ExoMars 2016 – Flight Dynamics operations for the targeting of the Schiaparelli module Entry Descent and Landing and the Trace Gas Orbiter Mars orbit insertion

D.Pellegrinetti[1], R.Guilanyà[1], P.Muñoz[1], R.Vidal[1], E.Basso[2], J.Schwartz[3] and U.Herfort[3].

[1] *GMV INSYEN at ESOC, Darmstadt, Germany, robert.guilanya@esa.int*
[2] *LSE SPACE at ESOC, Darmstadt, Germany*
[3] *ESA/ESOC, Darmstadt, Germany*

Abstract

The ExoMars 2016 composite Spacecraft consisted of the Trace Gas Orbiter (TGO) and an Entry Descent and Landing (EDL) demonstrator module, named Schiaparelli (EDM).
The first goal of the Mission consisted in targeting the Schiaparelli module EDL by means of a Deep Space Manoeuvre (DSM) and a sequence of Trim Correction Manoeuvres (TCMs) up to the TGO-EDM separation. The next step was to insert the TGO in a four Martian Solar Days (SOLs) orbit around Mars.
This paper is a-posteriori technical report about the planning activities and operations, conducted at the European Space Operations Centre (ESOC) within the Flight Dynamics (FD) Manoeuvre Optimization (MAN) team, for the DSM, the EDL fine targeting and the critical operational phase of the 14th of October 2016, when the commands for the TGO-EDM separation attitude, the Orbiter Retargeting Manoeuvre (ORM) and the Mars Orbit Insertion (MOI) manoeuvre were generated. Special focus is on orbit control activities.

Keywords: Entry Descent and Landing, Mars Orbit Insertion, Trace Gas Orbiter, Schiaparelli.

Introduction

The ExoMars 2016 composite Spacecraft (S/C) was launched on the 14th of March 2016, from the Baikonur Cosmodrome with the Russian Proton rocket .
The TGO Main Engine (ME) fired on the 28th of July and later on the 11th of August, implementing the DSM in two legs: the main leg (DSM-1) and its deterministic touch-up (DSM-2). The aim of the DSM was to centre the EDM entry corridor at a co-rotating Flight Path Angle (FPA) at Entry Interface Point (EIP, defined by a fixed radial distance from Mars centre of 3516 km) of -12.4°, and to target the landing site, specified by Areocentric longitude and latitude of 353.9° and -2.05° respectively (Meridiani Planum) [1]. The selected landing site was updated with respect to what was reported in [1], in order to minimize the risk of landing over hazardous regions.
Shortly after the DSMs, the fine tuning campaign for the EDL targeting started, including routinely Delta-DOR measurements for the Orbit Determination (OD) process and a sequence of stochastic TMCs before the TGO-EDM separation (shortly EDM separation, or simply separation in the following) on the 16th of October.
The Flight Dynamics operations starting on the 14th of October for commanding the separation attitude, the ORM and the MOI manoeuvre were highly critical. The ORM was scheduled twelve hours after separation and it was necessary for targeting the TGO periares, placing the TGO in a Mars collision free trajectory. The MOI was scheduled three days after separation and during EDL, when the TGO was also supposed to collect EDL data.
At this point, it is worth to mention that, despite the fact that the EDL phase ultimately failed to soft

land on Mars [2], Schiaparelli was accurately delivered to its descent trajectory and the TGO was successfully placed in a high eccentric orbit around Mars on the 19th of October 2016 after MOI execution. After the Inclination Change Manoeuvre, the Apocentre Lowering Manoeuvres and the intensive Aerobraking phase (15th March 2017 - 20th February 2018) [3], the TGO finally reached its science orbit in mid-April 2018.

