

VENUS EXPRESS AEROBRAKING

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Abstract: *Venus Express has been orbiting Venus for 5 years. It was originally designed to use aerobraking as a back-up in case of main engine failure but this feature has never been activated. This paper presents the analyses and tests performed by Astrium and ESA to demonstrate the actual feasibility of aerobraking in order to prepare the first ever European aerobraking campaign.*

Keywords: *Attitude control, trajectories, models, observability, mission control and operations*

1. SUMMARY OF VENUS EXPRESS CONTEXT AND MISSION

Venus Express (VEx) is an ESA research satellite developed by Astrium. Venus Express was launched on November 9th 2005 by a Soyuz-Fregat launcher from Baikonour and reached Venus on April 11th 2006.

The scientific goal of the mission is to investigate the structure, dynamics and composition of the atmosphere, the cloud system, selected surface properties and the interaction of the atmosphere and the solar wind at Venus. Venus Express is carrying seven scientific instruments (spectrometers, an imaging spectrometer, a four-band camera, a magnetometer and a plasma and energetic particle analyser) and is currently orbiting the second planet of the solar system at an altitude between 165 and 66,000 kilometers in a 24-hour period orbit).

Characterising and understanding the prevailing conditions and processes on the surface, in the atmosphere and in the near environment of Venus is of fundamental importance for understanding Venus as a planet and for understanding terrestrial planets in general. It is of particular interest to get a better picture of why Venus and our own planet have taken such different pathways in their evolution.

The mission was originally scheduled for two years of operation but has, thanks to its excellent performance and exciting data provided, been extended three times and is presently funded for operation until end of 2014.

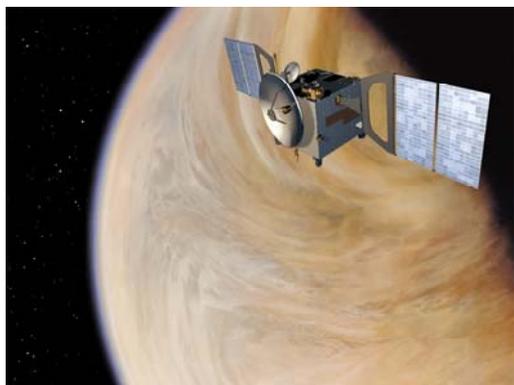


Figure 1: *Venus Express artistic impression*

2. AEROBRAKING INITIAL OBJECTIVES

The original purpose of aerobraking was to enable the spacecraft to reach the operational orbit acquisition in case of a failure of the main engine after the Venus orbit insertion operation or to save propellant if deemed necessary

The principle of aerobraking is to dive into Venus atmosphere and use air drag on spacecraft surfaces (especially on the solar arrays) for slowing down the spacecraft and hence reduce progressively the apocentre altitude and the orbit period (see figure 2).

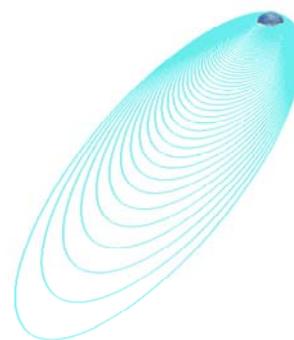


Figure 2: *Trajectories resulting from Aerobraking*

Once the target altitude for the apocentre is reached the aerobraking operations are completed by raising the pericentre back to an altitude where there is no longer air drag. This is achieved through one (or several) orbit correction manoeuvre(s) at the apocentre.

3. AEROBRAKING DESIGN

The proposed strategy would be to use a soft aerobraking, limited to a dynamic pressure between 0.2 and 0.3 N/m². This approach is not expected to induce any constraints at equipment level, or to exceed any specific thermal qualification level, even for the solar array.

The four 10N thrusters on the -Z panel provide the required attitude control during the aerobraking phase.

