# ExoMars 2016 – Flight Dynamics commanding during the aerobraking operations for the Trace Gas Orbiter

R.Guilanyà[1], A.Rivero[2]

[1] *GMV INSYEN at ESOC, Darmstadt, Germany, robert.guilanya@esa.int*
[2] *IMS Space Consultancy GmbH at ESOC, Darmstadt, Germany*

## Abstract

The Trace Gas Orbiter (TGO), from ESA's Mars robotic exploration program, is a satellite manufactured by Thales Alenia Space. Its mission objectives are to study the Martian atmosphere and to provide relay services to the current and future Mars landers. After Mars arrival, the TGO exploited the aerobraking technique to reach the final science orbit. The aerobraking technique consists in using the drag of the upper layers of the atmosphere to gradually decrease the spacecraft (S/C) velocity and to reach a lower energy orbit.

For the Flight Dynamics (FD) team, the aerobraking phase was highly demanding as they were responsible for the: navigation, trajectory design, telemetry monitoring and generation of the S/C commands [1] [2]. The purpose of the paper is to provide an insight on the S/C commanding, mostly on the GNC (Guidance Navigation and Control) part, for the different phases and situations during aerobraking.

**Keywords:** Mars, Aerobraking, Trace Gas orbiter, ExoMars.

## Introduction

The satellite, shown in Fig 1, was launched on the 14th March 2016 carrying the landing demonstrator module Schiaparelli (EDM). On the 19th October 2016, the TGO entered in a 4 Sol equatorial orbit around Mars after successfully performing the Mars Orbit Insertion manoeuvre [3] [4]. Afterwards, a series of chemical manoeuvres modified the original orbital period and inclination to 24h and 74 degrees. Then, in order to achieve the final orbit, the S/C performed aerobraking to reduce the orbital period to 2h.

Aerobraking operations were critical due to the unpredictability of the Mars atmosphere and long, due to the large S/C ballistic coefficient. They started on the 15th March 2017 and successfully completed on the 20th February 2018, after a total of 952 atmospheric passages and a DeltaV of 1017 m/s. They were divided into the following phases [1] [4]:

- Walk-in: Several pericentre lowering manoeuvres were executed to gradually decrease the pericentre altitude to assess the S/C performances and perform atmospheric calibrations.
- Main phase: The pericentre altitude was controlled within the aerobraking corridor.
- End-Game: The most critical phase, as the orbital period decreased, the S/C performed numerous aerobraking passes (up to 12 per day), with frequent interruption of the communications. For any non-nominal situation, the S/C could perform several aerobraking passes before the Control Centre could intervene. Once the orbital period was below 6h, the aerobraking regime was reduced by ~30% to increase robustness against the atmospheric variability.
- Walk-out: Leaving the aerobraking regime via a large pericentre raising manoeuvre.

In order to safely perform aerobraking, the operations relied on a high level of autonomy on board of the TGO [1] the most remarkable were:

- Capacity to autonomously shift the execution time of the on board commands making use of the Pericentre Time Estimation function (PTE).
- Capacity to perform a Flux Reduction Manoeuvres (FRM), a small pericentre raising manoeuvre (typically to increase the pericentre by 3 km) to control the aerobraking corridor. After the manoeuvre, the S/C continued performing aerobraking passages.
- Whenever a Safe Mode was triggered, the S/C performed a larger pericentre raising manoeuvre, called Pop-up, to leave the aerobraking regime. Also, all on-board commands were deleted.

The combination of the higher autonomy and the S/C capabilities let to a considerably complex S/C commanding. The following sections will describe the different commanding strategies.