Deep Space Manoeuvre planning and operations

The aim of the DSM was to centre the entry corridor at a co-rotating FPA of -12.4° at EIP and, target the landing site, defined by Areocentric longitude and latitude of 353.9° and -2.05° respectively. The manoeuvre was designed in two legs, DSM-1 and DSM-2, with the second leg a deterministic touch-up of the first and sized 5% of the total required DV. This way, an over-performance of the DSM-1, up to 5% of the total Delta-V (DV), would have been absorbed by the DSM-2 with no extra fuel penalty.
The DSM timing was obtained as the outcome of a full trajectory fuel optimization where the EDL was targeted and the ORM and MOI optimized as well in order to finally achieve a four SOLs orbit [1]. The time between DSM-1 and DSM-2 was fixed to 14 days, to guarantee accurate calibration of the main leg, and the DSM-1 timing was set free in the optimization. With the delay from the January Launch Window (LW) to the March LW, the timeline was compacted as the arrival date was kept fixed to the 19th October. Following the full trajectory optimization approach, we encountered a few launch dates for which the entry velocities were quite high for the EDL phase, violating the S/C manufacturer constraints. In those cases, we adopted an heuristic approach by fixing the DSM-1 timing in order to have a compliant entry velocity, to still have enough time between the last deterministic manoeuvre (DSM-2) and separation in order to perform accurate navigation for EDL targeting (see next chapter), and accepting a less optimal solution in terms of fuel. The S/C launch was planned the 14th of March, at the Launch Window Opening (LWO) opportunity. The corresponding nominal trajectory was optimal in terms of fuel, compliant with the EDL entry velocity requirements and allowing enough margin for performing accurate navigation. On that day, the launcher injection was fully nominal, leaving the S/C in its interplanetary cruise.
A ME test burn, named DSM-0, was planned 10 days prior to the DSM manoeuvre, with a fixed size of 1 m/s and optimized direction, in order to assess the ME performances. The DSM-1 and DSM-2 relative sizes were kept as described before and their start times slightly tuned to make them directly observable within a New Norcia ground station pass. The final outcome from the optimization for the FD cycle on the 12th July (DSM-0 commanding) is resumed in Table 1.

Table 1: DSM figures at DSM-0 commanding cycle.

Manoeuvre ID	Size (m/s)	Start Time (UTC-CAL)
DSM-0	1.000	16/07/18T11:00:000
DSM-1	334.371	16/07/28T09:30:000
DSM-2	17.598	16/08/11T09:30:000

Unexpectedly, at DSM-0 execution, the Spacecraft experienced a safe mode. The Orbit Determination Team (ORB) concluded that the S/C did not produce the expected thrust. The Attitude and Telemetry Observation team (ATT) confirmed that the S/C had ejected about 2.5 kg of oxidizer. Further investigation identified as the root cause of the anomaly the fact that the wiring to control the switches for the fuel latch valve and the redundant oxidizer latch valve were actually inverted. It turned out that, when the S/C executed the command to open the fuel latch valve, it was actually opening the redundant oxidizer valve. Therefore, the ME did not fire and it only provided a tiny thrust due to the ejection of the oxidizer. Then, the on board autonomy detected that the acceleration

during the manoeuvre was too low and triggered a safe mode six seconds after the planned burn start time.
To recover the plan, we (the MAN team) planned a second ME test (DSM-0 second attempt) for the 21st July at 11:00 UTC, still 1 m/s size and optimized direction, hoping that inverting the commands for the fuel and the redundant oxidizer latch valves would be sufficient to produce the wanted thrust. While studying various DSM delay scenarios and worst cases, the DSM-0 2nd attempt worked nominally and we could go ahead with the nominal plan.
It is important to mention that, without the small DSM-0 ME test manoeuvre, a direct attempt to execute the main DSM-1 leg and a consequent failure would have had a major change on the operations plan due to the delay to perform the DSMs.
The DSM-1 and DSM-2 ultimately executed nominally. Soon after the DSM-2, the EDL fine tuning campaign started. A trajectory sketch showing the main orbital events is portrayed in Fig. 1.

