EXOMARS MISSION ANALYSIS AND DESIGN - LAUNCH, CRUISE AND ARRIVAL ANALYSES

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ABSTRACT

ExoMars is ESA’s next mission to planet Mars. The probe is aimed for launch either in 2013 or in 2016. The project is currently undergoing Phase B1 studies under ESA management and Thales Alenia Space Italia project leadership. In that context, DEIMOS Space is responsible for the Mission Analysis and Design for the interplanetary and the entry, descent and landing (EDL) activities.

The present mission baseline is based on an Ariane 5 or Proton M launch in 2013 of a spacecraft Composite bearing a Carrier Module (CM) and a Descent Module (DM). A back-up option is proposed in 2016.

This paper presents the current status of the interplanetary mission design from launch up to the start of the EDL phase.

INTRODUCTION

ExoMars is ESA’s current mission to planet Mars. The probe is aimed for launch either in 2013 or in 2016. The project is currently undergoing Phase B1 studies under ESA management and Thales Alenia Space Italia (TAS-I) project leadership. In that context, DEIMOS Space is responsible for the Mission Analysis and Design for the interplanetary and the entry, descent and landing (EDL) activities.

The current mission baseline is based on an Ariane 5 or Proton M launch in 2013 of a spacecraft Composite bearing a Carrier Module (CM) and a Descent Module (DM). A back-up option is proposed in 2016.

The trajectory profile is characterized by: a) a direct transfer to Mars with an intermediate deep space maneuver (DSM), b) injection into a 4-sol waiting orbit (WO) at Mars and c) release of the DM from the Carrier, which enters Mars while the CM is burnt in Martian atmosphere.

After launch, the Composite is left into a direct escape trajectory. Once in interplanetary transfer the spacecraft is operated to perform a type 2 transfer to Mars. A DSM is introduced at mid transfer to adequately reach Mars optimizing the arrival spacecraft mass. Descent to Mars is imposed after the end of the corresponding Mars global dust storm (MGDS) season. After landing a Rover and a surface station package will be operated at least during 180 sols.

Under the mentioned transfer opportunities the arrival to Mars occurs in both opportunities close to the Martian perihelion, which means that Mars is under MGDS conditions. Descent to Mars is currently scheduled after the superior solar conjunction that is present some time after arrival and after the end of the MGDS season.

The paper analyzes the mentioned transfer and in-orbit options. In particular it exposes in detail the results of the interplanetary mission design and optimization in the different possible transfer cases to Mars and the waiting phase at Mars.

MISSION CONSTRAINTS

After the several iterations already carried out on the ExoMars mission design (see [1] and [2]) and system design, ESA has confirmed the following mission constraints:

- Mission shall be launched in 2013 as baseline. It shall be also possible to fly the mission with launch in 2016 opportunity as a back-up option
- Mission shall be compatible with a launch in Ariane 5 and a launch with Proton M launcher
- Transfer to Mars will be of type 2 (arrival in direct orbit after spacecraft orbit aphelion)
- Injection orbit in Mars will be a 4-sol orbit with a 500 km pericentre radius, although this was not a hard constraint and could be traded in case of need
- Descent to Mars shall occur after the latest of the next two events: a) end of the MGDS characterized by an approximate planet solar longitude of 340º and b) solar superior conjunction occurrence
- Operations of the landed Rover will be free of solar superior conjunctions during the nominal operational period of 180 sols

Another constraint imposed by the launcher is:

- Escape trajectories with Ariane 5 launcher are largely impacted for negative escape declinations by the re-entry of the rocket third stage. Thus a constraint was imposed to always depart from Earth with an almost null declination

The declination constraint for Ariane 5 launches directly impacts on the size of the DSM. If the launcher does not meet the required escape declination, the DSM will have to impart some change in transfer orbit inclination. This problem is not present for Proton M as the launch inclination is quite high (e.g. 48º) and any escape declination below that value can be achieved.

TRANSFER DESIGN

Transfer to Mars was optimized by means of a constraint optimizer that played with launch dates, arrival dates, Earth escape conditions, Mars arrival conditions and the date, size and orientation of the DSM. Optimization parameter was the spacecraft mass in Mars orbit. Launcher performances were extracted from references [3] to [6]. The process assumed for each infinite escape velocity and declination maximum injected mass by the launcher minus a 5% performance margin and minus a 190 kg adapter.

Once the optimum transfer of type 2 was obtained, 21-day launch windows were generated to furnish with a minimum set of launch opportunities both in 2013 and 2016 for both launchers Proton M and Ariane 5. Table 1 provides the transfer values obtained with Proton M launch for the two 21-day launch windows.

Table 1: Earth-Mars launch window conditions for transfers in 2013 and 2016 after Proton M launch

Relevant variable	2013 Window		2016 Window	
	Min	Max	Min	Max
Launch date	26/11/13	15/12/13	14/01/16	02/02/16
Arrival date	20/09/14	04/10/14	22/10/16	30/10/16
Departure velocity modulus (km/s)	2.6728	3.1492	2.0472	2.4284
Departure declination (deg)	17.36	26.93	-1.06	2.79
DSM value (m/s)	54.7	372.9	800.8	975.3
Arrival velocity modulus (km/s)	2.9436	3.1110	2.9409	3.0299

Similar values were obtained for Ariane 5 and are given in Table 2 with the exception of the launch declination, which was limited to a minimum value and impacted particularly the values of DSM and escape excess velocity.