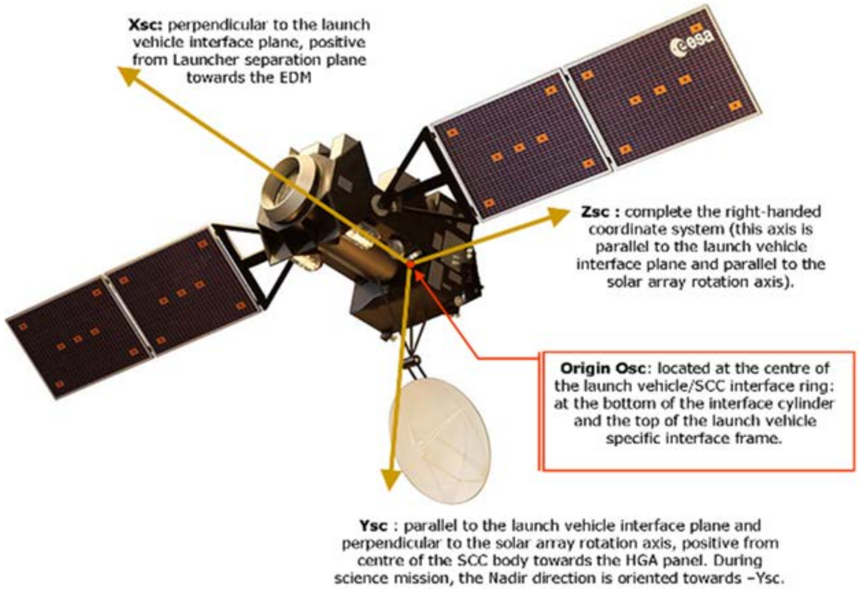


*Fig 1: TGO reference frame definition without the EDM.*

## Orbits with large orbital period

The following commanding strategy was applied from the start of the aerobraking to until interruption due to solar conjunction (orbital period reduction from 24h to 14h).

The scheme of the timeline within an orbit is shown in Fig 2 and detailed in Table 1. It can be divided in two configurations:

- Exo-atmospheric configuration: The S/C was commanded in a reaction wheels attitude control mode (NOMR). The articulation of the High Gain Antenna (HGA) remained in a fixed stowed position. Therefore, the S/C attitude had to guarantee that the antenna boresight was Earth pointed and the Sun on the $XY_{S/C}$ plane (i.e. perpendicular to the rotation axis of the solar arrays) towards $–X_{S/C}$ (to not violate S/C illumination constraints).

- Aerobraking configuration: In this configuration, the S/C was commanded in a thruster attitude control mode for aerobraking (AEBM). During the aerobraking pass, this mode had a large control dead-bands for rates and off-pointings: 30 deg and 1.0 deg/s for $Y_{S/C}$ and $Z_{S/C}$ and 15 deg and 0.2 deg/s for $X_{S/C}$. The attitude of the S/C was the theoretically aerodynamic stable one defined such that the co-rotating velocity was kept on the $XY_{S/C}$ plane about 7.5 deg from the $-X_{S/C}$ axis towards $+Y_{S/C}$, the $Z_{S/C}$ axis perpendicular to the orbital plane and the nadir direction remained on the $–Y_{S/C}$ face. The solar arrays (SA) were commanded perpendicular to the co-rotating velocity, exposing the back of the cells to the flow. The Antenna Pointing Mechanism

(APM) of the HGA was kept in stowed configuration. At the end of the aerobraking pass, the S/C was commanded to the Rate Damping sub-mode (AEBM-RD). This is a GNC sub-mode of the AEBM in which the controller reduces the residual rates before the S/C is commanded to NOMR.

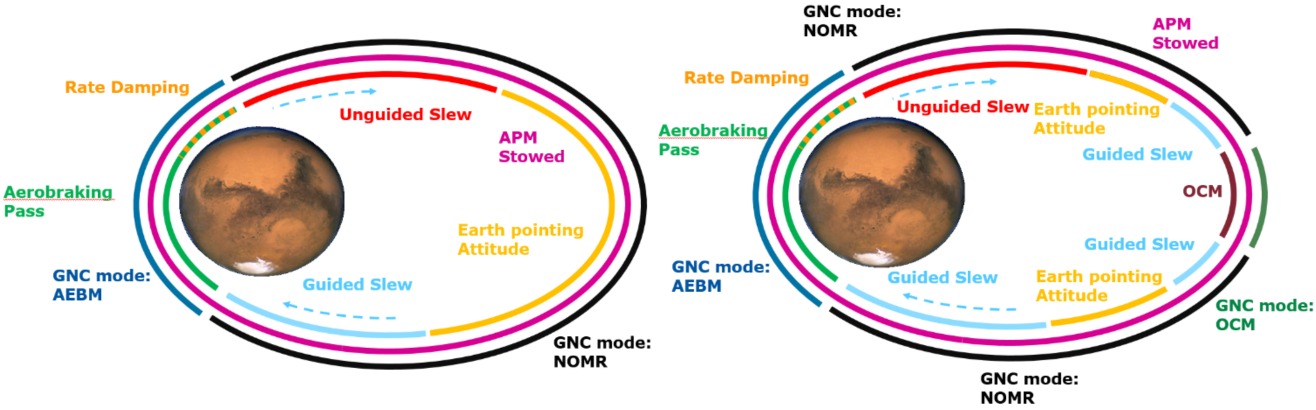


*Fig 2: Right timeline for long orbits with manoeuvre (OCM) and left without.*

The slew from Earth pointing attitude to the aerobraking one was performed with an attitude profile commanded by ground. However, the slew from aerobraking to Earth pointing was performed with an autonomous slew in NOMR (ground only commanded the target attitude), as the uncertainty on the initial attitude was very large. Whenever a pericentre control manoeuvre was required, the manoeuvre was centred at the apocentre and two additional slews in NOMR were added to go from Earth pointing to the manoeuvre attitude and return back.