All operations are pre-computed on ground for this phase. Just before the atmospheric pass which lasts a few

minutes, the satellite Z axis is approximately aligned with the orbital frame. Solar array (SA) wings are positioned with the solar cells facing +Z axis (so protected from the air flow) and the main engine axis is aligned with the satellite velocity vector. This position is selected because it is aerodynamically stable (see figure 3).

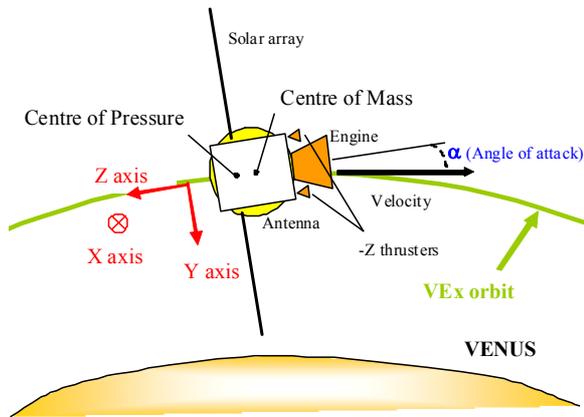


Figure 3: Aerobraking configuration

Important air drag torques are acting on the satellite during the atmospheric pass. Controlling these torques would lead to a propellant consumption that would counter-balance the mass gain brought by the aerobraking. It is therefore necessary for the satellite configuration to be aerodynamically stable. Such a stability is ensured if the Centre of Mass (CoM) is sufficiently ahead of the Centre of Pressure (CoP) with respect to the flight direction: this condition is fulfilled by the Venus Express design (the angle between the aerodynamically stable attitude and the velocity vector is the angle of attack α : see fig. 3).

During a control-free atmospheric pass, the satellite will oscillate about its stable position as the entry conditions are not perfect (initial small attitude and rate errors with respect to the stable attitude),.

It is not necessary to predict the exact stable reference attitude. Trying to control the attitude with a very high precision would lead to compensate for air drag torques and as a consequence to use thrusters and propellant. The solution is to relax the attitude pointing precision to $\pm 15^\circ$ and so reduce the thrusters activation during the atmospheric pass. Oscillation periods and dynamics pressure evolutions knowledge is used to precisely define the limits of this control dead-band. At the end of the atmospheric pass, the satellite attitude and rates are accurately controlled with thrusters until they reach a level compatible with the reaction wheels capacity allowing the transition to the 3-axis control using reaction wheels.

Figure 4 shows a typical aerobraking sequence. Slew manoeuvres must be performed between the Earth-Sun pointing attitude outside the pericentre crossing and the aerobraking attitude during atmosphere crossings.

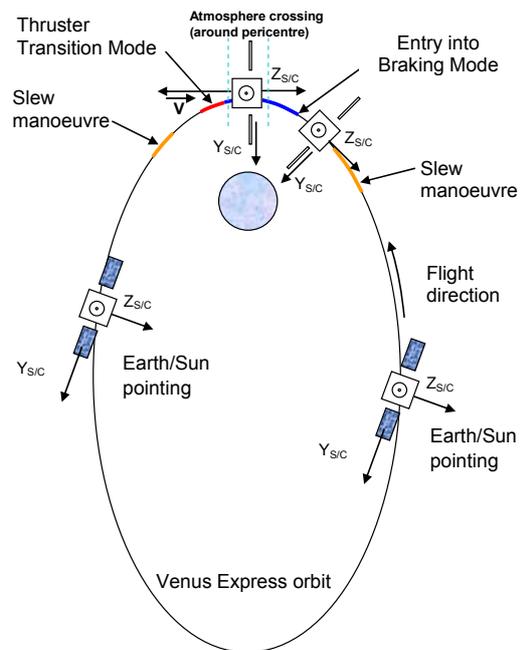


Figure 4: Example of aerobraking sequence (configuration with Sun and Earth at 90° from orbit plane)

4. REVIEWED AEROBRAKING OBJECTIVES

The Venus Express project requested to analyse the use of aerobraking to reduce the 24h current orbit period down to 18 hours or even 12 hours. Such a modified orbit will enable new improved and more frequent opportunities for scientific return observations. It will also provide a more stable orbit that needs less frequent control manoeuvres and thereby it will extend the mission. Finally, unique information on the atmosphere will be collected during the aerobraking itself.