Table 2: Earth-Mars launch window conditions for transfers in 2013 and 2016 after Ariane 5 launch

Relevant variable	2013 Window		2016 Window	
	Min	Max	Min	Max
Launch date	30/11/13	20/12/13	18/01/16	07/02/16
Arrival date	03/10/14	05/10/14	26/10/16	01/11/16
Departure velocity modulus (km/s)	2.3498	2.4293	1.9899	2.0974
Departure declination (deg)	0.04	0.04	-0.04	-0.04
DSM value (m/s)	918.6	979.7	1009.0	1013.7
Arrival velocity modulus (km/s)	2.6487	2.7725	2.9022	2.9506

Escape velocities in 2013 opportunity in the Proton M case are between 2.6 km/s and 3.2 km/s, whereas for Ariane 5 these are between 2.3 km/s and 2.5 km/s. The observed differences are obtained both due to the launcher performance curves and the additional constraint imposed on the escape declination for Ariane 5. In 2016 opportunity, escape infinite velocities are between 2.0 km/s and 2.5 km/s for Proton case and between 1.9 km/s and 2.1 km/s in Ariane 5 case. Differences here are smaller due to the lower required values of declination.

Differences in escape conditions also affect the size of the DSM which is rather small for Proton in 2013 but very high for Ariane 5 due to the need to compensate for the low inclination launch. DSM is naturally high in 2016 for both launchers due to a worse relative position of Earth and Mars for the transfer.

Arrival velocities in 2013 opportunity range between 2.9 km/s and 3.1 km/s for Proton and 2.6 km/s and 2.8 km/s for Ariane 5. In 2016, values are respectively between 2.9 km/s and 3.1 km/s and 2.9 km/s and 3.0 km/s. Relative differences between launchers in 2013 are also affected by the declination constraint.

Figure 1 provides the Ecliptic projection of the transfer to Mars with launch in 2013 with Proton M. Arrival to Mars occurs slightly before its perihelion pass. Transfer times range between 9.4 months and 10.1 months. The evolution of the distance to Sun, Earth and Mars is given in Figure 2. Arrival to Mars occurs at an Earth distance of 1.55 AU which is increasing towards a superior conjunction with the Sun. Figure 3 presents the evolution of Sun-S/C-Earth and Sun-Earth-S/C angles which also show a future convergence of the angles in a superior conjunction. Such situation occurs 9.0 months after arrival already out of the MGDS season.

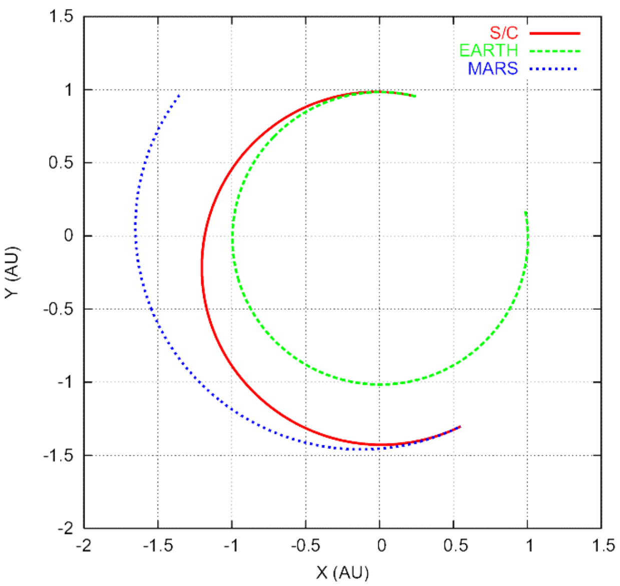

Figure 1: Ecliptic projection of Earth-Mars transfer of type 2 after launch in 2013

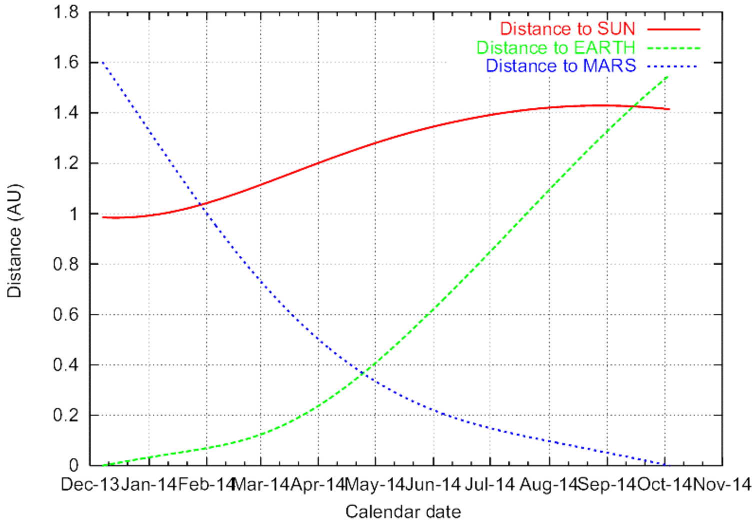

Figure 2: Evolution of S/C distance to Sun, Earth and Mars in T2 transfer in 2013 launch