*Table 1.Command timeline for long orbits without manoeuvres.*

| Event ID | Event description | Time |
|---|---|---|
| **$E_1$** | Start wheel off-loading | $E_2$ – 740 s |
| **$E_2$** | Start slew to aerobraking attitude | $E_6$ – slew duration from exo-atmospheric to aerobraking attitude<br>For short slews, $E_2$ should be at least 10 min before $E_6$ to guaranteed enough time for the accelerometers bias calibration |
| **$E_3$** | Start of on-board accelerometer bias calibration | $E_2$ + 10 s |
| **$E_4$** | Start SA rotation to aerobraking configuration | $E_6$ – (time required to move the SA from the exo-atmospheric configuration to the aerobraking one with a constant speed of 0.5deg/s) |
| **$E_5$** | End of on-board accelerometer bias calibration | $E_6$ – 10 s |
| **$E_6$** | Enter in AEBM mode | Time when the predicted dynamic pressure reached 5 mPa – 240 s margin (for PTE accuracy) |
| **$E_7$** | Enter in AEBM-RD sub-mode | Time when the predicted dynamic pressure reached 5 mPa + 240 s margin (for PTE accuracy) |
| **$E_8$** | Command the SA to Sun pointing (Cruise mode) | $E_9$ – 5 s |
| **$E_9$** | Enter in NOMR mode | $E_7$ + 240 s |

At the transition from AEBM to NOMR, the PTE function used the computed orbital period from the last two pericentre passages and the measured DeltaV of the current pass to compute the next pericentre time and shift all on-board commands [1]. In order to avoid that the following commands were not shifted to the past, the first non-aerobraking command had to start after a non-commanding period (driven by the worst case uncertainty on the orbital period prediction). An on board functionality was implemented to trigger a Safe Mode in the case the PTE function shifted the commands to the past.

## Orbits with short orbital period

The following commanding strategy was applied from the start of aerobraking post-conjunction until one month before aerobraking completion (orbital period reduction from 14h to 2h50min). Although this strategy was not a must for the first orbits, to avoid to change the commanding strategy in the middle of the operations, it was decided to use it at aerobraking restart.

The slewing capability was limited due to the large S/C intertias/small reaction wheels (e.g. the slew from aerobraking to exo-atmospheric attitude could take up to 54 min and the slew from the exo-atmospheric to aerobraking 30min). Therefore, with the previously described strategy, it was not possible to guarantee that within an orbit the minimum communication window and power availability constraint were achieved. Fig 3 shows the average input power on the SA which needed to be larger than 250 W/m$^2$ and the communication window availability for different commanding strategies (the red line fixed a design constraint of 30 min + two way light time). The possibility to perform the slews in thrusters, that can reduce the slew duration to 10 min, was also considered. However, this would require 600 g propellant per orbit, which could be converted to 1m/s DeltaV. As this value was comparable to the DeltaV achieved during an aerobraking passage (1.1 m/s during this phase), the option was discarded.

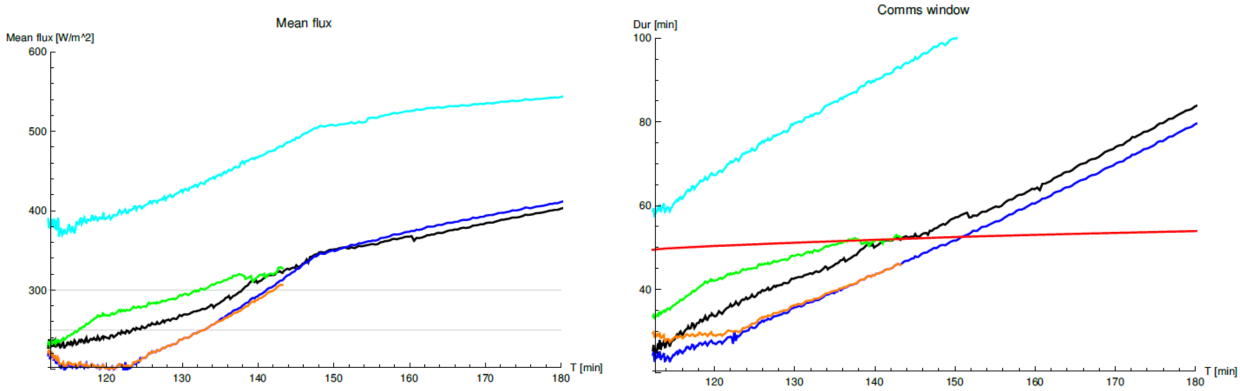


*Fig 3: Availability of power (left) and communications (right) for different commanding strategies in function of the orbital period. Black: constant roll during the pass without considering illumination constraints, Dark blue: constant roll considering attitude constraints, Green: variable roll without attitude constraints, Orange: variable roll with attitude constraints, Cyan: steering the HGA.*

From all the available options, the only solution was to steer the HGA to track the Earth (APM in cruise mode), as this strategy could guarantee enough power and communications.