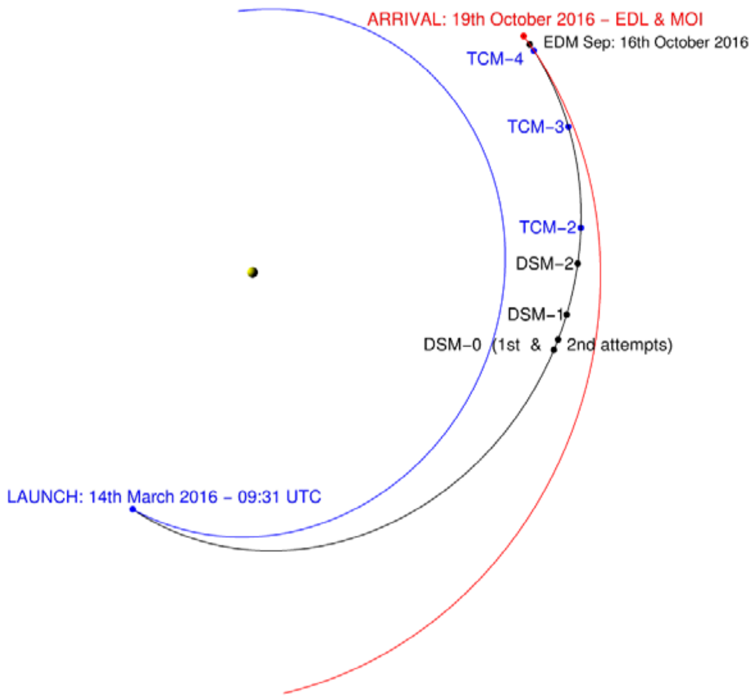

Fig. 1: TGO-EDM Interplanetary Trajectory sketch with main orbital events.

Entry Descent and Landing fine tuning

After DSM execution, the FPA and landing site were slightly off-target due to the small mis-performances of the DSM-2. Moreover, while the entry speed was roughly fixed to 5.785 km/s (co-rotating speed at EIP) compliant with the S/C manufacturer requirements, and could not consistently change, the other entry parameters (say the FPA) and the landing site uncertainties were still considerably high at this time.
In order to achieve a precise EDL targeting at EDM separation, a sequence of three stochastic TCMs, shown in Fig. 1, were planned together with an increased frequency of Delta-DOR measurements for the OD process starting after execution of the first TCM (a few Delta-DOR measurements were already included for the preparation of the DSMs). The sequence starts with the TCM-2, as the name TCM-1 was used for the Launcher injection correction manoeuvre which was not required as the launcher performances were nominal.
At each optimization, the upcoming TCM targeted back the FPA to the nominal value and the landing site to the desired spot on Mars, correcting the cumulative error up to the manoeuvre time.

The remaining two Degrees of Freedom (DoFs) given by the TGO-EDM longitudinal axis orientation at separation were exploited for targeting a zero Total Angle of Attack (AoA) at EIP, in order to ensure a stable entry attitude [1]. The last TCM-4 was foreseen on the 14^{th} October, 2 days and 6 hours before the EDM separation. The TCMs starting times and the obtained sizes at the time of their respective FD cycles are reported in Table 2.

Table 2: TCMs start times and optimized DVs.

TCM ID	Size (cm/s)	Start Time (UTC-CAL)
TCM-2	9.65	16/08/21T10:00:000
TCM-3	0.95	16/09/19T10:00:000
TCM-4	1.40	16/10/14T08:45:000

All the TCMs executed nominally, within the in-flight observed Reaction Control Thrusters (RCT) performance.
After the execution of each TCM, and prior to the commanding of the next one, navigation analysis were carried out in parallel by the ORB and the MAN teams.
The ORB team was mapping the trajectory with the corresponding uncertainties onto the B-plane over the required FPA entry corridor (-12.4° ± 0.27°). We were propagating the nominal trajectory from an initial state vector obtained from the OD solutions down to the Mars surface, and obtaining the dispersions in the landing coordinates and in the entry conditions from a Montecarlo run, with a sufficient number of trajectory samples, say N, with $N \geq 1000$.
The 3-DOFs EDL trajectory modelling, that we developed at ESOC and validated with the S/C manufacturer against their complete 6-DOFs models, was used for the EDL landing site targeting through the atmospheric flight and for the navigation analysis. The models description is available in [1]. The inputs for the Montecarlo runs were the covariance matrix associated to the initial state vector provided by the ORB team, and a list of dynamic parameters uncertainties modelled according to the S/C manufacturer recommendations and described as well in [1]. The TGO attitude control uncertainty model was calibrated in-flight, in particular, the assumed uniform distributions on the TGO y and z axis controllers were reduced to ±0.324°. The Mars Climate Database (MCD) was updated to the latest version 4.3 extension 5, and, still following the S/C manufacturer recommendations, the atmospheric scenario was fixed to the scenario 102 for EDL targeting and navigation analysis. Uncertainties in the next TCM, when included in the optimization, were added according to the observed RCT performances.
The landing dispersion obtained for a few relevant cases are represented in Fig. 2 and Fig. 3 over the Mars Orbiter Laser Altimeter (MOLA) map of Mars [4]. The red ellipse represents the applicable reference landing ellipse, with semi-major axis of 50 km and semi-minor-axis of 7 km, for the flown trajectory (LWO case): the landing accuracy to be achieved with the EDL fine tuning, established by the project, was defined by the 99% of the cases to fall within the reference ellipse [1]. Regarding the requirements on the FPA accuracy at the end of the EDL fine tuning phase, still the 99% of the cases should have fallen within the entry corridor previously defined. Entry conditions for FPA are resumed in Table 3. The three cases represent the following operational scenarios:

- TCM-2 calibrated with a few Delta-DOR data included in the OD process (Fig. 2, left). TCM-3 is not optimized for the EDL targeting. The resulting nominal trajectory landing spot is south-west off-target at 353.79° longitude and -2.17° latitude, about 9.64 km away from the selected landing site. The requirements for the entry corridor accuracy and the landing accuracy were not met yet at this point: as the TCM-2 manoeuvre was quite far from the separation event and, ultimately, to the landing event, it was expected that its mis-performances would have produced that kind of error in the predicted landing site. Also those kind of dispersions in the entry conditions and landing coordinates (see Fig. 2 (left) and Table 3) were expected, due to the propagation of the OD solution uncertainties.

• State of knowledge at the TCM-3 commanding cycle, with several Delta-DOR measurements included in the OD process and the TCM-3 optimized for the EDL targeting (Fig. 2, right). The TCM-3 uncertainty is included in the navigation analysis. The landing spot of the nominal trajectory is re-targeted thanks to the TCM-3 DOFs. Entry dispersion for the FPA and landing dispersion results are quite similar to the previous post TCM-2 case except for the Cross-track accuracy: the TCM-3 uncertainties slightly worsened the situation for the Along-track landing accuracy which does not result improved, but the contribution of the Delta-DOR measurements clearly improved the Cross-track accuracy. Also at this point, the requirements were, as expected, still not fulfilled.

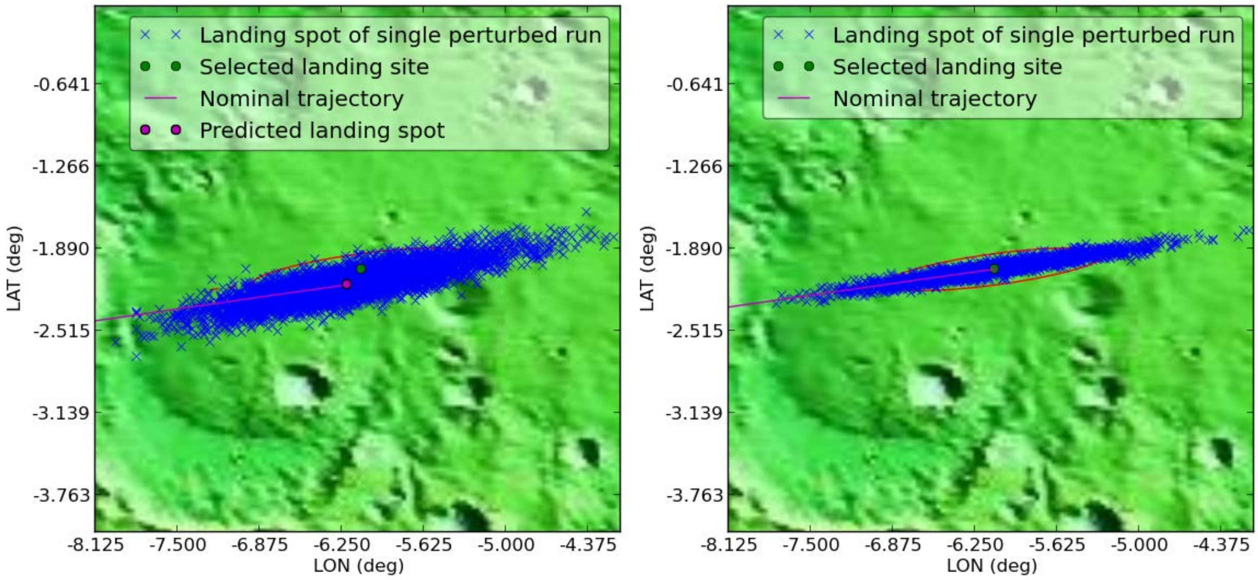

Fig. 2: Landing dispersions after TCM-2 calibration (left), prior to TCM-3 execution (right).

