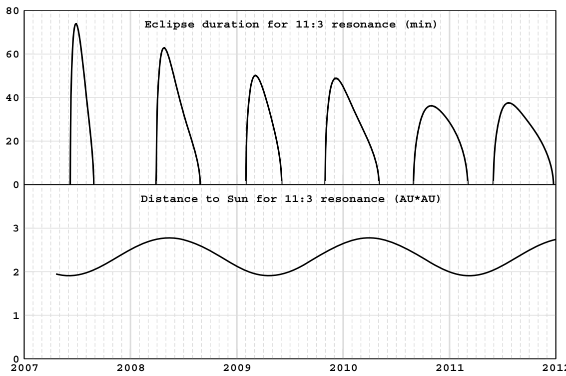

Figure 5: Eclipse duration vs. distance to Sun for 11:3 resonance

Target resonance	11:3		18:5		25:7		7:2	
Year	2010	2011	2010	2011	2010	2011	2010	2011
Days with Sun above horizon	0	0	120	100	191	152	319	279
Max. elevation (deg)	-1.3	-1.3	10.4	15.6	21.8	22.6	39.8	42.8
Min. elevation (deg)	-44.6	-45.7	-25.1	-26.6	-16.9	-19.9	-1.7	-2.8

Table 2: Number of days per year with the Sun above the local horizon of the sub-satellite point for resonances 11:3, 18:5, 25:7 and

The eclipse season from April to August 2008 is of particular importance, because Mars will be at its aphelion. The maximum duration of the eclipses is around 63 minutes for this season. The eclipse season from November 2009 to April 2010 also takes place at Mars aphelion, but the maximum eclipse duration is smaller, around 49 minutes. Nevertheless, the available power might be lower due to solar panel degradation.

Table 3 and Figure 6 summarize the duration of the eclipse seasons up to end 2011 for the different resonances proposed, assuming a change of orbit in April 2007.

Max. duration (min)	11:3	18:5	25:7	7:2
Season 1	73.9	75.2	75.8	77.2
Season 2	62.8	66.4	68.2	73.0
Season 3	50.1	54.8	57.5	65.0
Season 4	48.9	54.8	58.9	69.7
Season 5	36.2	41.0	44.4	53.9
Season 6	37.6	43.8	48.8	63.3

Table 3: Eclipse maximum duration for the resonances proposed.

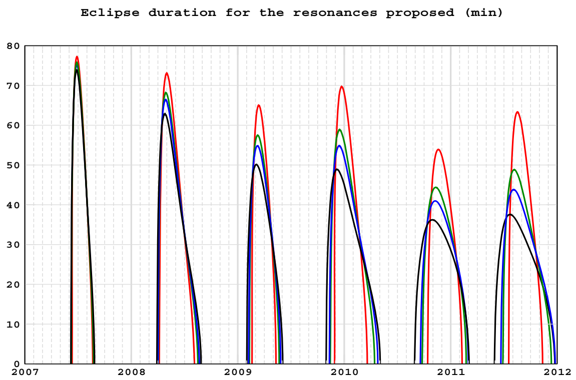

Figure 6: Eclipse duration for 11:3 (black), 18:5 (blue), 25:7 (green) and 7:2 (red) resonances.

It can be seen that larger target orbital period causes longer eclipses in the future, especially in the case of the 7:2 resonance, for which a maximum duration of above 20 minutes more than for the current orbit takes place during the fourth eclipse season, from November 2009 to April 2010. Given the natural degradation of batteries and solar arrays it is doubtful that such long eclipses can be sustained.

ESA has taken the decision to perform a change to the 18:5 resonance in 2007. The future orbit improves somewhat the illumination conditions for the years to come, while it is clear that in this sense it is not as advantageous as the 25:7 or the 7:2 resonances. The decision has been made by trading off the needs of both day side and night side instruments, the assessment of the power situation, given the eclipse duration and expected degradation of batteries and solar array and the need for a cautious use with propellant resources. A further change of the reference orbit in the future (maybe to the 25:7 or to the 7:2) resonances is possible.

The orbit change was originally foreseen for April 2007. It was then delayed to August to avoid conflicts with important science observations. Later, NASA has requested tracking of Phoenix by Mars Express during Entry Descend and Landing (EDL). In order to reduce the propellant needed to phase Mars Express adequately for this support, it has been decided to combine the manoeuvres for the orbit change to the 18:5 resonance with the manoeuvres to achieve phasing with Phoenix. To accommodate this, the orbit change is now foreseen for the timeframe November/December 2007.

Currently the Mars Express tanks are almost empty. In this situation it cannot be excluded that pressurant gas is ingested by the Propellant Management Device (PMD) of the tanks. Hence, the size of manoeuvres has to be limited to use less propellant than the capacity of the PMD, allowing for quiet periods for refilling it between manoeuvres. This corresponds approximately to a maximum manoeuvre size of 2 m/s. Hence the total delta-V required to perform the orbit change (approximately 7 m/s) has to be split at least in 4 instalments.

For operational reasons manoeuvres will be scheduled once per week.