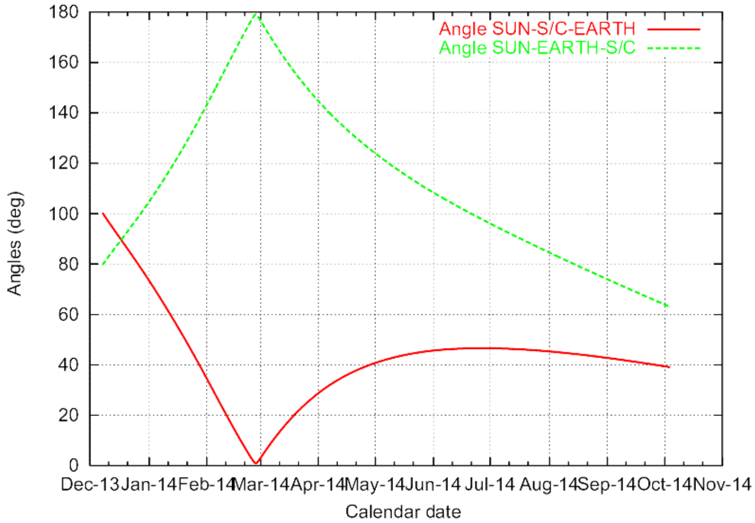

Figure 3: Evolution of relevant angles in T2 transfer in 2013 launch

Figure 4, Figure 5 and Figure 6 respectively provide the same curves but for the 2016 transfer opportunity with Proton M launch. Arrival to Mars occurs very close to Martian perihelion. Earth-Mars distance at arrival reaches 1.25 AU and increasing. Transfer times range between 8.7 months and 9.3 months. In this case the future solar superior conjunction occurs 9.6 months after arrival, also out of the MGDS season.

The issue regarding the superior conjunction relates to a requirement to wait until that is over to perform the release of the DM and the planetary entry operations. In such case, the required 180 sols of Rover operations would be free of solar conjunctions.

Similar curves are available for Ariane 5 launch but are not herein presented for economy in the length of the paper.

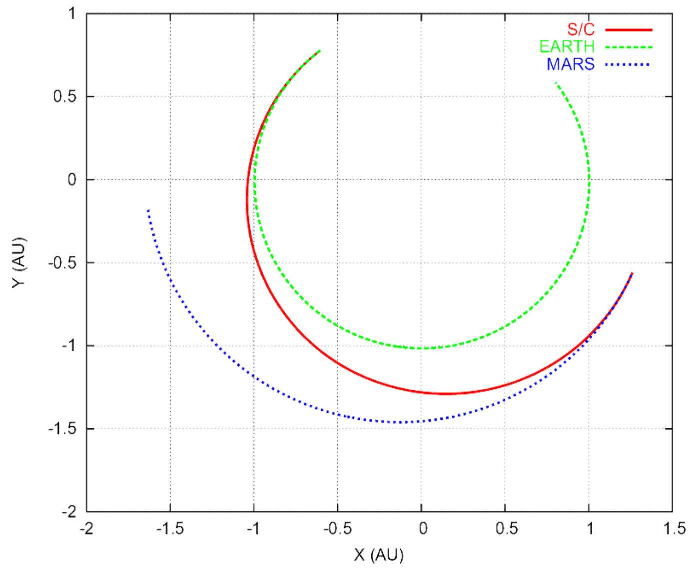

Figure 4: Ecliptic projection of Earth-Mars transfer of type 2 after launch in 2016

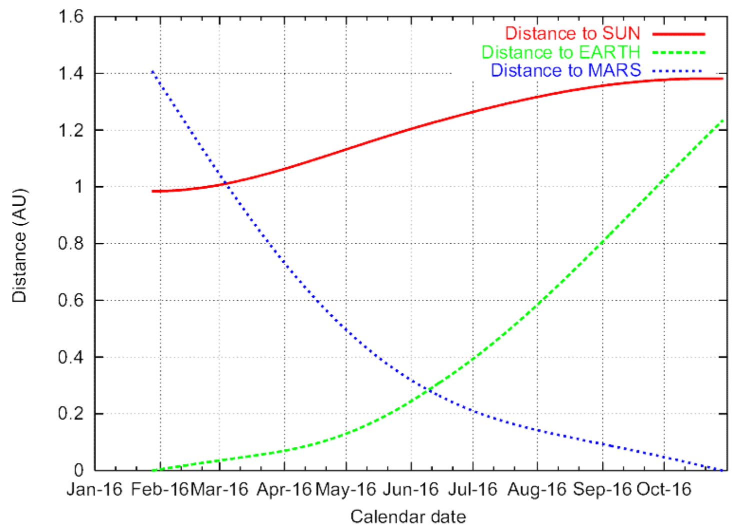

Figure 5: Evolution of S/C distance to Sun, Earth and Mars in T2 transfer in 2016 launch