Furthermore, the attitude profiles were optimised to minimize the slew duration and maximize the HGA contact periods. They were re-defined as follows:

- Aerobraking attitude: The co-rotating velocity was kept on the $XY_{S/C}$ plane about 7.5 deg from the $-X_{S/C}$ axis towards $+Y_{S/C}$ and the $Z_{S/C}$ axis perpendicular to the Sun. From the two possible solutions, that one that guaranteed no violation of the S/C illumination constraints and minimized the HGA outage at the AEBM-RD transition was selected.

- Exo-atmospheric attitude: It was defined as the aerobraking attitude at AEBM-RD transition (to minimise the autonomous slew duration) provided that the Earth was inside the domain of the HGA in this attitude. Otherwise, the selected attitude was the aerobraking attitude with the minimum slew around Z (to keep the SA perpendicular to the Sun) that moved the Earth inside the domain of the HGA without violating illumination constraints.

The timeline for this orbits is shown in Fig 4.

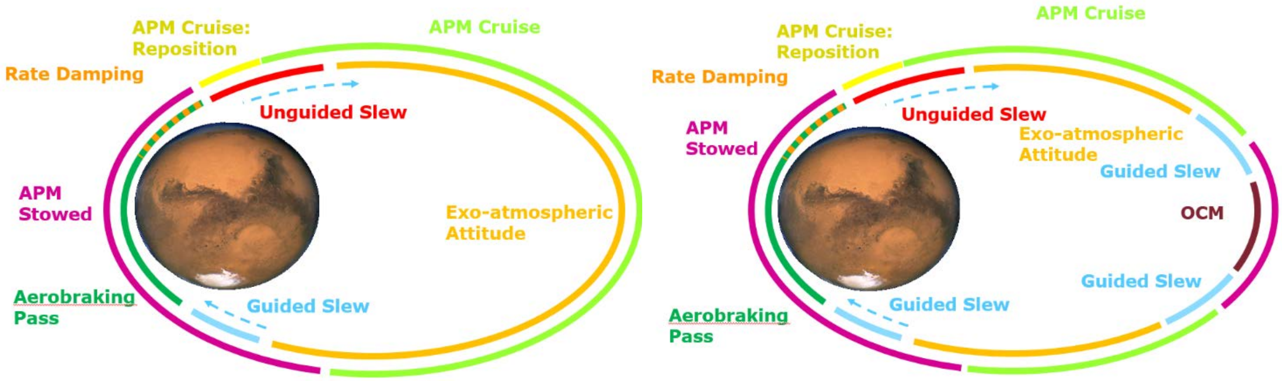


*Fig 4: Timeline for short orbits with manoeuvre (right) and without (left). The GNC modes have been omitted for clarity purposes.*

## Final phase of the End-Game

The following commanding strategy was applied during the last month of aerobraking (orbital period reduction from 2h50min to 2h). This strategy was applied as an update to the one described in the previous section.

*Orbits with manoeuvres*

As represented in Fig 5, the timeline for an orbit with a manoeuvre could be further compressed if the autonomous slew targeted the manoeuvre attitude and the slew back to Earth pointing was performed using thrusters (NOMP slew). An analysis was performed comparing the commanding strategy for orbits with manoeuvres following the approach from Fig 4 (named "Long strategy") and the one from Fig 5 (named "Short strategy") for pericentre raising and lowering manoeuvres. The results are shown in Fig 6. The left plot shows the time available to complete the manoeuvre activities before the apocentre (a negative value means that the manoeuvre central time has to be shifted after the apocentre by the same amount). The right plot shows the difference between the available time (delta time between the first command for the following aerobraking pass and the AEBM to NOMR transition of the previous one) and the time needed to perform all the manoeuvre activities (a negative value means there is not time to perform the OCM activities before the activities for the next pass starts). For orbits with a pericentre raising manoeuvre, both timelines were almost equivalent, so the long strategy was kept. However, for orbits with a pericentre lowering manoeuvre, it was necessary to use the Short strategy to be able to fit all the manoeuvre activities within the available time, as the Long strategy had a negative total time margin. The reason for this behaviour is the attitude definition during the aerobraking pass. This was very close to the required attitude for a pericentre raising manoeuvre (as the thrusters were located on the $-X_{S/C}$ face). As a consequence, for orbits with a pericentre lowering manoeuvre, the guided slew from the exo-atmospheric attitude to the manoeuvre attitude and back were too long to fit within the available time. On the other side, the Short strategy allowed to perform the manoeuvre activities, however; the autonomous slew in NOMR to the manoeuvre attitude was longer than using the 2 slews from the Long strategy (the wheel rates during the autonomous slew were further limited than during a guided slew). Hence, the commanded central time of the manoeuvre needed to be shifted by 8 min after the apocentre.