The approach will be to allow a natural decay of the pericentre down to 130-140 km and use the atmosphere forces against the surface of the spacecraft to dissipate kinetic energy slowing down the velocity thus progressively reducing the apocentre altitude.

Operational experience of aerobraking will also provide Europe with a key expertise useful to prepare future missions to planetary bodies with atmospheres, including ExoMars or a Mars sample return mission. The VEx aerobraking campaign, if performed, will last several months.

5. CURRENT FLIGHT EXPERIENCE: AIR DRAG EXPERIMENT

ESA has already started a series of Air Drag Experiment (ADE) campaigns where the effect of the drag is measured by the change in the orbit (radio tracking) and by monitoring the torque acting on the spacecraft.

The main purpose of these campaigns is to perform measurements of the atmospheric density at low altitudes, below 200 km, in the polar latitudes.

The scheduling of the campaign makes use of the fact that the orbit pericentre evolves due to solar perturbations. Before 2009, this drift was directed upwards but since 2009 this drift is directed downwards (see figure 5). By adjusting the solar array configuration it is possible to observe on the reaction wheels the disturbing torques induced by air drag on the panels and hence assess the atmospheric density.

Figure 5 displays a typical evolution of VEx orbital decay and shows the existence of plateaus during which the pericentre altitude remains relatively constant. These plateaus are currently used by ESOC to perform the ADE.

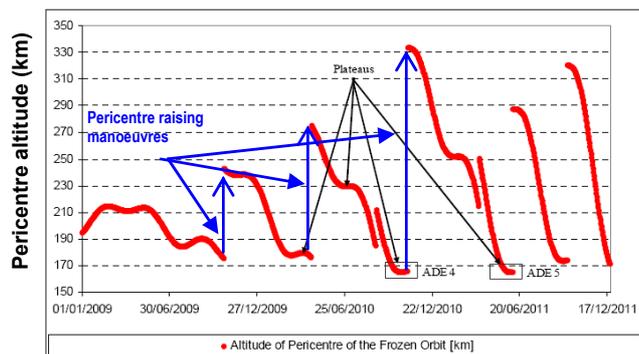


Figure 5: Orbital decay and manoeuvres

The results presented in the following sections 5.1 and 5.2 below are mainly repeated from [2].

5.1 Assessment of atmospheric torques

One of the objectives of the ADE campaign was the identification of aerodynamic torques in order to refine the aerodynamic torque models. As detailed in ref. [2], by adjusting the orientation of the solar panels before, during and after the atmosphere crossing, it was possible to isolate the impact of aerodynamic torques from other disturbing torques, like gravity gradient and solar radiation pressure on the reaction wheels (see figure 6).

Note that the air drag disturbing torques could be observed even for relatively high altitudes (> 165 km) thanks to the significant asymmetry introduced by the tilted solar panels.

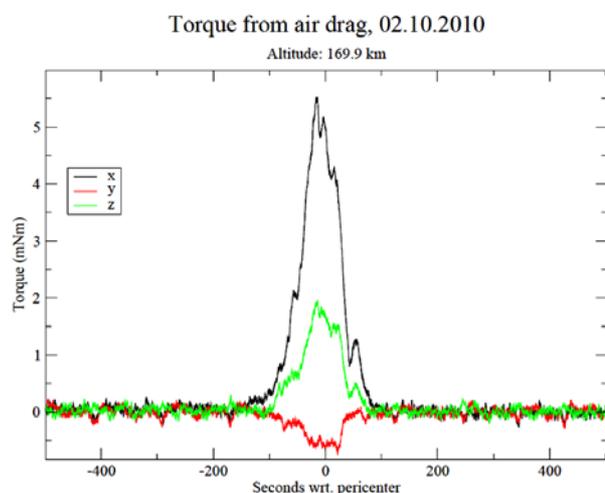


Figure 6: Measured air drag torques

5.2 Assessment of atmospheric density and aerodynamic torque models coefficients

The next step was to determine the atmospheric parameters (for polar orbits) and to identify the aerodynamic torque model coefficients.

