OPERATIONAL APPROACH FOR THE EXOMARS AEROBRAKING

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Abstract: *ExoMars is the future ESA Martian exploration program with two missions to be launched in 2016 and in 2018. The 2016 mission consists of a composite spacecraft integrated by an orbiter and an entry descend and landing module (EDM). The lander is separated from the orbiter during the last phase of the approach to Mars and performs entry descend and landing (EDL) on Mars. After separation, the orbiter trajectory is deflected, and the orbiter performs a Mars orbit insertion (MOI). The MOI sequence of maneuvers brings the orbiter to a 1-sol orbit. From there, the orbiter is brought to its final relay and science orbit using aerobraking techniques.*

The aerobraking consists in using the drag of the upper layers of the atmosphere to decrease the spacecraft velocity and reach a target orbit. In the case of ExoMars, the aerobraking will circularize the initial high elliptical orbit, after the Mars insertion, to a circular operational orbit. The whole duration of the aerobraking will take several months. Aerobraking involves risk, because the spacecraft is operated close to the acceptable limits in thermal loads. Therefore, a robust operational strategy has to be defined. This paper will analyze the aerobraking phase in detail and present the ESOC proposed operational strategy to control the spacecraft within the nominal orbit during the aerobraking phase.

Keywords: *ExoMars, Aerobraking, EMCD, Mars atmospheric density.*

1. Introduction

ExoMars baseline trajectory considers the aerobraking as a sequence to circularize the high elliptical orbit after the Mars insertion. The aerobraking is spaceflight maneuver to reduce the orbit energy of a spacecraft. The orbit energy is transformed into heat when the spacecraft crosses the high layers of the atmosphere. Hence, parameters as the heat flux and the heat loads need to be controlled during each atmospheric pass. The heat flux is the rate of heat energy transferred to a surface, and the heat load is the total amount of heat energy transferred to a surface. Furthermore, due to the drag effect, the dynamic pressure on the spacecraft has to be also considered.
In order to keep the spacecraft integrity and assure an efficient aerobraking, pericenter control maneuvers will be performed at the apocenter to control the entry corridor of the spacecraft. As an assumption, the nominal trajectory considers maneuvers every 2 days.

For the nominal trajectory, the maneuvers are computed considering a complete knowledge of the Martian atmosphere, the European Mars Climate Database v 4.3 (EMCD) [1] is used as atmospheric model.
Then, an operational approach is applied. The maneuvers are computed without considering previous knowledge of the atmosphere. The only data available are the measurements from the on board accelerometers during different passes and the drag perturbation on the orbit measured by orbit determination. Then, these maneuvers are evaluated with the EMCD considered as the "real atmosphere". For the most of the aerobraking, the results show that it is possible to optimize groups of four maneuvers considering the highest density profile scenario from previous passes. However, at the end of the aerobraking, when the orbital period is below 2h and the number of passes high, each maneuver has to be optimized independently.

2. Nominal aerobraking trajectory

2.1. Aerobraking phases

The aerobraking includes three phases:

- Walk-in phase: It is composed by a group of pericenter lowering maneuvers to gradually decrease the pericenter, until an aerobraking altitude is reached. During this phase, no previous knowledge of the atmosphere will be available. Each maneuver needs to be optimized independently after obtaining atmosphere data from the pericenter height achieved in the previous maneuver.

- Main aerobraking phase: This is the main part of the aerobraking. Normally several pericenter control maneuvers, covering a period of several days, will be optimized as a block. The optimization will target to obtain the maximum performance of the aerobraking compatible with the spacecraft integrity.

- Walk-out phase: The last phase of the aerobraking includes several pericenter raising maneuvers. They will gradually decrease the aerobraking effect until the final target apocenter is reached. This phase is characterized by a large numbers of aerobraking passes and each of them with a high duration. To ensure the safety of the spacecraft, short turn-around time for operations is considered, with an optimization of one maneuver each time.

2.2. ESOC operational constraints

2.2.1. Target apocenter

The aerobraking shall reduce the initial radius of the apocenter around 37000 km to a final apocenter of 3797.51 km of radius or 400 km of altitude with respect to Mars equatorial mean radius. After that, pericenter raising maneuvers will be performed to obtain the science circular orbit of 400 km altitude.

2.2.2. Aerodynamic constrains

The aerodynamic constraints applicable during the aerobraking are:

- The dynamic pressure Eq 1:

$$Dpr = 1/2\,\rho v^2 \quad (1)$$

- Free stream heat flux by unit surface Eq 2:

$$Hfl = 1/2\,\rho v^3 \quad (2)$$

- Free stream heat loads by unit surface Eq 3:

$$Hlo = \int Hfl \cdot dt \quad (3)$$

Where Dpr is in Pa, Hfl in W/m^2 and Hlo in J/m^2.
v: modulus of the aerodynamic velocity in m/s
ρ: air density kg/m^3

ESOC operational constraints require a 100% margin with respect to the spacecraft design limitations. Thus, the maximum values targeted during operations are:

- Maximum peak free stream heat flux: 1400 W/m^2
- Maximum peak dynamic pressure: 0.30 Pa.
- Maximum free stream heat load per pass: 250 kJ/m^2

2.2.3. Survivability of the spacecraft

ESOC requires that the operational plan shall guarantee the integrity of the spacecraft for 48h when the spacecraft is not capable to perform nominal activities planned on the ground. The worst case scenario is the situation in which the spacecraft fails to perform a planned pericenter control maneuver. Also in this case, the spacecraft shall survive 48h more.

The requirements of survivability are:

- Not to violate any aerodynamic constrain during 48h after the interruption of the scheduled plan.
- Not to decrease the apocenter less than 350 km of altitude during 48h after the interruption of the scheduled plan.

Note that under normal conditions, if the spacecraft detects a violation of the minimum altitude or an aerodynamic constraint, it will perform an autonomous small pericenter raising maneuver. Furthermore, if the spacecraft enters in safe mode, it will perform an autonomous large pericenter raising maneuver. However, the survivability requirement has to be fulfilled even in the case the emergency maneuver fails.

2.2.4. Visibility constraints

ESOC requires that no aerobraking shall be performed with a Sun-Earth-Spacecraft angle (SES) below to 10 deg.