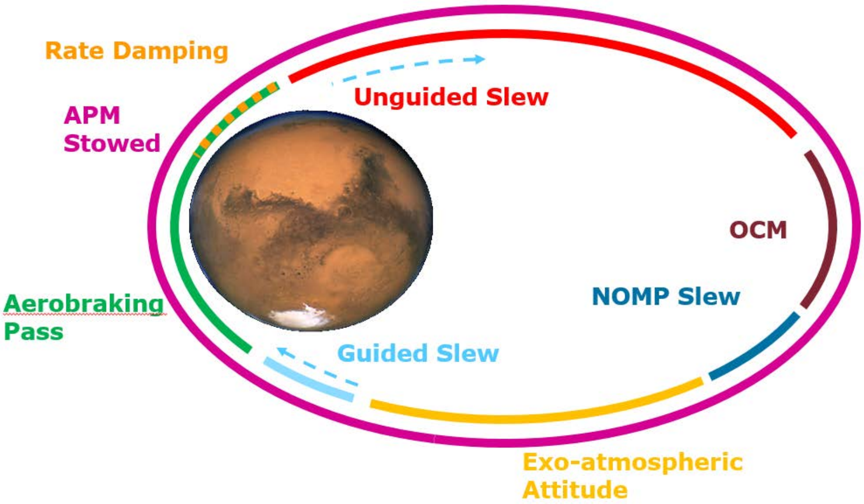


*Fig 5 . Orbit with a direct slew to the OCM and the slew back performed in thrusters.*

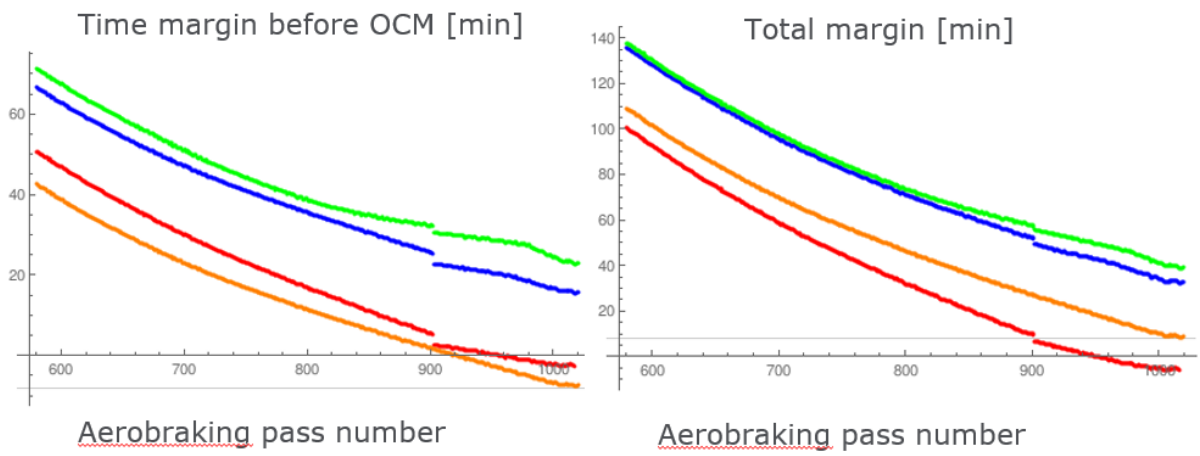


*Fig 6. Time available before apocentre (left) and total time available in an orbit (right) in function of the aerobraking pass number and for different commanding strategies. Blue: pericentre raising manoeuvre using Long strategy (Fig 4) and Green using Short strategy (Fig 5). Red: pericentre lowering manoeuvre with Long strategy and orange with Short strategy.*

On top of that, the values on Fig 6 did not consider any margin to avoid the commands were shifted to the past. Therefore, it was decided to use the 8 min of the total margin available to define the non-commanding period for all orbits with manoeuvres (operational experience showed that the error on predicting the orbital period, which defined this region, was always below that). As a consequence, the commanded central time of the lowering manoeuvres needed to be shifted 8 min more, leaving the manoeuvre central time 16 min after the apocentre.

Although the Short strategy was validated and tested, it was never used in flight, as during this aerobraking phase there was no need to perform a pericentre lowering manoeuvre (e.g. to avoid closest approach with other satellites).