This information (detailed in [2]) is a good starting point for the aerobraking operations since it can be used during the walk-in phase to set the initial value for the plateaus altitude.

ESOC analyses have confirmed the variability of Venus atmosphere between successive orbits: evolutions with time, space and illumination conditions. Further refining of the atmospheric model will be performed during the next ADE campaigns under preparation.

6. PREPARATION OF AEROBRAKING OPERATIONS

Parallel to ADE campaigns, since July 2010, Astrium is analysing the feasibility of the aerobraking scenario proposed by ESA from an aerothermal and dynamic point of view (feasibility analysis to be completed by May 2011).

The analysis also addresses the operational aspects: transition to and from aerobraking attitude, optimisation of spacecraft attitude during the operations, management of contingencies.

The findings of the analysis will allow supporting the decision whether an aerobraking campaign with VEx can be performed safely, and whether a 12-or 18-hour can be reached within a reasonable time. Indeed, if thermal constraints lead to consider relatively high pericentre altitudes, the resulting aerodynamic pressure will be too low and the orbit period reduction may require a large amount of atmosphere crossings.

6.1 Thermal analyses

6.1.1 Preliminary assessment

An initial assessment of the situation showed that the key issue to demonstrate the feasibility of the aerobraking was the thermal behaviour of the spacecraft under the aerothermal flux while passing through the atmosphere.

Venus environment is quite constraining because of the short distance to the sun. This induces a much higher solar illumination (about 2650 W/m^2) than at Mars. The solar illumination leads to a significant heating of the different spacecraft components and will add to the aerothermal flux. The two main elements exposed to the aerothermal flux are the MLI (Multi-Layer Insulation) covering the spacecraft $-Z$ face and the solar arrays.

This preliminary assessment led to the identification of favourable and unfavourable orbit configurations corresponding to different solar aspect angles with respect to VEx orbital plane (see figures 7 and 8). As VEx orbit is almost polar and remains inertial the solar aspect angle varies along the year (see figure 7).

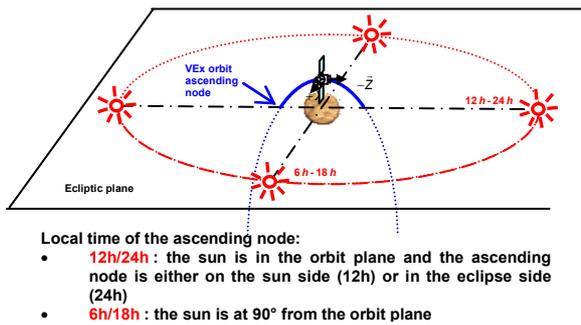


Figure 7: Solar aspect angles with respect to VEx orbit over 1 Venusian year (225 Earth days)

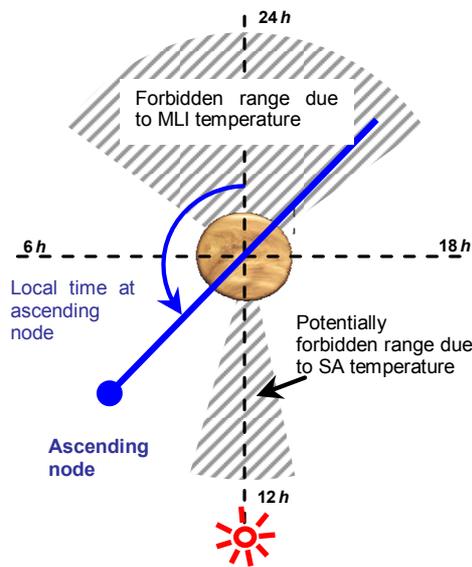


Figure 8: Critical zones

Figure 8 shows that 2 zones are especially critical from a thermal point of view:

- when the ascending node of VEx orbit is close to 24 hours (midnight): in this case, the spacecraft $-Z$ face will be facing the sun at pericentre crossing, so the MLI on this face will be exposed to full solar illumination and to the aerothermal flux. Likewise, the back of the solar arrays will be exposed to both the aerothermal flux and the solar illumination.
- when the ascending node is close to 12 hours (noon): in this case, the solar array back will be facing the aerothermal flux whereas the front side of the solar array will be exposed to solar illumination

On the contrary, when the local time of the ascending node is close to 6 hours or 18 hours (sun direction normal to VEx orbital plane), the situation is much more favourable as the elements which are exposed to the aerothermal flux (MLI and solar arrays) are almost not illuminated by the sun.

As these favourable configurations correspond to the middle of the plateaus, the initial assessment showed that there was no show stopper. However it was necessary to

further analyse the thermal behaviour during such plateaus to conclude on the actual feasibility of the aerobraking for Venus Express by means of thermal simulation (see section 6.1.2).

The preliminary assessment also consisted in determining the operational point for the detailed analyses. The target dynamic pressure targeted by ESA of 0.3 N/m^2 corresponds to a peak aerothermal flux of about 3000 W/m^2 . A simplified thermal model of the MLI and the solar arrays shows that this peak aerothermal flux is compatible with both MLI and SA qualification temperatures (respectively 350°C and 146°C) with some margin.

Figure 9 shows the aerothermal flux profile during an atmosphere crossing.

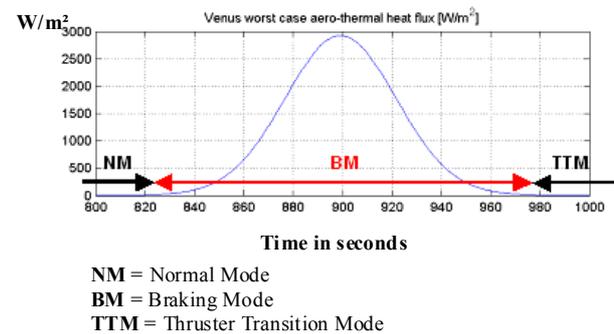


Figure 9: Aerothermal flux profile

6.1.2 Thermal simulation cases

There were two stages in the thermal simulations aiming at proving that the aerobraking could be performed during the plateaus:

- First stage considered a reference (ideal) case corresponding to the middle of the plateaus with the sun exactly at 90° from the orbital plane. Under this conditions, the solar arrays and the $-Z$ face are not illuminated by the sun during the atmosphere crossing
- Second stage considered two worst cases corresponding to the edges of the plateaus: the solar aspect angle is about 66° from the orbital plane (the plateaus in 2012 last for about 1 month, corresponding to $\pm 24^\circ$ solar aspect angle variation). Under this conditions, the solar arrays and the $-Z$ face are partially illuminated by the sun during the atmosphere crossing

In order to attain some thermal margins at solar array level, the simulation cases included a transient phase preceding the atmosphere crossing where the solar arrays are cooled down by turning the edge towards the sun

All the simulations have been performed with a peak aerothermal flux of 3000 W/m^2 .

A complete 18-hour orbit simulation monitoring the evolution of temperatures on different spacecraft faces and sub-systems, has confirmed the MLI located on the $-Z$ face as a key driving element. This simulation has also permitted to analyse the temperature evolution of the solar

arrays but also of different S/C equipments and faces: Figure 10 shows the simulation result for the evolution of solar array temperatures at pericentre during the reference case. The benefits of cooling down the solar array before the atmosphere crossing are very clear. The simulation shows a comfortable margin with respect to the SA qualification limits (see section 6.1.3).