2.3. Orbiter initial state

The interplanetary trajectory of the ExoMars composite spacecraft is optimized to land the EDM at a latitude of 1.82 south and a longitude 6.15 west.
After the separation, the orbiter performs a Mars insertion, MOI. Then, several maneuvers are performed to modify the inclination and reduce the orbital period to 1-sol. The final pre-aerobraking orbit is defined in Tab. 1:

Table 1. Pre-aerobraking orbit

* In Mars Mean Equatorial of Date (MMED) reference system

Date (UTC) (Cal)	04-11-2016
Radius of the pericenter (km)	3619
Radius of the apocenter (km)	37165
Inclination* (deg)	74
RAAN* (deg)	324.5
Argument of the pericenter* (deg)	185.0
True anomaly (deg)	90
Mass (kg)	1762

2.4. Mars atmosphere

Mars atmosphere is simulated by the EMCD v4.3 [1]. The used atmospheric scenario is M24 which mimics the Mars atmosphere as observed by the MGS (Mars Global Surveyor) from 1999-2001 combined with an averaged solar EUV (Extreme UltaViolet) condition.
Then, to assure continuity from an environment with atmosphere to the outer space, at 200 km of altitude, the atmosphere model is switched from EMCD v4.3 to a simple exponential model based on:

- Base density: $5.38 \cdot 10^{-12}$ kg/m^3
- Base Height: 230 km
- Scale Height: 22.893 km
- Fixed temperature
- No wind

2.5. Trajectory results

2.5.1. Walk-in phase

The walk-in phase is performed by a group of 5 pericenter lowering maneuvers at the apocenter. Those maneuvers are decreasing in Delta-V to be robust against misperformances on the GNC and the uncertainties on the atmosphere.
For operational reasons, each maneuver is separated by 3 revolutions (considering the initial period of the orbit, this is approximately 3 Sols). Thus, data from 2 pericenter passes can be analysed to obtain an atmospheric density profile. Furthermore, there is still one Sol to perform accurate orbit determination and optimise the next maneuver.
One week is left before performing the last maneuver. This will allow collecting more data about the Martian atmosphere.
Table 2 defines the walk-in maneuvers:

Table 2. Pericenter lowering maneuvers during walk-in phase

Maneuver	Delta-V (m/s)	Delta on Rpe (km)	Min pericenter altitude above the areoid (km)	Max aerodynamic acc. (mm/s^2)	Max. Dpr (Pa)	Max. Hfl (W/m^2)
1st	4.63	-81.1	165.2	0.08	0.002	11.4
2nd	1.73	-30.0	136.7	1.02	0.032	150.2
3rd	0.58	-10.0	128.1	3.62	0.112	532.5
4th	0.29	-5.0	124.5	6.66	0.206	979.2
5th	0.29	-4.9	120.2	9.54	0.295	1400.0

The condition for each maneuvers are set as follow:

- All of them are centered on the apocenter.
- Maneuver 2, 3 and 4 have a fix Delta on radius of pericenter (Rpe).
- Maneuver 5, the maximum Delta on Rpe allowed is 5 km.
- Maneuver 1 should have a Delta on Rpe that:
    - During the 7 days waiting time between maneuver 4th and 5th, the maximum head flux on the pericenter shall be below 1200 W/m^2.
    - One of the 3 pericenter passes after the 5th maneuver has a heat flux of 1400 W/m^2, and the other two have a lower heat flux.

2.5.2. Main phase

The main phase is based by several maneuvers, performed on the apocenter, which control the pericenter high. From the ESOC requirements, each maneuver shall assure:

- Not to violate any aerodynamic constraint until the next maneuver + 48h.
- Not to decrease the apocenter height below 350 km until the next maneuver + 48h.

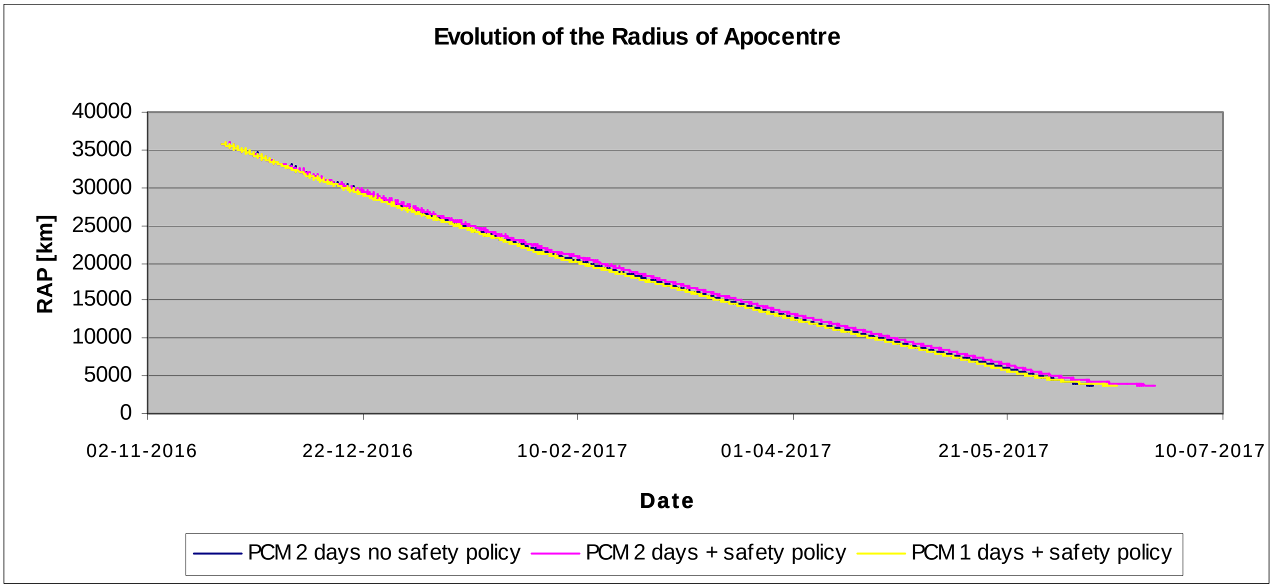
Due to the survivability requirement, the worst case to be analyzed is when the spacecraft enters in safe mode at the moment to perform a pericenter control maneuver (PCM) and no autonomous pericenter raising maneuver is performed. Then, the previous maneuver has to assure 48h without violating any aerodynamic constraint and also assure the apocenter height remains above 350 km.

Two strategies are analyzed:

- One PCM at approximately every 2 days.
- One PCM at approximately every day.