4. GROUND-TRACK CONTROL

As already mentioned, the main optical instruments of Mars Express are slit sensors with a projection on the surface perpendicular to the ground track. When these optical instruments are operated, they image a swath around the ground track, of increasing amplitude with S/C height. Hence, at pericentre the swaths reach their narrowest point.

The separation of the ground tracks shall be such that the swaths of the narrowest slit, which is 12 deg wide (from the High Resolution Stereo Camera, HRSC) do not leave any gaps, with some margin.

For a given pericentre height, the separation of the ground tracks at pericentre decreases with the pericentre latitude. Hence, if the condition of minimum overlap is satisfied when the pericentre is at the equator, at higher latitudes significantly larger overlaps are produced, making the imaging less effective.

To avoid this in the past, a continuous adjustment of the orbital period was performed, such that the overlap of adjacent swaths was always minimum. This was accomplished by performing dedicated frequent trajectory correction manoeuvres at apocentre or by reaction wheel desaturation activities in dedicated attitudes. The activities to optimise the overlap of adjacent ground tracks are referred hereafter as ground track control.

Figure 7 illustrates the concept of the ground-track overlap and separation for two adjacent ground tracks. The solid lines represent the motion of the sub-satellite point on the Martian surface, whereas the areas between pairs of dashed lines represent the field of view of HRSC.

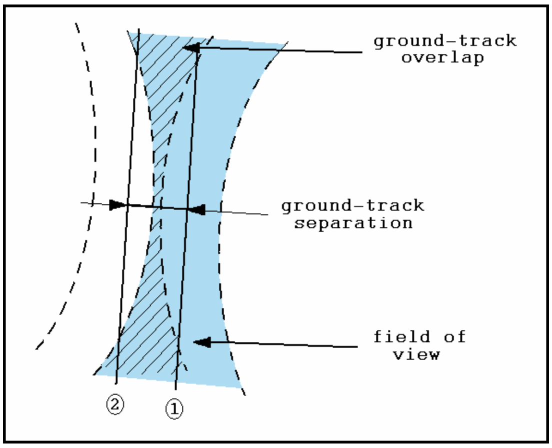

Figure 7: Ground-track overlap and separation concept.

Based on flight experience the ground track control has a cost of 1 kg propellant per year. The ground track control was desired by the Mars Express camera team, as it minimises overlaps and maximises coverage. ESOC Flight dynamics has challenged this approach, as it is expensive in terms of propellant and add complexity to operations. Instead, ESOC proposes to bias the S/C pointing direction to achieve ideal overlap (skipping periodically observations at some revolution). The ground track control has therefore been abandoned.

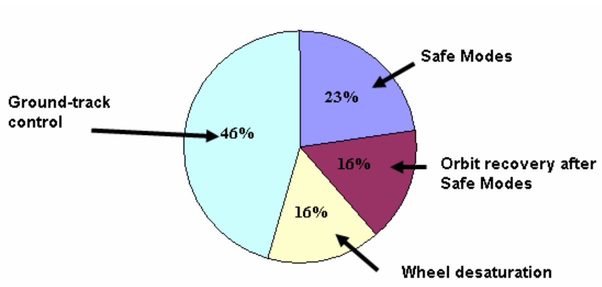

Figure 8: Mars Express average propellant usage.

5. SUPPORT FOR NASA PHOENIX LANDING

NASA Phoenix Mars Lander was launched on August 4th 2007 from Cape Canaveral on board a three-stage Delta II rocket to study the north polar region of Mars in search of water and life evidences. Arrival at Mars is expected on May 25th 2008, after more than nine months of interplanetary cruise.

ESA has been requested by NASA to employ Mars Express to provide back-up track functions during Phoenix EDL. In order to provide this support the Mars Express orbit shall be adequately phased with the Phoenix incoming trajectory.

NASA specifies to ESA the required Mars Express latitude at a given epoch to allow visibility with Phoenix. The latitude requirement from NASA is converted to a constraint to fly over a corresponding true anomaly at a given epoch. To achieve this Mars Express has to adjust its phase in the orbit (i.e. advance or delay its time of flight over pericentre).

The phase adjustment can be achieved by a pair of manoeuvres, one biasing the orbital period, then staying a number of revolutions with changed period and one manoeuvre to reset the original period. The cost of this activity increases proportionally with the required change of phase and decreases inversely proportionally with the time span spent at the biased orbital period. For example, for a change of only 1 minute phase performed with two manoeuvres separated 1 day 40cm/s are required.

In general a much larger change in phase may be needed, to cover all possible arrival conditions of Phoenix (which depend strongly on e.g. Phoenix launch epoch). In the extreme an adjustment of up to half orbital period might be required. Hence the activity performed in this way would have either an unaffordable propellant cost for Mars Express or it would have to be conducted over a time span of many weeks. During this time span the ground track repetition scheme is completely lost, thus disturbing science objectives of MEX.