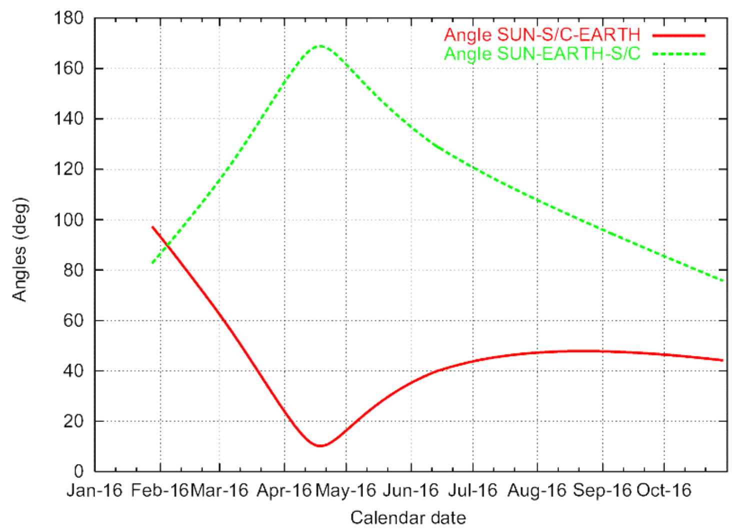

Figure 6: Evolution of relevant angles in T2 transfer in 2016 launch

RELEASE CONDITIONS

Before analyzing the injection conditions in Mars, it is necessary presenting the possible release conditions after the waiting phase in the injected orbit at Mars. This exposition approach is chosen due to the importance of the selection of the landing site first, which drives the selection of the injection conditions.

A 4-sol orbit with 500 km pericentre height was preliminary proposed as the injection orbit at Mars due to a number of reasons: a) its recurrence to Mars solar period, b) its stability against the Martian and solar gravity field influence, c) easy injection as the apocentre is high (~95,000 km height over Mars), d) almost two day descent phase to Mars after de-orbit maneuver, which allows for contingency procedures to take place before entry in case of need.

Such waiting orbit (WO) is flown by the spacecraft from injection up to the moment the solar superior conjunction is over. Taking the arrival dates at Mars and the dates of the conjunctions it is possible to derive the minimum waiting time at Mars. In 2013 opportunity this amounts to roughly 272 days and in 2016 to roughly 289 days.

The evolution of the WO under the effect of the gravity field of Mars (GMM-2B up to degree and order 5) and the gravity of the Sun was propagated from insertion to the atmospheric entry interface point (EIP) at 120 km height for all possible injection points (mapped in the B-plane). This allowed obtaining diagrams of achievable latitude versus local solar time at EIP and the projected surface impact point (SIP) both in 2013 and 2016 opportunities. The SIP was calculated by extending the spacecraft track an amount of pre-computed kilometers obtained from an atmospheric propagation as a function of the flight path angle (FPA) at the EIP.

Figure 7 and Figure 8 present the results of the abovementioned computations together with the terminator line corresponding to each of the descent days. Diagrams were obtained for an arrival FPA at EIP of –15º. Other diagrams for –11º and –18º were also produced to cover a range of possible arrival conditions but are not included herein for economy of space. Permissible FPA values at EIP are currently under assessment within the EDL contract for ExoMars.