One simulation including maneuvers every 2 days without considering the safety policy of a potential failure of maneuvers is performed. This is done only to show the effect of the survivability requirement, but it is not considered a valid operational approach.

Figure 1. Evolution of the radius of the apocenter during the aerobraking



To consider potential failures of maneuvers increases the duration of the aerobraking by several days (Fig. 1).

If a maneuver is performed each day, the aerobraking corridor can be better adjusted and the whole phase is slightly shorter than performing a maneuver every 2 days.

The duration for the different scenarios is shown in Tab. 3. Note that for these simulations a continuous aerobraking phase has been assumed disregarding the need to interrupt aerobraking for bridging conjunction. In real operations, aerobraking will be interrupted latest at Sun-Earth-spacecraft angle of 10 degrees.

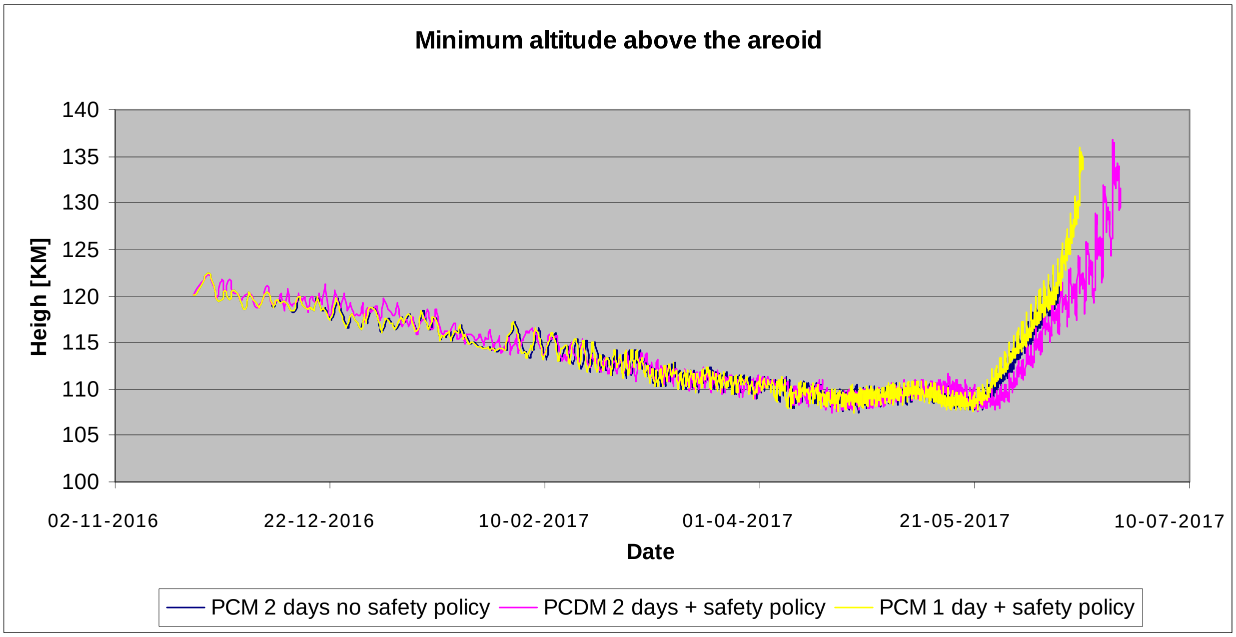
Table 3. Aerobraking duration

	Start	End	Duration (days)
PCM 2 days no safety policy	04-11-2016	09-06-2017	218
PCM 1 day + safety policy	04-11-2016	15-06-2017	223
PCM 2 days + safety policy	04-11-2016	24-06-2017	232

Table 4. Conjunction periods

	Start	End
SES < 10 deg	24-06-2017	27-08-2017
SES < 5 deg	11-07-2017	11-08-2017

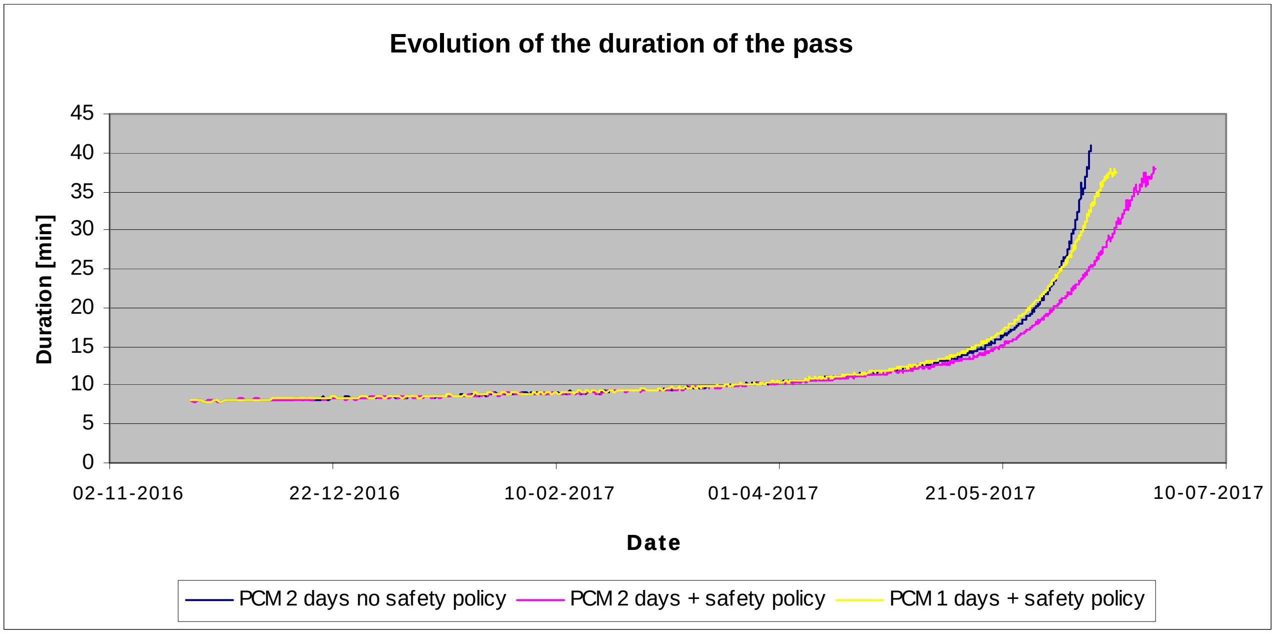
Figure 2. Evolution of the minimum altitude during a pass



As the spacecraft velocity is decreasing, the pericenter shall be reduced in order to obtain higher density and keep the maximum value of aerodynamic constraints constant, Fig. 2. The active constraint is the peak heat flux and the dynamic pressure.