For this reason it was considered adequate to combine the orbit change manoeuvres of Mars Express to the 18:5 resonance with the phasing with Phoenix. Indeed, by shifting the whole orbit change activity over a period of two weeks, it is possible to achieve a change in the phase of the resulting orbit by more than one orbital period. This approach is in addition cost neutral, as the 7 m/s required for the orbit change need to be done anyway. The phasing of Phoenix is obtained just by selecting the time of the manoeuvres.

The problem of this approach was that the orbit change of Mars Express to the new 18:5 resonance could be implemented only once NASA would specify the target phase of Mars Express. As the arrival trajectory of Phoenix is strongly dependent on the launch date NASA could only provide this information with certainty after Phoenix launch. The Mars Express manoeuvres had to be scheduled afterwards.

The mission planning of Mars Express is performed with a lead time of about 3 months. This process requires accurate prediction of the S/C trajectory, as most of the science observations are driven to targets on the Mars surface. For this reason the Mars Express orbit change has now been scheduled to take place starting in mid November.

The phasing of Phoenix is achieved by advancing or delaying the delta-V as required. In practice, six fixed slots separated by one week have been reserved, and the total delta-V of approximately 7 m/s is distributed among the slots as convenient.

Table 4 summarizes the size of the manoeuvres obtained for two extreme phasing cases, by concentrating delta-V at the beginning or at the end of the slots. In the first case, the three first manoeuvres are fixed to the maximum allowed value of 2 m/s, and the fourth manoeuvre is adjusted to achieve accurately the 18:5 resonance, obtaining a size of 0.94 m/s; the fifth and sixth slots are not used. For the second case, the first and second slots are skipped, the three last manoeuvres are fixed to 2 m/s, and the third manoeuvre is optimised, obtaining also a value of 0.94 m/s.

OCM size (m/s)	Case 1	Case 2
Manoeuvre 1	2.00	-
Manoeuvre 2	2.00	-
Manoeuvre 3	2.00	0.94
Manoeuvre 4	0.94	2.00
Manoeuvre 5	-	2.00
Manoeuvre 6	-	2.00
Total ΔV	6.94	6.94

Table 4: Comparison of extreme cases.

Pericentre passages after the last manoeuvre slot show a difference for these two extreme cases of about 7.58 hours, which is more than one orbital. Therefore, it is clear that any phasing requirement from NASA can be accommodated by shifting delta-V between among the 6 available manoeuvre slots.

After the successful launch of Phoenix, NASA has specified the target latitude of Mars Express at Phoenix EDL. ESOC FD has responded to this with an optimisation of the manoeuvres for the change to the 18:5 resonance, fulfilling the requested phasing.

6. PHOBOS FLY-BY REQUIREMENTS

In the context of the extension of the operational orbit of Mars Express, a new requirement for close fly-bys at Phobos was specified by the scientific community in order to improve the knowledge on the larger and closer of the two Martian moons. Close encounters with Phobos with different observation conditions (e.g. day side, night side approach) shall be satisfied in the future opportunities.

The pericentre of Mars Express in lower than the Phobos orbital radius, but the apocentre is higher. Due to the drift of the argument of pericentre and to the polar orientation of the Mars Express orbit it is clear that periodic crosses of the two orbits occur. Indeed, when the Mars Express pericentre is at equator the two orbits are interlaced (i.e. the MEX orbit has a cross of the Phobos orbital plane inside the Phobos orbit and one outside, building so to say a chain of two members. This is not so when the Mars Express pericentre is at one of the poles, in which case the members of the chain are loose. Hence for each full revolution of the argument of pericentre there are 4 crosses of the two orbits, i.e. approximately one crossing every 150 days in average.

The fact that the orbits of Mars Express and Phobos cross each other at a given time does not directly imply that the distance between the S/C and the moon is small at that time as both can be in any point in the orbit, far from the point of crossing.

However also around the time of crossing of the two orbits the distance between both orbits is small. For instance, during the 4 days before the crossing to the 4 days after the crossing the two orbits have points of closest distance below 200 km. This period corresponds to about 26 orbits of Mars Express. For the various of these orbits, the positions of Phobos at the times in which Mars Express reaches the point of minimum distance between the orbit are scattered along the Phobos orbit, and just some of these points come naturally close to the crossing point as well, generating a close encounter.

In the past no special effort has been put to optimise the approaches of Mars Express and Phobos. Whenever a crossing of the two orbits occurred, some close encounter took place in some of the orbit before or after the crossing of the orbits.

In the future it is intended to optimise the conditions of such close encounter. This will be done by making a slight change of the orbital period between two crossings of the orbit, in the order of a few seconds, such that the S/C and Phobos are at an adequate phase at the time of the encounter. The change of period shall be small, as to be within the tolerances allowed for the ground track overlap.

ABBREVIATIONS AND SYMBOLS

ΔV	Velocity increment
ASPERA	Energetic Neutral Atoms Analyser
ESA	European Space Agency
HRSC	High Resolution Stereo Camera
MaRS	Mars Radio Science Experiment
MARSIS	Sub-surface Sounding Radar Altimeter
MEX	Mars Express
NASA	National Aeronautics and Space Administration
OCM	Orbit Control Manoeuvre
S/C	Spacecraft
WOL	Wheel Off-Loading