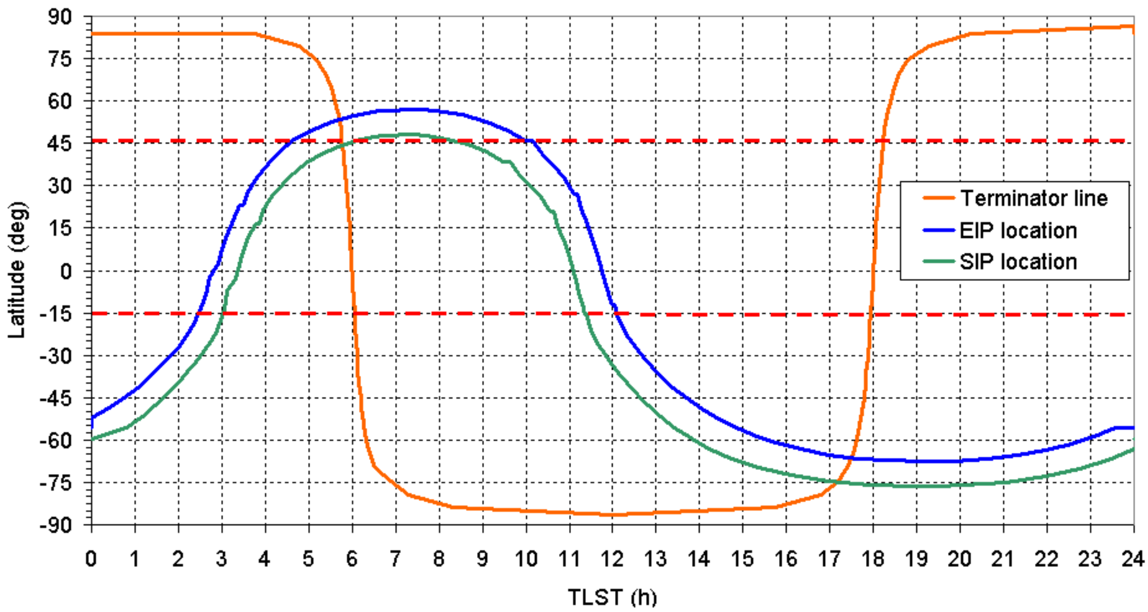

Figure 7: EIP, SIP & terminator location in 2013 opportunity for FPA=-15º at EIP

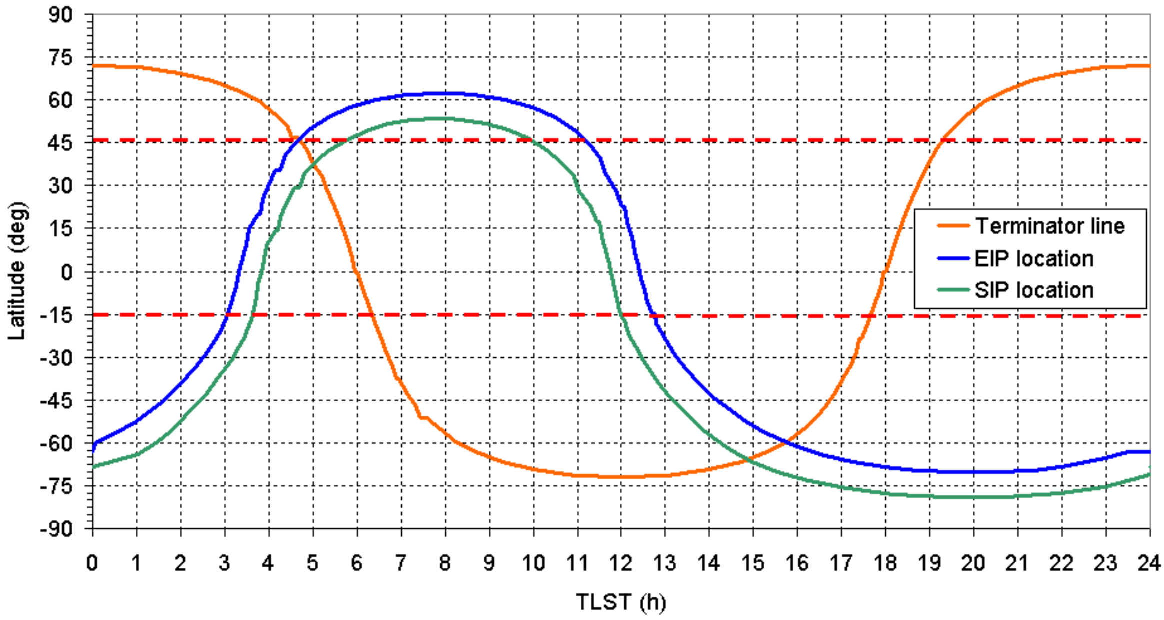

Figure 8: EIP, SIP & terminator location in 2016 opportunity for FPA=-15º at EIP

These diagrams are important because they relate two important requirements: 1) the required achievable landing latitude band between 15ºS and 45ºN and 2) the LST at arrival which needs to be above 8:00 and before 15:00. The first threshold is imposed to allow feeding of the Rover batteries from the Sun just after dawn and the second threshold is imposed to allow performing the first Rover activities after landing still in daylight.

Allowed branch in 2013 allows landing at Mars between 8:30 a.m. and 11:20 a.m., whereas in 2016 landing would occur between 10:00 a.m. and 12:00 a.m. Those arrival options correspond to retrograde arrivals to the EIP which will be needed in both cases to comply with the imposed constraints in LST and latitude.

Such final values mapped from the insertion conditions at Mars permit obtaining those conditions bringing the spacecraft to the desired end points on the surface. Such relations were used to analyze the resulting WO and their features (stability, eclipses, etc.). Results were discretized for final latitudes of SIP at 15ºS, 0ºN, 15ºN, 30ºN and 45ºN.

INJECTION IN MARS ORBIT

Injection in Mars will be realized by means of a main engine burn which has been preliminary assessed at the level of 424 N and 318 specific impulse. Given the arrival velocities, arrival masses to Mars and the engine parameters, it is possible to compute the required size of the Mass Orbit Injection (MOI) burn. The size of the MOI was optimized to achieve minimum fuel consumption for given arrival velocity and spacecraft mass for a grid of those values. Results of such optimization process are provided in Figure 9 for different arrival masses to Mars between 1000 kg and 5000 kg. The gravity losses obtained after such analyses can be as high as 40% for 5,000 kg arrival spacecraft, 35% for a 4,000 kg S/C and 28% for a 3,000 kg S/C. This last value is approximately the arrival mass value in the ExoMars case.

This model of MOI was included in the optimization process to include the consumption in this operation in the computation of the injected final mass at Mars.

Once the arrival velocities and masses were obtained from the interplanetary optimization process and the injection conditions to arrive to the required landing latitudes were inferred from the WO propagation analysis it was possible to project the MOI in space. Such projection allowed providing to the system designers with relevant data on MOI duration, orientation wrt to Sun and Earth, eclipses during MOI.

Figure 10 provides the evolution of the thrust-S/C-Sun angle during MOI for the 5 cases that allow arriving to the selected SIP latitudes in the 2013 case. Figure 11 provide the same information for the 2016 opportunity. As observed, the profiles are relatively similar and they allow analyzing the optimal orientation of the solar panels wrt to the thrust direction. Same type of plots was obtained for the thrust-S/C-Earth angle.

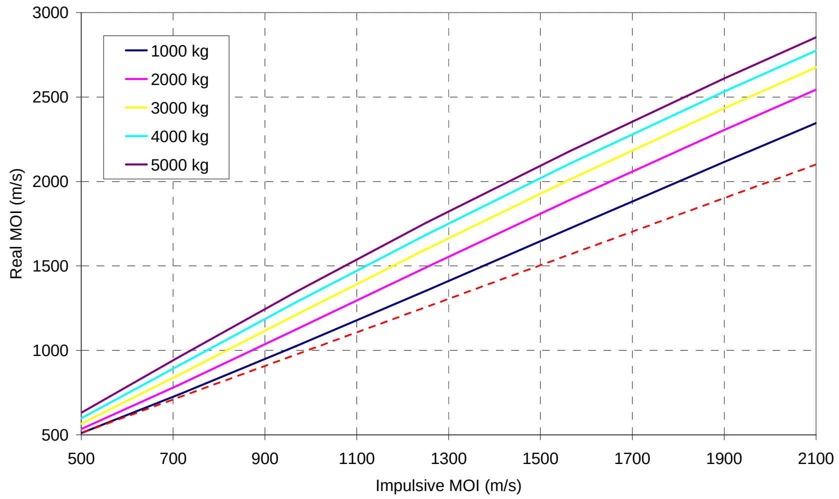

Figure 9: MOI size as function of the ideal MOI size by using a 424 N engine, 318 s Isp (injecting into a 4-sol orbit with 500 km pericentre height)