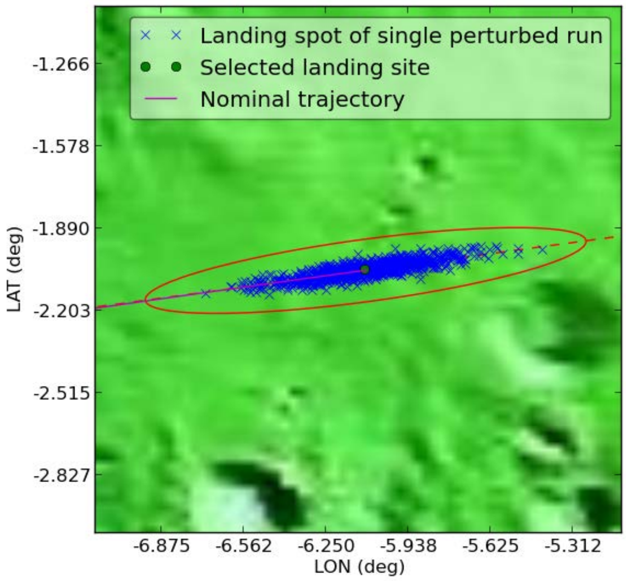

Fig. 3: Landing dispersion prior to TCM-4 execution.

• Situation at the commanding cycle for the TCM-4 manoeuvre, on the 12th of October, with TCM-4 optimized for EDL targeting and its uncertainty included (Fig. 3). The entry conditions requirements for FPA and landing accuracy requirements were, finally, fulfilled.

Interesting fact is to notice how the AoA dispersion at EIP, reported in Table 3, resulted quite the same through the three cases, as it mostly depended on the TGO-EDM attitude separation and separation mechanism accuracies, which were modelled consistently through our analysis. The AoA 3-σ was in all cases well below the S/C requirements for ensuring a stable EDM attitude dynamics throughout the EDL phase. Aerodynamic figures like maximum heat flux peak, heat loads and Mach number at parachute trigger, were also monitored during the process and assessed always below the S/C survival limits [1] in all cases (even when the entry corridor accuracy was not yet met at the TCM-2 and TCM-3 FD cycles).

Table 3: 3-σ Entry conditions for FPA and AoA at EIP and landing dispersion.

Case ID	FPA (deg)	AoA (deg)	Along-track/Cross-track landing dispersions (km)
Post TCM-2	0.6°	1.78°	102.9 - 13.2
Pre TCM-3	0.6°	1.76°	103.1 - 5.2
Pre TCM-4	0.19°	1.75°	33.8 - 3.3

Planning and Operations for the EDM Separation Attitude, ORM and MOI

On the 14th October 2016 the FD cycle was performed in order to finally command the TGO-EDM separation attitude, the ORM parameters and the MOI parameters.
The last remaining two DOFs of the separation attitude could be exploited at this point, with the knowledge of the TCM-4 performances, for different targeting options:

- Target again the landing site and accept an eventual deviation from zero of the AoA at EIP. This case would also intrinsically provide the nominal FPA targeting.
- Target zero AoA at EIP and accept an eventual off-target from the selected landing site and FPA.
- Target the FPA at EIP and minimize the AoA at EIP.
- Constrain the AoA within 2.0° (the maximum AoA accepted by the S/C manufacturer to be eventually targeted was 2.0°) and minimize the distance to the landing site.

From the output of our runs, it was decided to go for the landing site targeting, accepting a nominal off-zero AoA at EIP of 0.24°. The third and fourth cases gave the same results as the first one. The results between the first and second case are summarized in Table 4.

Table 4: TGO-EDM separation Attitude study cases.