At the walk-out, the duration of the passes increases, Fig. 3. Thus the active constraint is the heat loads and the minimum altitude of the apocenter.

Figure 3. Duration of the pass (when altitude below 200 km)



At the beginning of the aerobraking, the heat flux is the active constraint, Fig. 4. Then, the active constraint is the dynamic pressure, Fig. 5.

Figure 4. Evolution of the heat flux

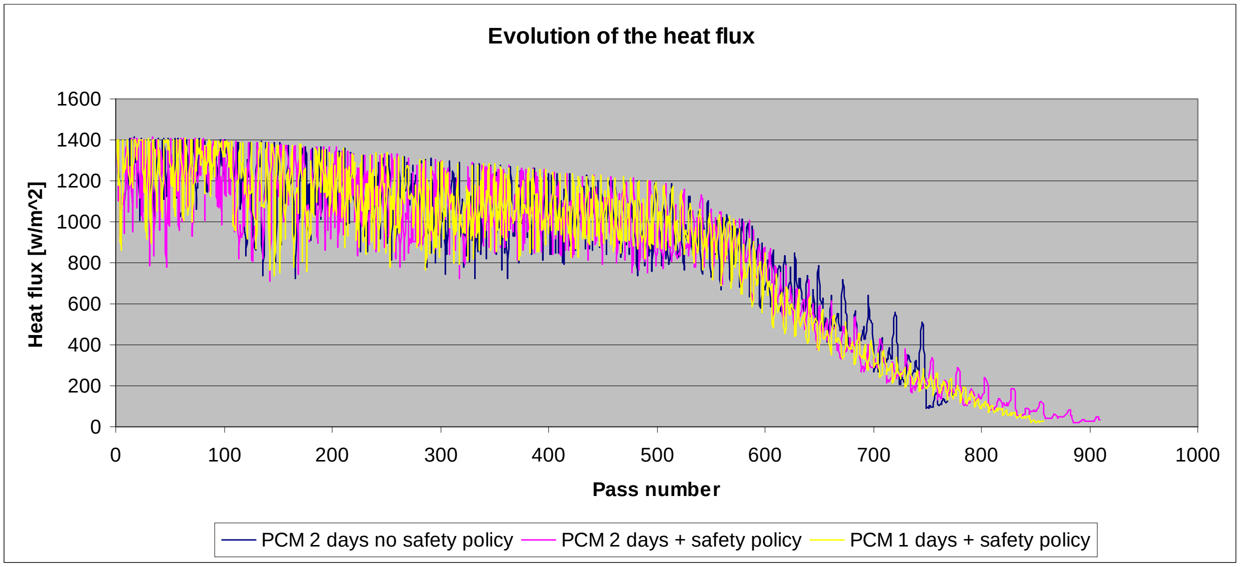
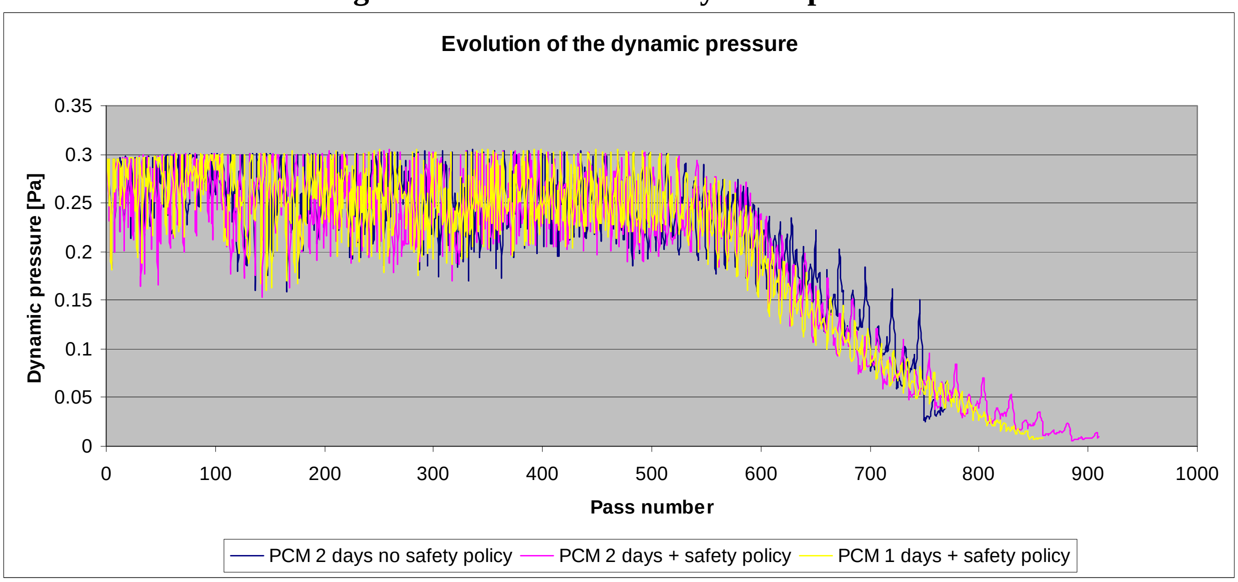