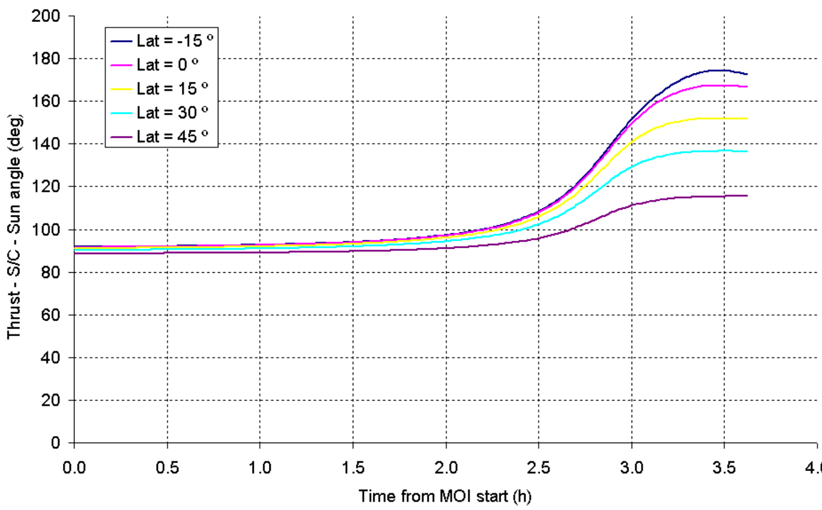

Figure 10: Thrust-S/C-Sun angle, opportunity 2013, WO bringing to the desired SIP latitude

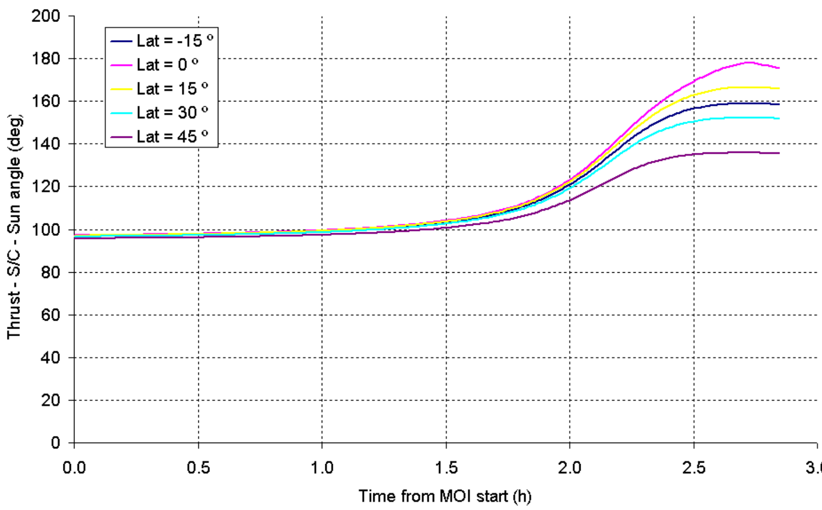

Figure 11: Thrust-S/C-Sun angle, opportunity 2016, WO bringing to the desired SIP latitude

WAITING ORBIT EVOLUTION

The analysis of the WO was then performed after the analysis of the injection conditions. In this case the most relevant aspects to analyze were the stability of the orbit (in particular its effect on the pericentre height) and the presence of solar eclipses.

The first factor related to the analysis of the possibilities that the pericentre height lowered down to risky values (e.g. below 200 km height). This effect is mainly induced by the third body effect exerted by the Sun which can dramatically reduce the pericentre. However, it was observed that during the propagation times of the WO, both in 2013 and 2016 such critical case could be avoided. Figure 12 provides the pericentre height in 2013 opportunity and Figure 13 for 2016. In all cases pericentre height at the beginning tends to lower down, reaching a value close to 260 km in 2013 case and 280 km in 2016 case, both above 200 km. After such segment, the Sun effect made the height increase towards safer values.

The above analysis allowed concluding that the WO was stable enough for the purposes of the mission.