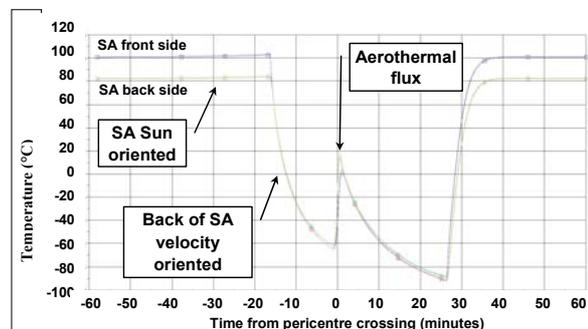


Figure 10: Evolution of SA temperature (reference case simulation)

6.1.3 Correlation between in-flight measurements and thermal models

The thermal analyses performed by Astrium rely on ground models. In parallel to the simulations cases, Astrium has got data from the Mission Control team at ESOC to correlate on-board telemetry (thermistors) with thermal model outputs in order to better assess the actual margins.

The correlation has been focused on the solar array which is the most exposed surface during aerobraking.

The correlation concerns two aspects: the impact of sun illumination and the impact of aerothermal flux.

Concerning the impact of sun illumination, the initial comparison of on-board thermistors telemetry and the SA model output has shown that the model overestimates the SA temperature by 30°C. After close examination of the situation the difference was explained by three main factors:

- the front side of the real SA is covered by alternating stripes of OSR and solar cells, whereas the model only considers an average material (with average optical properties),
- the on-board SA thermistor is on the back of the array on a portion located behind an OSR stripe,
- the ageing assumptions in the model are pessimistic with respect to reality

It will therefore be possible to review simulation models in order to determine the expected on-board temperatures.

An accurate in-flight vs model correlation of the aerothermal flux on the SA would require observing a significant aerothermal flux on-board at pericentre, but this can only be achieved for quite low pericentre altitudes which cannot be envisaged before the actual aerobraking operations. This will remain as an open point until aerobraking operations are done

6.2 Dynamic disturbances and guiding options

In addition to thermal analyses, Astrium have examined the dynamic behaviour of the S/C during the atmosphere crossing.

Two main guiding options for the aerobraking mode attitude have been considered during the analysis of the disturbing torques:

- a rotating guidance (the baseline when VEx was developed) : the spacecraft $-Z$ axis is aligned with the current velocity vector (orbital frame)
- a fixed guidance: the spacecraft $-Z$ axis is aligned with the velocity vector at the pericentre

The analyses have shown that the first option is sensitive to timing errors (uncertainty on the pericentre crossing time), which directly translate into alignment errors between the supposed velocity vector direction and the actual direction. The consequence is a significant dynamic transient when entering the atmosphere. Indeed, ESOC estimates the timing errors to 300s (which is equivalent to 15° angular error), whereas the direction of the pericentre is known to better than 1°.

Therefore the second option (fixed guiding), adapted to Venus Express conditions (150s atmospheric crossing) is preferred. In this configuration, the angular errors are high at atmosphere entrance and exit, but at these points the atmosphere density is low.

This guidance option can be used either during the plateaus (atmosphere crossing in thruster-controlled mode) or during the walk-in phase preceding the plateaus (atmosphere crossing in wheel-controlled mode)

6.3 Operations strategy

The main concern during the aerobraking operations is to avoid putting the spacecraft in danger.

Experience from aerobraking in the USA has proven that operations are quite resource demanding.

Several aspects of the operations have been examined for Venus Express among which:

- the aerobraking phases, from the walk-in to the termination
- the aerobraking altitude corridor management
- the contingency management

6.3.1 Aerobraking phases

Within the aerobraking operations, the walk-in is a crucial phase as the orbit pericentre will progressively reach the operational altitude (see section 5). The analyses have proved that it will be necessary to adjust the target plateau altitude for the pericentre as the walk-in progresses. The adjustment will be based on the targeted aerodynamic pressure and on the existing on-board observables.