Case ID	FPA (deg)	AoA (deg)	Distance to landing site (km)
Landing Targeting	-12.399°	0.239°	0
AoATargeting	-12.402°	0°	0.346

The last Montecarlo run, performed with a limited number of samples (N=200) in order to have an assessment before the commands upload, gave positive results regarding the entry corridor and landing accuracies. These results were finally confirmed with a 1000 samples run for which the landing dispersion is shown in Fig. 4 (left) and the entry conditions uncertainties reported in Table 5.
The start of the last thrusted part of the descent (not modelled by us [1]), at 1000 m altitude over the surface, was expected at 14 h 47 min and 43.2 sec UTC with an uncertainty of ±6.4 seconds (1-σ), at a Solar Local Time of about 13.27 hours. The expected atmospheric flight duration was about 7 minutes (from the higher atmospheric layers at 230 km altitude over MOLA to touch down).
The separation mechanism experienced an over-performance larger than expected, considering the S/C manufacturer uncertainty estimate: about 33.5 cm/s vs the mechanism design DV of 32 cm/s, roughly corresponding to a 5-σ value [5]. An EDL trajectory with the reconstructed separation DV,

provided by the S/C manufacturer, was computed, confirming the expected landing location still well within the reference ellipse. The predicted landing location was at 353.7798° longitude and -2.0864° latitude, at about 7.44 km short-range from the selected landing site (see Fig. 4 (right)). Unfortunately, after a successful entry and after having reached sub-sonic regime under the parachute correctly inflated, the EDM experienced an anomaly causing the backshell release earlier than expected, leading to a hard touch down on the surface of Mars [2][5]. The hard touch-down location, later reconstructed using the Mars Reconnaissance Orbiter (MRO) data, was identified at 353.7924° longitude and -2.0524° latitude [5], about 6.4 km short-range from the selected landing site (shown in both pictures portrayed in Fig. 4). It is quite astonishing how close the final hard-touch down location ended up w.r.t. the last mentioned EDL trajectory expected landing spot: only 2.15 km north-east away. The comparison is shown in Fig. 4 (right).

Table 5: 3-σ Entry conditions for FPA and AoA at EIP and Landing dispersion at TGO-EDM attitude commanding cycle.

FPA (deg)	AoA (deg)	Along-track/Cross-track landing dispersions (km)
0.146°	1.7°	26.9 - 2.7

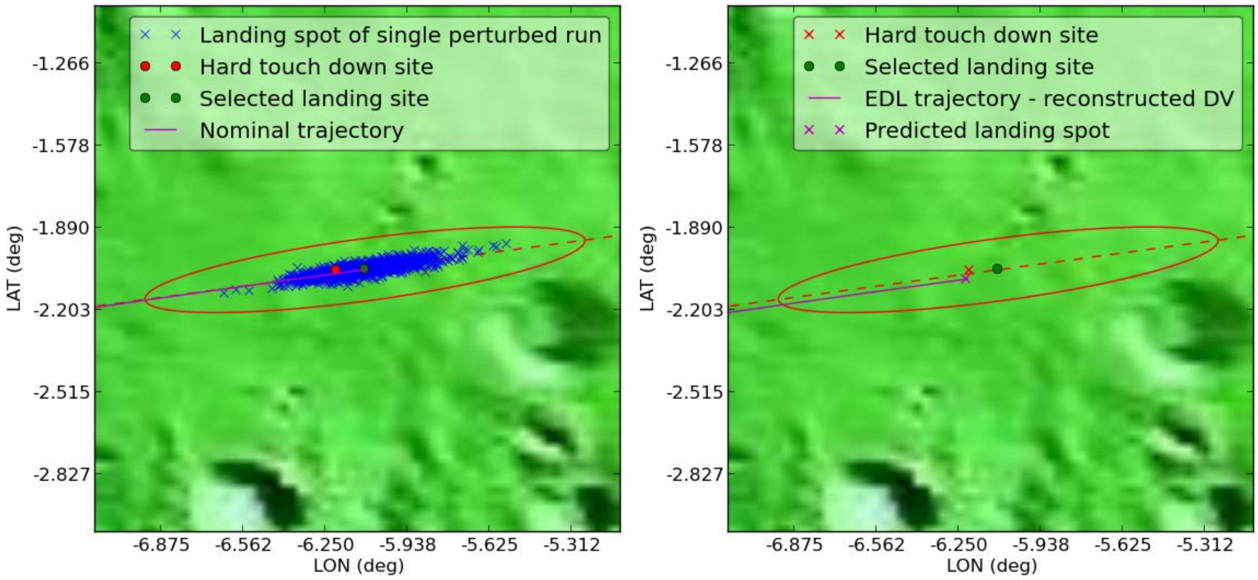

Fig. 4: Landing dispersion at the EDM separation attitude commanding cycle (left) - the hard touch down site is also shown. Comparison between the hard touch down site and the landing spot from the EDM trajectory including the reconstructed separation performances (right).