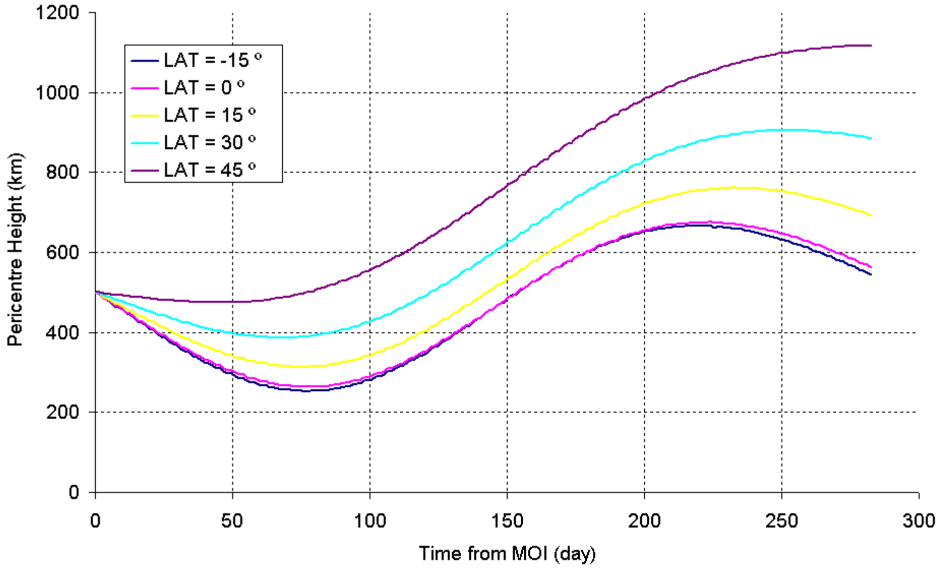

Figure 12: Pericentre height evolution for the WO bringing to the desired SIP latitude, opportunity 2013

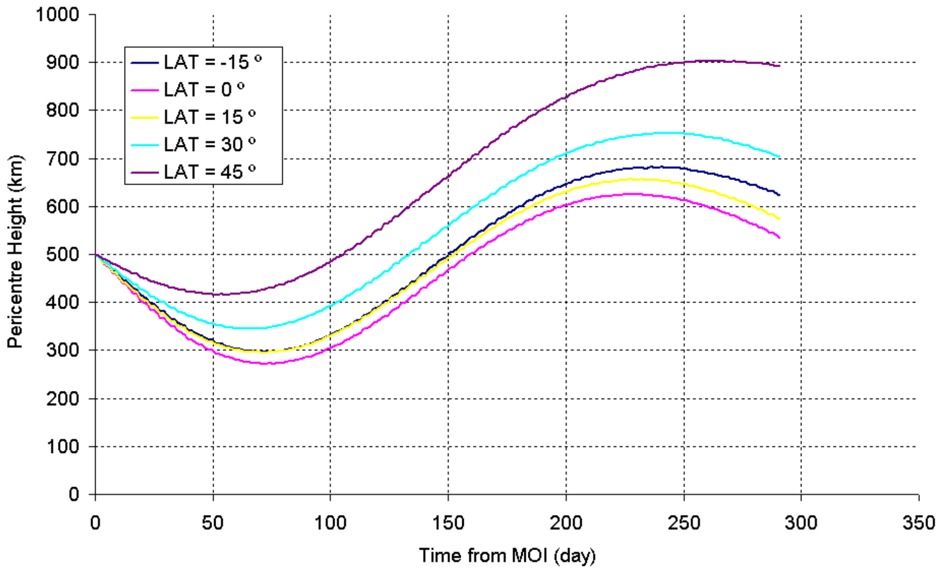

Figure 13: Pericentre height evolution for the WO bringing to the desired SIP latitude, opportunity 2016

Another important aspect of analysis in WO was the occurrence of eclipses. Figure 14 and Figure 15 provide the duration of such events for both opportunities and the selected final latitudes. In those plots it is possible to observe that very long cases of eclipse might occur in both opportunities, with a special worse case in 2013 opportunity. There, eclipses are longer than 10 hours. Such long eclipses are due to the fact that the WO apsides line evolves such that in the worse case it orients along the Sun-Mars direction with the apocentre in the anti-solar direction seen from Mars.

This is in fact a driver for the design of the spacecraft batteries that is currently under a trade-off analysis to evaluate the suitability of possible eclipse mitigation options as:

- Performing plane change maneuvers
- Reducing the apocentre of the WO to more favorable situations (reducing apocentre to 33,600 km would allow reducing the maximum eclipses to 4 hours)

Analyses on this aspect are currently underway to allow achieving a solution for this problem.

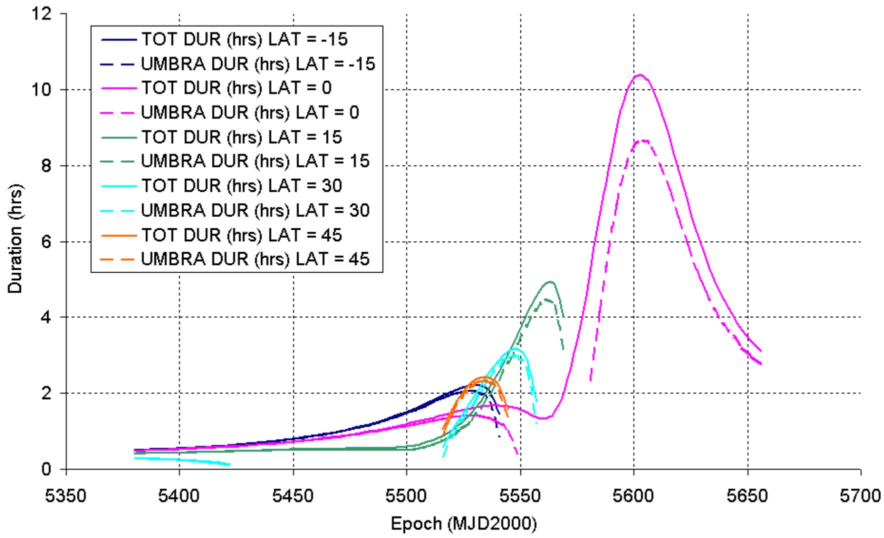

Figure 14: Sun eclipses duration, opportunity 2013, retrograde orbits bringing to the desired SIP latitude