*Introduction of an extra commanding cycle the "Mini cycle"*

The TGO had the capability to perform an autonomous pericentre raising manoeuvres FRM or Pop-ups. The execution time of those manoeuvres was not shifted by the PTE. Hence, to guarantee the spacecraft safety, an on-board functionality was implemented to trigger a Safe Mode whenever those times became obsolete. The function monitored the delta PTE (DT PTE), time difference between the pericentre time computed on-board and the FD predicted one, and it triggered a Safe Mode if the DT PTE exceeded 1/8 of the orbital period. Therefore, to avoid triggering a Safe Mode, FD had to guarantee that the predicted pericentre time error was below this threshold. This was not a major concert at the start of the aerobraking, it was allowed a deviation of up to 3h, but at the end, the maximum deviation allowed was 15 min.
Flight Dynamics commanding cycles were performed once every 2 days during the Main phase. However, at the End-Game, the commanding cycles were performed daily to have accurate orbit predictions. Nevertheless, for the final phase of the End-Game, it was decided to add a small commanding cycle, the Mini cycle. The purpose of this cycle was to update the times of the autonomous manoeuvres with a more recent orbit and modify the DT PTE threshold at each orbit to increase robustness against triggering a Safe Mode. Table 2 shows daily FD commanding cycle for the last month of aerobraking and the Fig 7 shows the effect of the Mini cycle.

*Table 2. FD commanding cycle with the implementation of the Mini cycle strategy.*

| Time | Event |
|---|---|
| **12:00 Z** | Data cut-off (DCO). |
| **DCO + 5 h** | Typical delivery time for the FD Mini cycle and aerobraking commands (update of the mission timeline) for uplink. |
| **DCO + 12h** | Deadline for FD Mini cycle and aerobraking commands delivery for uplink. |
| **DCO + 12h** | First execution time of the Mini cycle commands. |
| **DCO + 24h** | Execution time of the commands to delete the old aerobraking commands and update the mission timeline with more recent predictions. |
| **DCO + 144h** | Latest execution time (nominally only the first 24h were needed). |

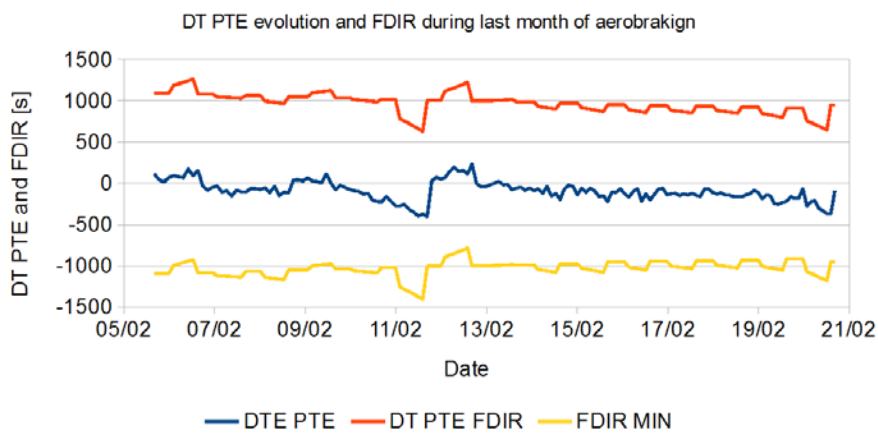


*Fig 7. In Blue DT PTE evolution during the last month of aerobraking. In Red and the Yellow the maximum and minimum deviation allowed.*

To remark that the deadline for the Mini cycle products delivery to the Flight Control Team (FCT) did not allow time for uplink. This was implemented like this as a FCT request, as they preferred to receive only one FD delivery. As FD was delivering much earlier than the deadline, there was always time for the uplink before the execution time started. Nevertheless, the FCT had a contingency procedure prepared to modify the FD commands in the case there was no enough time for uplink. This procedure was never needed.

## Orbits with a Flux Reduction Manoeuvre

The purpose of the FRM was to raise the pericentre to reduce the aerobraking regime if the heat flux (acceleration during the pass) or heat loads (solar array temperature) exceeded a certain threshold or the orbiter period became too low. The later was inactive as it was set to 108 min and the solar array temperature was set by the FCT: -250 deg and +145 deg were used for the whole phase (although it was not needed, there was a monitoring on the minimum temperature). Regarding to the acceleration, FD was responsible to set the threshold. A summary on the evolution of the acceleration threshold can be seen in Fig 8. During the main phase, it was decreased to add margin with respect to the S/C survivability limits (2800 W/m$^2$), while for the End-Game or during the orbit crossing with Phobos, the limit was increased to reduce the probability of triggering it and hence; improve the orbit predictability (note that at the final phase of the End-Game, the DT PTE threshold was as low as 15 min. So, a FRM would certainly lead to a Safe Mode with a Pop-up and, probably, to the early termination of the aerobraking, as a new walk-in would not be feasible). Fig 8 also shows that a FRM triggered once on the 19$^{th}$ September raising the pericentre by 3.2 km.