Figure 5. Evolution of the dynamic pressure



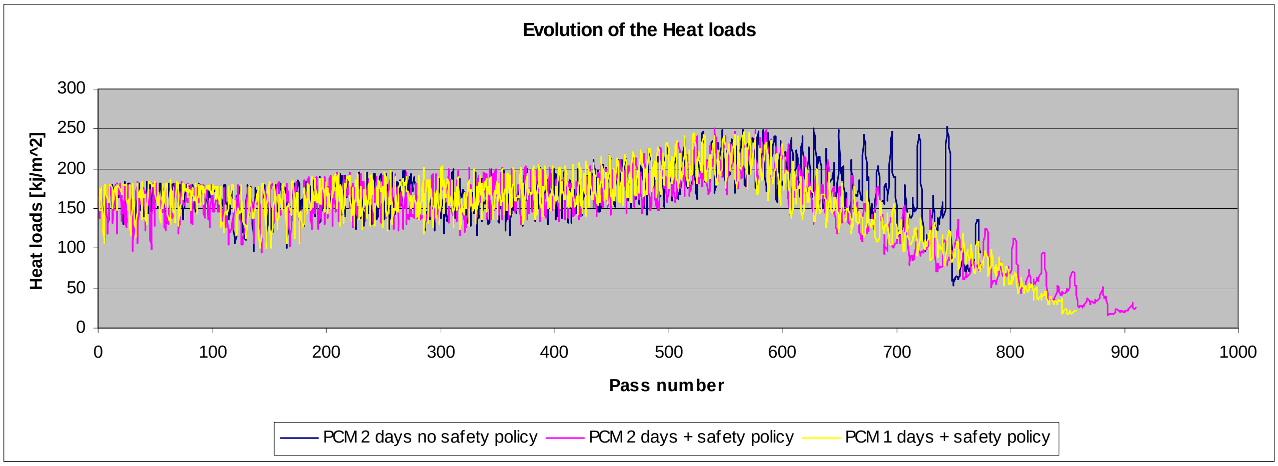
2.5.3. Walk-out phase

This phase consist in performing several maneuvers to raise the pericenter but without leaving the aerobraking.

During this phase there are two active constraints:

- The heat loads: They are active during most of the walk-out. As the duration of the pass increases, the integral of the head flux becomes the sizing constraint of the PCM.
- Minimum altitude of the apocenter 350km: During the last passes the active constraint is to avoid a decay of the apocenter below an altitude of 350km during the time between maneuvers + 48h of survivability.

Figure 6. Heat loads evolution in function of the pass



The walk-out phase starts approximately at the pass 600. The maximum heat load is only achieved in the simulation without safety policy. This happens because in the other cases the maximum head loads are found on the 48 extra propagated hours,

Also, the blue line shows that at the last passes the heat loads are not an active constraint anymore. This is because, from that point, the active constraint is to avoid decreasing the altitude of the apocenter less than 350km for at least 48h.

This also happens to the other two cases.