During the walk-in phase, it will be necessary to refine the atmosphere model using the approach already introduced for ADE operations.

The walk-in phase will provide the opportunity to check whether the impact of the aerothermal flux on the equipments (especially the solar array) is as expected through the observation of the evolution of temperature for the different units.

Finally, with the increase of atmosphere density and of the aerodynamic disturbances, it will be possible to calibrate the alignment of the Centre of Pressure with respect to the Centre of Mass in order to better define the guidance profile during the main aerobraking phase.

6.3.2 Aerobraking corridor management

The thermal analyses have determined a maximum acceptable aerothermal flux. Because of the variability of Venus atmosphere (see section 5.2 and ref. [2]), it is necessary to set a maximum operational peak aerothermal flux in order to avoid exceeding the S/C thermal limits. It might be necessary to adjust (increase) the pericentre altitude during the plateaus to avoid damaging the S/C. The selection of a corridor upper limit will simplify the operations at the expense of reduced aerobraking efficiency.

Figure 11 shows the principle of the aerobraking corridor.

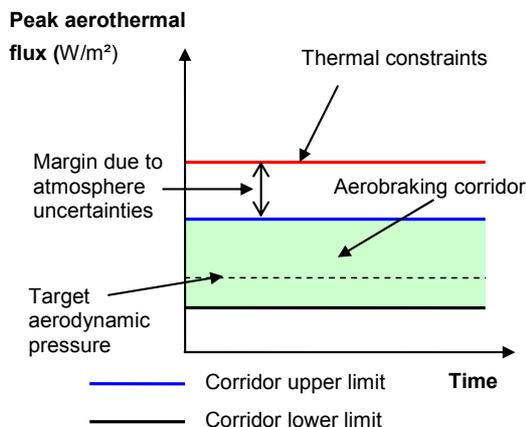


Figure 11: Aerobraking corridor principle

6.3.3 Contingency management

Two spacecraft critical situations during aerobraking operations have been considered:

- a non-anticipated Safe Mode triggering
- an unexpected increase of atmosphere density (leading to an unwanted increase of S/C temperatures)

During aerobraking operations, the **Safe Mode might trigger**: the main risk is that the spacecraft crosses the atmosphere in the Safe Mode attitude which is not designed to be compatible with atmosphere crossing.

As no modification of the existing Safe Mode is foreseen, to the analysis has focused on assessing the risk of Safe

Mode triggering. The situation is particularly critical in the hours preceding the pericentre crossing as there is not enough time to recover the spacecraft and resume the aerobraking attitude.

The **detection of an unexpected increase of atmosphere density** through the observation of disturbing torques, of accelerations or of significant temperature raise may lead to take protective measures.

In both contingency cases, the risk reduction actions have to be managed at operations level:

- by avoiding unnecessary (or complex) operations in the hours preceding the pericentre pass,
- by on ground processing of the spacecraft telemetry as soon as possible after the pericentre crossing in order to undertake protective actions for the following pass, if needed,
- by reducing the ground reaction time to recover the satellite from a Safe Mode,
- by preparing in advance the required commands to cope with a contingency case (e.g. manoeuvre to raise the pericentre) so that they can be uploaded quickly in case of need,
- by considering sufficient margins in the aerobraking corridor and reduce the sensitivity to atmosphere density variations.

Some of these strategies have already been put in place by ESOC during ADE campaigns (see [2]).

7. CONCLUSION

Using ESOC inputs (ADE experiment results, S/C telemetry, operations experience), Astrium has analysed the feasibility of the aerobraking at Venus for Venus Express. The results (to be completed current 2011) indicate that aerobraking would be possible during the plateaus with dynamic pressure $\leq 0.3 \text{ N/m}^2$.

The main challenge during the aerobraking operations phase will be to warrant the spacecraft safety considering the variability of Venus atmosphere, the limitations on the spacecraft design and the telemetry available for correlation.

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