The ORM and MOI parameters were computed together, with the separation DV and the nominal optimized values reported in Table 6. The ORM, planned only twelve hours after separation, was optimized in direction and size in order to target the TGO periares, placing the TGO in a Mars collision free trajectory and to ensure a timed flyover over the EDL phase during MOI execution. This step was necessary in order to collect EDL data sent to TGO by the EDM during the atmospheric flight. The effect of the ORM on the TGO trajectory on the B-plane are shown in Fig. 5. The impact contours represented in the figure include also the Martian atmosphere.
The minimum topocentric altitude resulting from the ORM optimization and expected during the MOI, was about 575 km. The MOI timing, size and direction were optimized in order to target a four SOLs orbit. The obtained direction profile was mainly against the instantaneous orbital velocity (in order to most efficiently brake the S/C to get in a closed orbit) and the huge DV obtained was corresponding to a 2 hours 22 minutes ME off-modulation burn. The geometry during MOI

execution is shown in Fig. 6. In the figure, the main events during MOI execution are also shown.

*Table 6: Parameters for EDM separation, ORM & MOI. ** DV received by the EDM.*

Event ID	DV (m/s)	Start time (UTC-CAL)
Separation	0.320** (by design)	16/10/16T14:42:00.000
ORM	11.659	16/10/17T02:42:00.000
MOI	1559.193	16/10/19T12:04:39.734

The three events in chain, here described in such a tough timeline, went all nominal, but it should be noted that a separation failure would have compromised the mission.

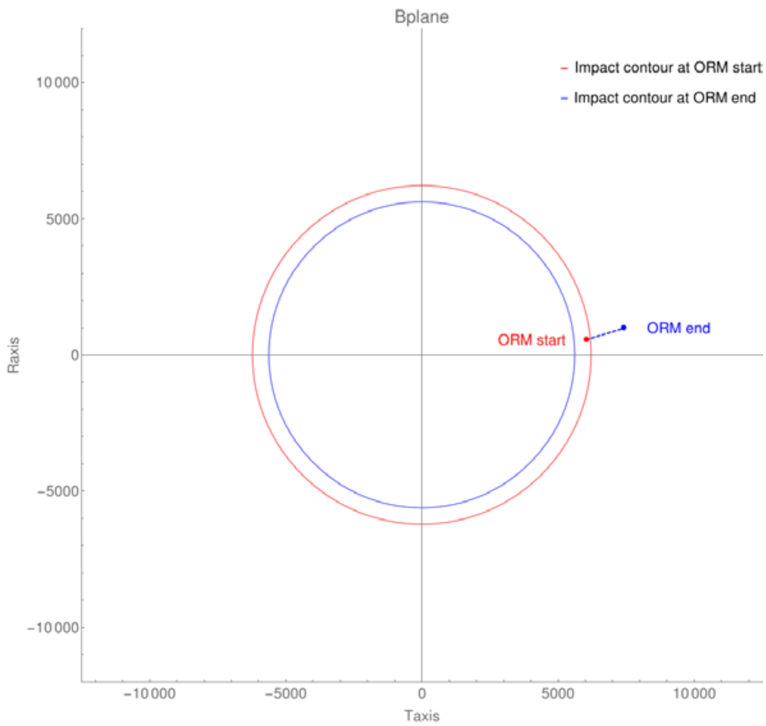

Fig. 5: ORM effect on the TGO trajectory on the B-plane.