Figure 7. Heat flux evolution after maneuver 107

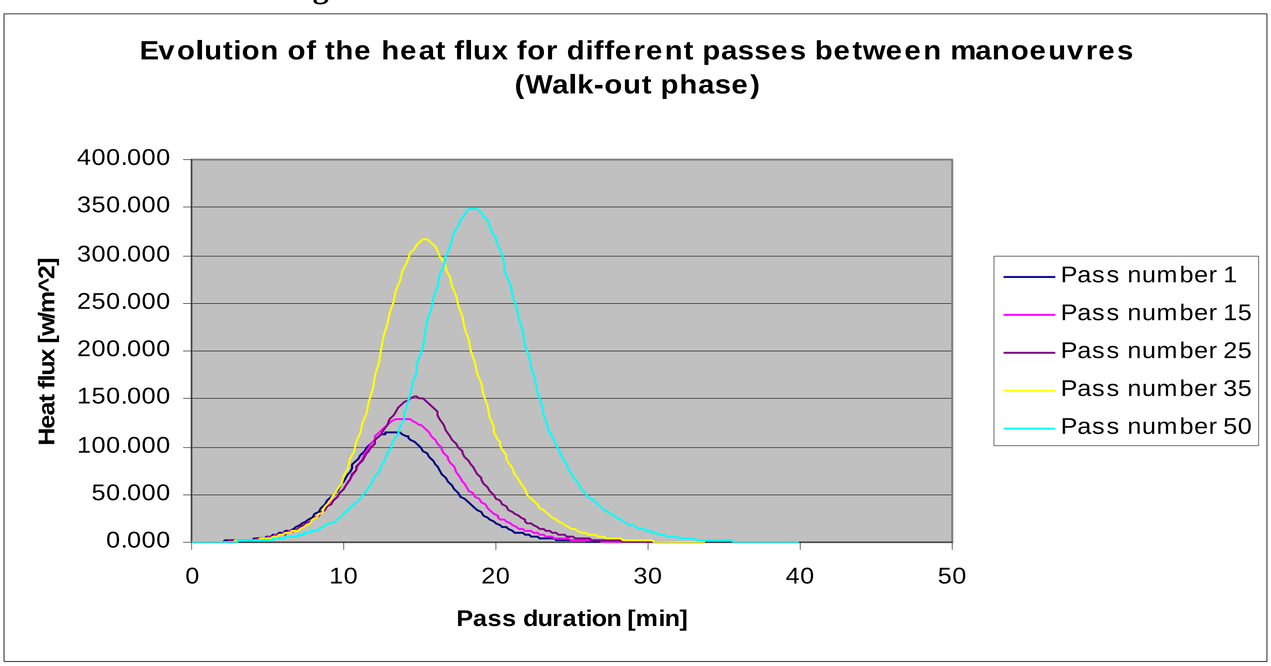


Figure 8. Heat loads after different maneuvers

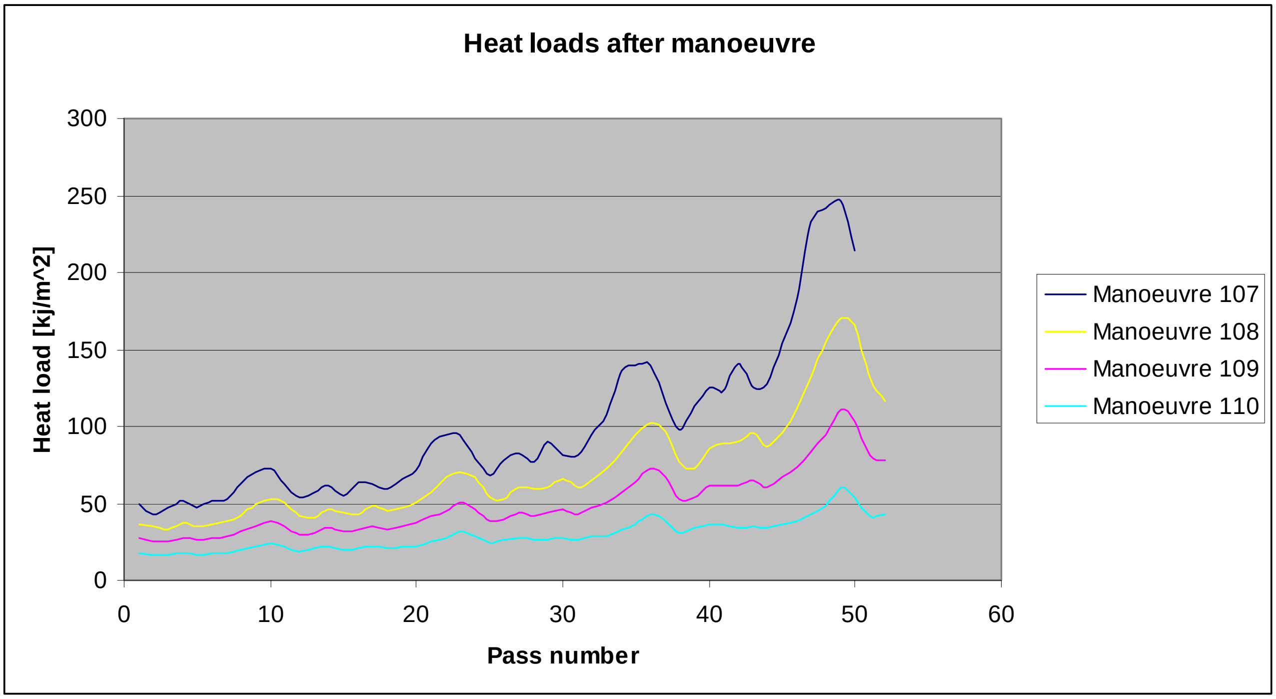


Figure 7 plots the evolution of the heat flux after the maneuver 107 (from a total of 110). The peak values increase each pass, so the active constraint is at the pass number 49. However, if there is no maneuver failure, the pass number 49 will never exist, because the next PCM (maneuver 108) will be performed after the pass 25.

Figure 8 confirms that the active constraints are on these 48 extra propagated hours.
Moreover, it shows that the last maneuvers (108, 109 and 110) the heat loads are not a constraint anymore, since the minimum altitude of the apocenter is the active one.

2.5.4. Maneuvers

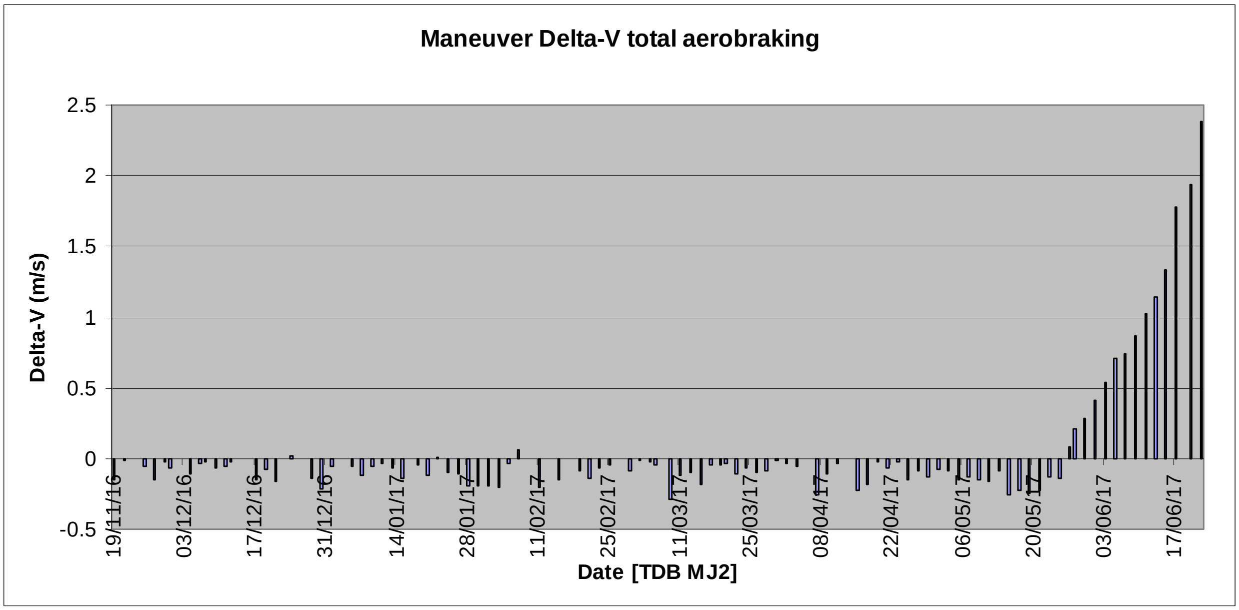
The baseline strategy for the aerobraking contains 110 control maneuvers.

Figure 9 represents the magnitude of the 110 maneuvers. In the figure the convention is used to represent maneuver along the spacecraft velocity as positive Delta-V and maneuvers opposite to the spacecraft velocity as negative Delta-V.

During main part of the aerobraking the pericenter is lowered. This is because after the walk-in the altitude of the pericenter tends to naturally increase. Also, as the spacecraft velocity is decreasing, the pericenter has to be lowered to obtain efficient aerobraking within the aerodynamic constraints.

Finally, during the walk-out there are several maneuvers which gradually increase the Delta-V.

Figure 9. Nominal maneuvers performed during the aerobraking



At the end of the walk-out phase the total consumed Delta-V is the following (without including initial pericenter lowering and final circularization):

Table 5. Total Delta-V consumed for the PCM

PCM 2 days no safety policy	15.51 m/s
PCM 1 day + safety policy	22.19 m/s
PCM 2 days + safety policy	22.18 m/s

3. Operational Approach

All the previous simulations have been performed considering perfect knowledge of the atmosphere. It is not expected that ground models will be accurate enough to support aerobraking operations in an open loop fashion.

Hence, a strategy shall be defined that uses in-flight measurements of the atmospheric density during the aerobraking operations.

The main drivers of this strategy must be:

- 1st safety and robustness
- 2nd performance of the aerobraking (duration)

3.1. Atmosphere Modeling

It is assumed that the ground has no previous knowledge of the atmosphere. This knowledge is gained only observing the performance during the aerobraking. The main sources of atmospheric data are:

- Aerodynamic acceleration: The aerodynamic acceleration is derived from accelerometer measurement. The aerodynamic velocity is approximated by the spacecraft velocity in Mars fixed reference frame (Mars Mean Equatorial of Date non inertial) and is used together with the aerodynamic acceleration to derive the density profile.
- Orbit determination: The overall effect of each aerobraking pass is computed by orbit determination techniques and is used to obtain a calibration factor for the acceleration profile and for the density profile.