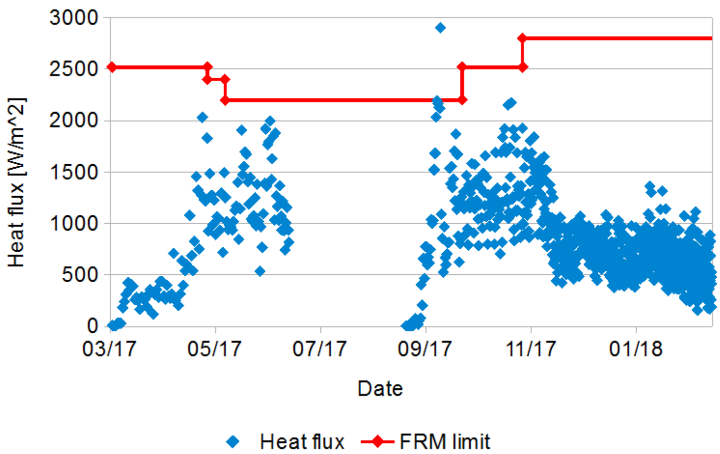


*Fig 8. Reconstructed Heat flux and commanded threshold for FRM triggering.*

The FRM commands were a timeline, executed on top of the nominal aerobraking commands, containing a pericentre raising manoeuvre and a pair of thrusted slews (NOMP), from the exo-atmospheric attitude to the manoeuvre attitude and back as shown in Fig 9. In the case the HGA was deployed (orbits using the timeline from Fig 4), the FRM commands stowed the antenna and kept it stowed until the nominal commands deployed it again after the next aerobraking pass. So, for this orbits there was no Earth contact just after the FRM, contrary to the orbits from Fig 2 as the S/C attitude allowed to have contact with the HGA stowed

The commands for a FRM also deleted all the manoeuvres in the mission timeline (MTL) to avoid that a planned pericentre lowering manoeuvre executed after a FRM. However, this approach was not robust in the case a FRM triggering before the MTL was populated.
The commanding strategy during aerobraking was the following:

- FD delivers the commands to the FCT for uplink.
- FCT uplinks the commands.

- The commands stay on-board in a separate telecomand file (TC file) until a FD command gives the action to delete the old MTL and populate it again copying the commands from the TC file. By design, from the FD delivery to the population of the MTL there was at least 1 day, during the Main phase, and 12h, during the End-Game. This time delay was necessary to provide the FCT with multiple uplink opportunities with two different ground stations. In nominal conditions, the commands were uplinked as soon as FD delivered them. Therefore, the new MTL stayed in a separate file on-board for several hours, before the MTL was populated. Hence, in the case the new set of commands contained a manoeuvre and a FRM triggered after the uplink occurred, but before the MTL population, the manoeuvre would not be removed without ground intervention.

To avoid this situation, at the beginning of the aerobraking, it was decided that a FRM deletes also the file with the new commands. So, if a FRM triggered, the new commands were not used. However, after conjunction, as the orbital period became lower and the DT PTE threshold decreased, it was decided to not delete the new commands, as they were based on a recent orbit, with better predictions. The already available operational experience showed that the atmospheric predictions would not differ in a way that FD commanded a pericentre lowering manoeuvre when, in reality, a raising manoeuvre was required.

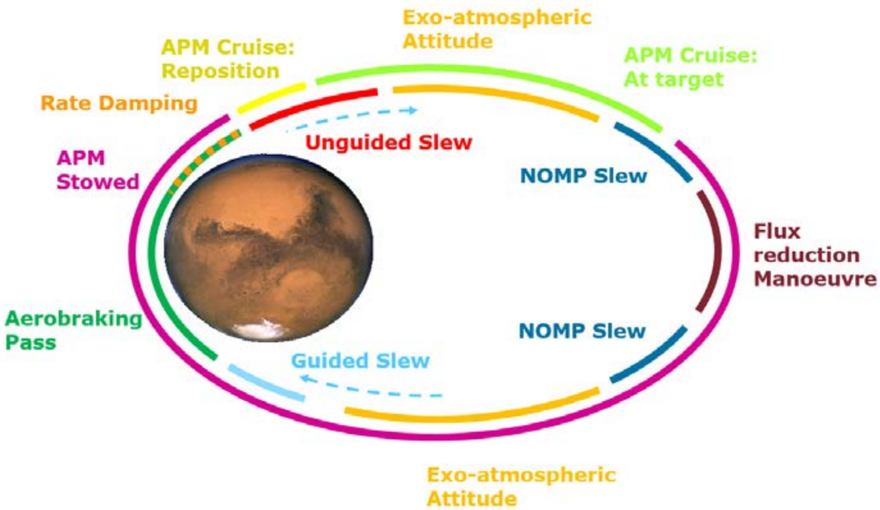


*Fig 9. Timeline for an orbit a without manoeuvre with the HGA deployed and a FRM.*