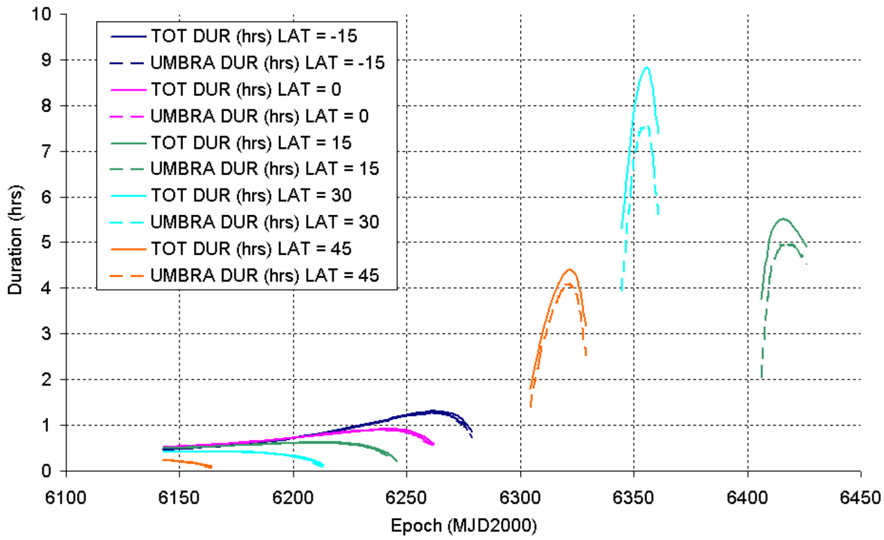

Figure 15: Sun eclipses duration, opportunity 2016, retrograde orbits bringing to the desired SIP latitude

MISSION DELTA-V BUDGETS

The total delta-V budget for each of the mission cases was arrived at by adding a number of further elements to the ones already obtained for DSM, MOI and operations at Mars plus navigation budget and margins.

The navigation budget was preliminary accounted for in the computations assuming that: 30 m/s are needed to compensate the dispersion after Earth escape, 5 m/s are needed for cruise trajectory maintenance, 1% of the DSM is needed to correct for the dispersion in the maneuver implementation (which is considered achievable by proper staging of the burn) and finally 15 m/s are needed for the final targeting prior to the MOI.

The de-orbit budget from the WO to the descent orbit to Mars is assumed at 20 m/s and an extra 300 m/s is added for further operations at Mars and contingency considerations (required by ESA).

Finally, a 5% margin is included in the overall delta-V in order to comply with ESA's margins policy. Table 3 provides the summary values including all the above concepts for the computation of the total delta-V budget in the Proton M case. Table 4 presents the same computation for the Ariane 5 case.

Baseline options launched by Proton M present the smaller delta-V budget due to the small DSM in comparison to Ariane 5 launch case. Comparing options in 2013 and 2016, the second present larger values due to the less favorable transfer conditions.

It has to be mentioned that there is still a concept to add to the previous assessment of the total delta-V budget that is the amount of propellant for AOCS operations. This was regarded at system level.

Table 3: Delta-V budget for transfers in 2013 and 2016 after Proton M launch

Relevant variable	**2013 Window**		**2016 Window**	
	Min	Max	Min	Max
Launch date	26/11/13	15/12/13	14/01/16	02/02/16
DSM value (m/s)	54.7	372.9	800.8	975.3
MOI delta-V (m/s)	1283.7	1429.9	1235.9	1311.1
Navigation budget (m/s)	50.5	53.7	58.0	59.8
De-orbit delta-V (m/s)	20.0	20.0	20.0	20.0
Extra budget (m/s)	300.0	300.0	300.0	300.0
Total DV budget (m/s)	**1947.8**	**2131.8**	**2614.5**	**2720.5**

Table 4: Delta-V budget for transfers in 2013 and 2016 after Ariane 5 launch

Relevant variable	**2013 Window**		**2016 Window**	
	Min	Max	Min	Max
Launch date	30/11/13	20/12/13	18/01/16	07/02/16
DSM value (m/s)	918.6	979.7	1009.0	1013.7
MOI delta-V + GL (m/s)	988.7	1084.5	1181.7	1221.3
Navigation budget (m/s)	59.2	59.8	60.1	60.1
De-orbit delta-V (m/s)	20.0	20.0	20.0	20.0
Extra budget (m/s)	300.0	300.0	300.0	300.0
Total DV budget (m/s)	**2464.6**	**2501.4**	**2703.9**	**2741.3**

CONCLUSIONS

A detailed mission analysis of the options to travel to Mars was performed for ESA's ExoMars Project within the study constraints. This study included the assessment of the escape phase, the interplanetary cruise, the arrival conditions and the in-orbit operations in Mars. The assessments encompassed launches by Proton M and Ariane 5 in direct escape, direct transfer scenario and elliptic arrival of the DM to Mars.

Results of the study included for all the scenarios the assessment of the mission delta-V budgets, analysis of operations, definition of timelines and the production of the ancillary information required for the system level assessments. Thales Alenia Space is currently using all these results for the design of the spacecraft system and the design of the operations.

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