Statistics over 7 days in the past are used to prepare operations for the future passes. The highest observed density profile will be taken to optimize the following maneuvers.

Nevertheless, the measured density data is only available for a certain altitude range which limited by the actually flown altitude and by the sensitivity on the accelerometers. Densities are extrapolated by an exponential model with:

- Base density: As the density at the lowest/highest altitude for which measured data are available.
- Base height: As the height where the base density was taken
- Scale factor: Average values from ground based models (EMCD), or also derived from the overall effect of the aerobraking passes observed from orbit determination.

3.2. Study case

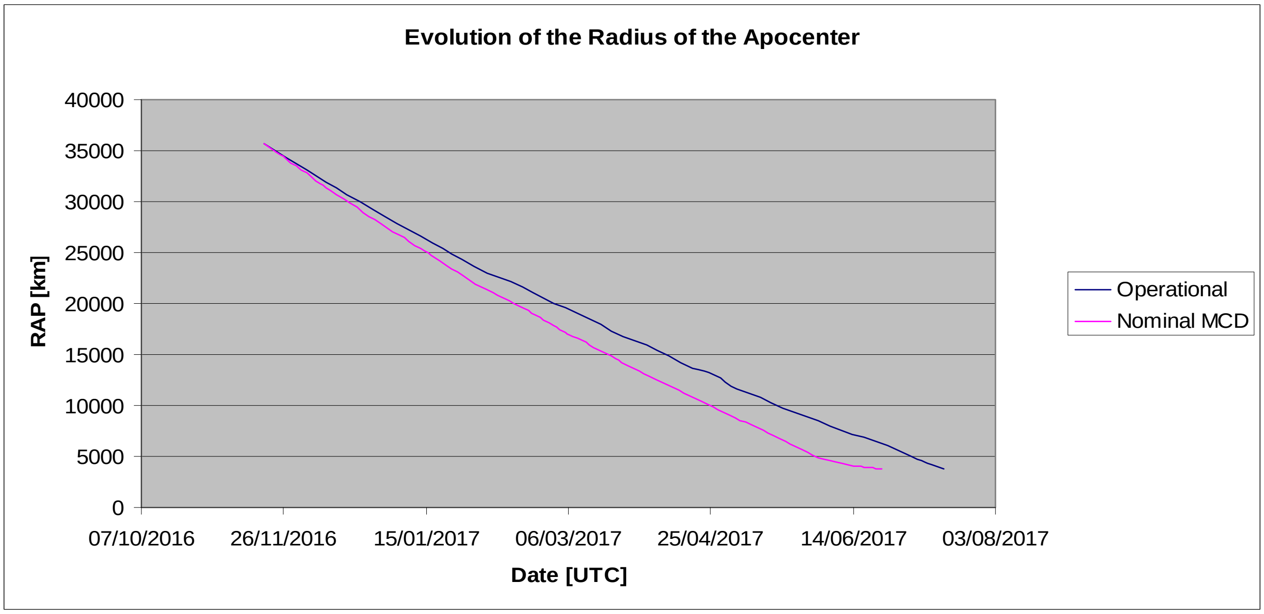
In order to simulate the operations, a study of the whole aerobraking phase has been performed:

- 4 maneuvers are optimized in one run using the same atmospheric profile.
- The atmospheric profile is the highest density profile derived from the last 7 days of aerobraking.
- 2 days between maneuvers are considered. This is in total 8 days of aerobraking.
- The EMCD M24 atmosphere has been considered as the “real world”.
- The actual trajectory evolution is evaluated using the “real world” atmospheric model. New acceleration data are obtained to optimize the following 4 maneuvers.

3.2.1. Results for the nominal operational case

The measured profile with highest density is taken for the preparation of future maneuvers. Because of this, the actual atmosphere density is normally lower than predicted. The resulting aerodynamic parameters (Dpr, Hfl and Hlo) are below the targeted values and the aerobraking is suboptimal, hence longer, compared to the case assuming perfect atmosphere knowledge.

Figure 10. Comparison between the optimal case and the operational



The total duration of the aerobraking considering the operation strategy exposed above is 254 days. Then, the aerobraking will not finish before the solar conjunction in summer 2017.

If aerobraking is started before the summer conjunction 2017 it will have to be interrupted to bridge the conjunction. This shall be done by implementing a maneuver raising the pericenter to a safe altitude. Aerobraking can be continued in this case by performing an additional walk-in after conjunction.

The decrease on apocenter is faster in the operational case during the walk-out phase. This is shown on the slope of the curve; the operational curve is sharper than the nominal EMCD one. This will be discussed later.

3.2.2. Main aerobraking phase

The operational approach appears to be robust to the atmosphere uncertainties for the main aerobraking phase. Table 6 shows the maximum achieved values for different cases:

Table 6. Comparison between maximum achieved value in the EMCD and its predicted value with the atmospheric profile

Worst pass of the 4th optimization	**Predicted**	**EMCD "real"**
Max dynamic pressure (Pa)	0.30	0.30
Max heat flux (W/m^2)	1387	1423
Max heat loads (kJ/m^2)	188	183
Worst pass of the 19th optimization	**Predicted**	**EMCD "real"**
Max dynamic pressure (Pa)	0.30	0.34
Max heat flux (W/m^2)	1288	1486
Max heat loads (kJ/m^2)	212	214