### *FRM as a Pop-up*

During the first walk-in, it was decided to apply a conservative approach whenever a FRM was triggered. The commands of the FRM were modified to replicate the effect of a Pop-up without going to Safe Mode (called FRM as a Pop-up), i.e the raising manoeuvre was seized to leave the aerobraking regime and the following aerobraking commands were deleted. Although the procedure was tested and commanded, the FRM never triggered. After obtaining aerobraking operational experience, the FRM were commanded using the nominal procedure at the end of the first walk-in.

### *Flip/Flop mechanism*

The series of commands to be executed when a FRM triggered were saved in a TC file. So, whenever the thresholds were exceeded in AEBM the commands from the TC file were copied to the MTL and the FRM sequence was executed. Originally, there was only one TC file available, which was updated as soon as the commands were uplinked. However, for the period from command uplink to MTL population, the FRM commands were not consistent with the MTL commands (the TC file contained the new FRM commands while the MTL still contained the old ones). To overcome this situation, the Flip/Flop mechanism was implemented. Two TC files were available and a command was set to select which one to be used. So, during an uplink the not used TC file was updated and after the new commands were copied to the MTL, the not used file became the applicable one.

## Walk-out

The walk-out was performed with a pericentre raising manoeuvre. Two walk-out were performed, one before conjunction start, with a manoeuvre of 8.6 m/s, and another one when the targeted apocentre altitude was reached, with a manoeuvre of 22.5 m/s. The commanding strategy was slightly different than for a nominal manoeuvre:

- After the manoeuvre, no more aerobraking passes were commanded. So, if the manoeuvre did not perform successfully, a Safe Mode would be triggered when the S/C entered the atmosphere. Then, a Pop-up would raise the pericentre outside the aerobraking regime and stop aerobraking operations.
- The walk-out manoeuvre was not deleted by a FRM.
- It was not allowed to perform a FRM at the same apocentre of the walk-out OCM.
- The Safe Mode Pop-ups were commanded for further apocentres after the walk-out manoeuvre, to provide the S/C autonomy with several attempts to perform the Pop-up.
- The execution of the FRMs and Pop-ups was based on an orbit without the walk-out OCM, as it was given priority to raise more efficiently the pericentre in the case the walk-out OCM did not execute.

## Conclusion

Almost one year of intense aerobraking operations were required to decrease the apocentre altitude from 33160 km to 1049 km. The Flight Dynamics team had several important responsibilities, one of them was to prepare the majority of the S/C commanding. The paper was focused on the complexity of this task and it provided a description of the different commanding strategies that were used. It also reported on how they were adapted in function of the operations needs and S/C capabilities, which proves that a flexible S/C GNC software and ground operations tools are required.

## Acknowledgments

The authors thank the Operations team, in particular the Flight Dynamics team in the interplanetary section at ESA/ESOC, who worked hardly, even during weekends or public holidays, to complete successfully the aerobraking phase. Special thanks to the industrial team in Thales Alenia Space and the Mission Design and Navigation section at NASA/JPL for providing their advices and support during this complex operational phase.

# References


1. 15th International Conference on Space Operations (SpaceOps): "*Thousand times through the Atmosphere of Mars: Aerobraking the ExoMars Trace Gas Orbiter*", Michel Denis, Peter Schmitz, Silvia Sangiorgi, Robert Guilanyà, Pia Mitschoerfer, Mario Montagna, Hervé Renault, Nicolas Kutrowski, May 2018.
2. 15th International Conference on Space Operations (SpaceOps): "*Flight Dynamics Operational Experience from ExoMars TGO aerobraking campaign at Mars*", F.Castellini, G.Bellei, B.Godard, May 2018.
3. 27th International Symposium on Space Flight Dynamics (ISSFD): "*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, R.Guilanyà, P.Muñoz, R.Vidal, E.Basso, J.Schwartz and U.Herfort, February 2019.
4. 23rd International Symposium on Space Flight Dynamics (ISSFD): "*Operational approach for the ExoMars aerobraking*", Robert Guilanyà, Vicente Companys, November 2012.