For such a contingency scenario we prepared a trajectory with a second separation attempt exploiting a late TCM-5 for EDL re-targeting. The TCM-5 was planned 12 hours after nominal separation time, in place of the original ORM, and the second separation attempt planned 8 hours later. In this case, the separation attitude parameters for targeting the zero AoA at EIP were commanded together with the TCM-5 parameters and the ORM ones, now scheduled 8 hours after the second separation attempt. Also, the MOI was re-optimized but not loaded on board. The complexity of this operational phase laid on the fact that both nominal and contingency separation plus the ORM timeline commands had to be up-loaded at once. Then, once the S/C detected the separation, the contingency commands would have been autonomously deleted. If the separation was not detected, the nominal commands would have been deleted.
In case of an eventual second separation attempt failure, it would have been not operationally feasible to perform the Mars orbit insertion with the EDM still on board the TGO. We were then prepared to command a fly-by targeting manoeuvre one day after the contingency ORM and, with the EDM attached, perform a powered fly-by in order to reach a 1:1 resonant orbit with Mars and attempt the Mars orbit insertion half a Mars year later. This trajectory would allow a capture within the nominal propellant allocation, even in the case the EDM was not ejected during the interplanetary

flight.
Regarding the ORM, of course, a complete failure would have been critical as the TGO was in collision course with Mars, but we were pretty confident as the RCT was properly tested in-flight and well performing. The ORM was anyhow calibrated and at that point a new optimization of the MOI performed, in order to see whether an update of its parameters was necessary. It turned out that the ORM performed nominal and we decided to continue with the already prepared MOI parameters. MOI performances were of course critical as any under-performance over 7.7% would have not resulted in a closed orbit bringing most probably to the loss of mission. Also smaller under-performances (starting from 4%) were highly critical scenarios as the high eccentric closed orbit obtained would have been quite unstable due to third body Solar perturbations, and enter in collision course with Mars at the second periares after capture. In that case, we would have been required to react soon, placing a periares control manoeuvre, latest, at the second apoares after capture, and completing the MOI afterwards. Although there was more margin, MOI over-performances could also produce critical scenarios, i.e. an over-performance of 6.5% would have reduced the periares altitude after MOI down to 250 km. Smaller over-performances would have caused also a lower periares altitude w.r.t. the nominal one, but we would have had enough time to recover and correct the mis-performance with an apoares manoeuvre. The MOI performed nominal, as it was first assessed with the occultation duration (Fig. 6). Based on the following OD, the manoeuvre slightly under-performed leaving an apoares altitude of 2860 km above the target and an orbital period of 4 hours 6 minutes longer than the targeted four SOLs.

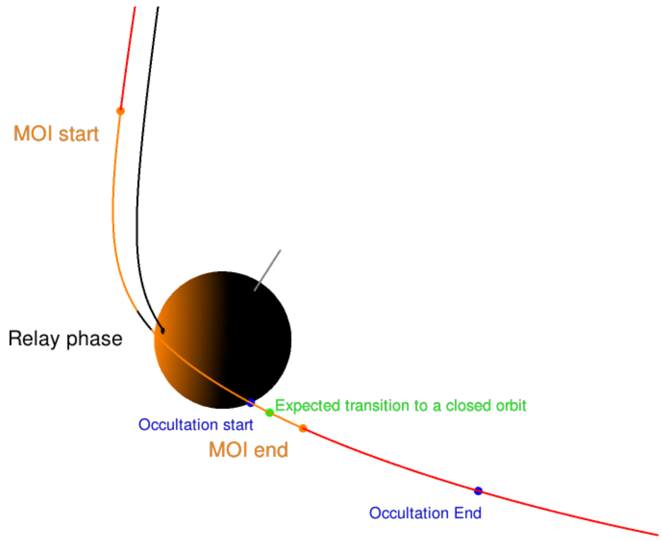

Fig. 6: MOI geometry (red line: TGO trajectory, black line: EDM trajectory).

Conclusions

This paper resumes the activities performed by the Flight Dynamics Manoeuvre Optimization team during the Deep Space Manoeuvre, Schiaparelli module Entry Descent and Landing fine targeting and the Trace Gas Orbiter Mars Orbit Insertion. The main rationales behind the trajectory design and the orbit control planning were given, and the navigation analyses that were carried out during the critical operations were presented. In particular, it is shown how, the Schiaparelli module was accurately delivered into its descent trajectory, and the Trace Gas Orbiter placed in its four Solar Days orbit around Mars.

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