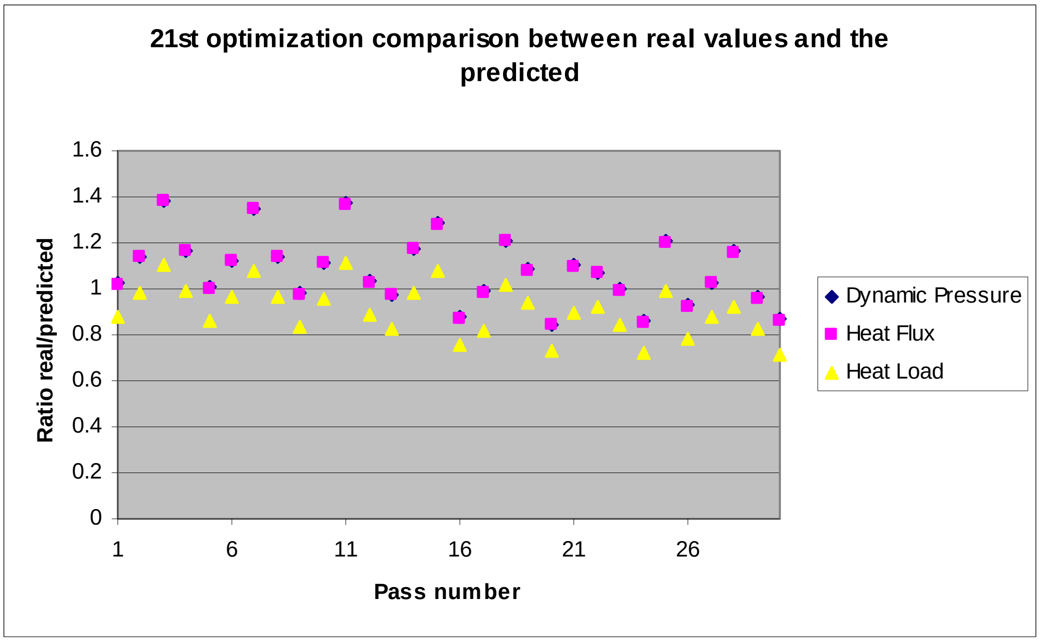
Due to the 100% design margin of the aerobraking operations the spacecraft integrity is guaranteed.

Table 7 and Fig. 11 show the worst case encountered during the main aerobraking phase.

Table 7. Worst case achieved during the main phase

Worst pass of the 21st optimization	Predicted	EMCD "real"
Max dynamic pressure (Pa)	0.28	0.38
Max heat flux (W/m^2)	1212	1673
Max heat loads (kJ/m^2)	207	235

Figure 11. Ratio of maximum achieved aerodynamic constraints and maximum expected for the passes between maneuver 21st and 22nd



Since the optimization 20th had a low density profile, the predicted density profile for the optimization 21st is underestimated. Thus, the aerodynamic constraints are violated. As mentioned before, protection is provided by the operations design margin in the constraints and by the spacecraft capability to perform autonomous pericenter raising maneuvers.

This case shows that indeed autonomous pericenter raising maneuvers are likely to occur and shall be considered as a nominal activity. Furthermore, the EMCD "real atmosphere" does not consider dust storms, because the M24 average is being used. Therefore, more cases as this could appear in a real situation.

3.2.3. Walk-out phase

The walk-out phase is highly critical. Pairs of maneuvers are optimized in one go, instead of groups of 4 maneuvers as for the main aerobraking phase. Hence, a better approximation of the

Martian atmosphere is obtained. Even thus, the expected values for the aerodynamic constraints are severely violated at the last maneuvers of the walk-out. Then, the apocenter is reduced faster than the predicted.

Table 8. Maximum achieved value in the EMCD and its predicted value with the atmospheric profile during the walk-out

Worst pass for the penultimate optimization before end	**Predicted**	**EMCD "real"**
Max dynamic pressure (Pa)	0.12	0.19
Max heat flux (W/m^2)	419	700
Max heat loads (kJ/m^2)	151	258
Worst pass for the last optimization before end	**Predicted**	**EMCD "real"**
Max dynamic pressure (Pa)	0.07	0.20
Max heat flux (W/m^2)	263	697
Max heat loads (kJ/m^2)	122	359

As it is shown on the predicted maximum values of heat loads, at this phase the active constrain is not to decrease the apocenter below 350 km in 48 h.
The predicted values are much below the "real". In any case the integrity of the spacecraft is guaranteed, thanks to the 100 % operational design margin, the spacecraft capability to perform autonomous pericenter raising maneuvers and the low target aerodynamic constraint values during the walk-out.

Another problem on the walk-out is the error to determine the final radius of the apocenter. While the predicted simulation determines an apocenter of 3962 km after the last 2 maneuvers, the EMCD "real" apocenter is at 3763 km, almost 200 km below the expected value. However, if the apocenter decreases less than a threshold a pop-up maneuver will be performed.

To improve the strategy, a single maneuver is optimized with the same atmospheric profile. This means one optimization contains only 2 days of aerobraking. Then, the aerobraking is performed slower than the previous case and the aerodynamic constraints are not severely violated.

Table 9. Worst passes during at the walk-out

Worst passes during the walk-out	**Predicted**	**EMCD "real"**
Max dynamic pressure (Pa)	0.15	0.23
Max heat flux (W/m^2)	544	825
Max heat loads (kJ/m^2)	176	266
Max dynamic pressure (Pa)	0.12	0.19
Max heat flux (W/m^2)	453	679
Max heat loads (kJ/m^2)	156	237
Max dynamic pressure (Pa)	0.07	0.12
Max heat flux (W/m^2)	253	446
Max heat loads (kJ/m^2)	112	191

Table 10. Worst pass after the last maneuver

Worst pass of the last optimization	Predicted	EMCD "real"
Max dynamic pressure (Pa)	0.00	0.00
Max heat flux (W/m^2)	9	3
Max heat loads (kJ/m^2)	10	3

Table 10 represents the end of the aerobraking, when the target apocenter reaches 400 km altitude.

4. Conclusion

In order to define the maneuver strategies, a complete aerobraking phase has been simulated assuming perfect knowledge of the atmosphere. The duration of the aerobraking is more affected by the safety policy (i.e. survivability in case of interruption of maneuvers) than the frequency of PCM.

Furthermore, an operational approach for conducting aerobraking has been defined, that is independent of an accurate, a-priori, knowledge of the atmosphere.

This study determines that the aerobraking will not be completed before the conjunction season in July 2017 due to:

- The applied safety policy in case of maneuver interruption.
- The operational approach delays the aerobraking compared to the optimum case (perfect knowledge of the atmosphere).
- Any contingency will delay the aerobraking:
  - Violation of an aerodynamic constraint, which lead to a small pericenter raising maneuver.
  - Safe mode which leads to a large pericenter raising maneuver.
- In the future, more time margins might be introduced.

The following topics of investigation are:

- Determine a strategy to avoid the conjunction
- Define a more complex methodology of an operational approach, which considers the necessary time to determine an atmospheric profile, optimize new maneuvers and command them to the spacecraft.

7. References

[1] F.Forget, E.Millour, S.R.Lewis, "Mars Climate Database v4.3 User Manual MCDv4.3 User Manual", April 2008, EMCD Live access Server: http://www-mars.lmd.jussieu.fr