FLIGHT DYNAMICS OPERATIONS FOR VENUS EXPRESS AEROBRAKING CAMPAIGN: A SUCCESSFUL END OF LIFE EXPERIMENT

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Abstract: *This paper presents the first ever aerobraking campaign performed by the European Space Agency. First, an overview of the history and methods for aerobraking operations are provided. This frame is used to explain the particularities of the approach selected for Venus Express, a very special one due to the nature of the experiment. Then the operational challenges and solutions are explained for all ESOC Flight Dynamics involved disciplines.*

Keywords: *Aerobraking, Venus, Venus Express.*

1 Introduction

Launched in 2005, having reached Venus orbit in 2006, ESA's Venus Express probe saw its nominal mission of 2 years being successfully extended several times. It was reaching its end of life when it carried out aerobraking operations for the first time in the agency's history, between May and July 2014. 6 months later, it ran out of propellant and entered the atmosphere. Venus Express was a 3-axis stabilised satellite equipped with science objectives to study the atmosphere, the plasma environment, and the surface of Venus in detail via 7 instruments: a plasma analyser and a magnetometer for the in-situ observations, a combination of spectrometers, spectro-imagers and imagers covering a wavelength range from ultraviolet to thermal infrared as well as a radio science experiment for remote sensing [7]. The spacecraft had a nominal highly eccentric polar orbit, of 24 hours, with its pericentre over the North pole of the planet.
Aerobraking is a technique which aims at circularising orbits by dissipating the orbital energy during crossings of the atmosphere. On Venus Express, an aerobraking mode was implemented to be able to correct potential failures during Venus orbit insertion. Since the mode was never foreseen to use under nominal circumstances, it was only possible to use this mode by accepting significant risk. This finally led to the decision to undertake an aerobraking campaign as an end of life experiment aiming at exploring Venus' atmosphere in low altitude regions.

2 Basic principles of Aerobraking

Aerobraking was first demonstrated by Japan's Hiten lunar mission with two passages in Earth's atmosphere in 1991. In 1993, NASA gathered its first experience with the Magellan probe after the nominal mission was completed, before applying it to reach the nominal science orbit to three successive Mars orbiters: Mars Global Surveyor in 1996, Mars Odyssey in 2001, and Mars Reconnaissance Orbiter in 2006.

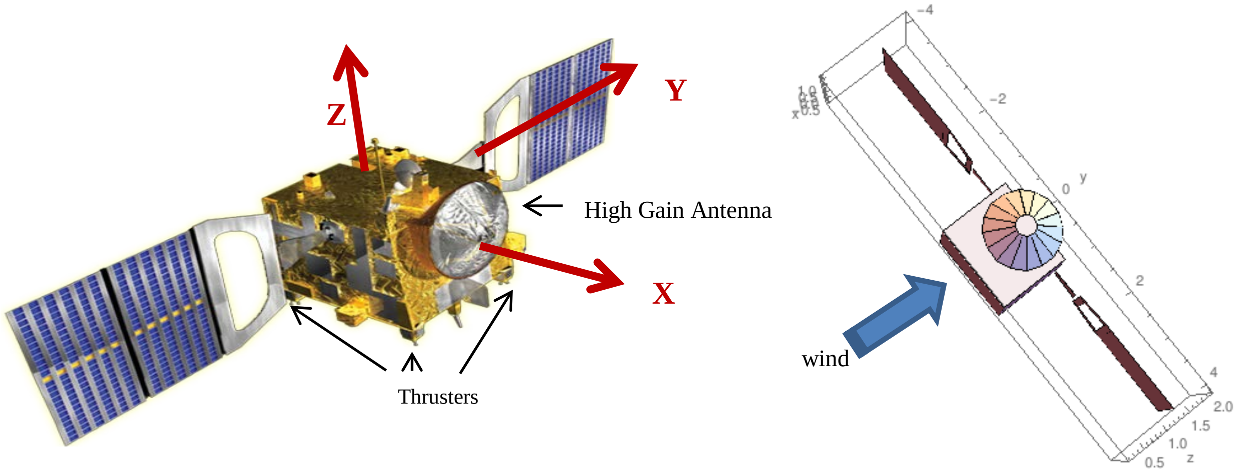

Figure 1: Venus Express spacecraft. On the right, in aerobraking configuration.

As mentioned above, aerobraking is a technique based on reducing orbital energy, therefore it is essentially applied to interplanetary missions in order to lower the apocentre around a planet with an atmosphere, once the capture manoeuvre has been performed by other means. The basic principle of a campaign consists in lowering the pericentre of the orbit into the atmosphere and placing the spacecraft into an attitude which maximises the drag at each passage. Once, orbit after orbit, the apocentre altitude has decreased to the desired one, the pericentre is raised again by chemical propulsion. However, while crossing the atmosphere, the interactions between the spacecraft and the molecules subject the spacecraft to mechanical loads and heat flows which must remain below safe limits. Also, the spacecraft must be in the dedicated safe and efficient attitude control mode at atmosphere crossing, while keeping time to perform the other mandatory activities, including contact with the Earth for tracking and commanding, during the remainder of the orbit. Some spacecraft or mission particularities, such as Earth Sun planet conjunctions, orbit natural evolution [3] and attitude control system limitations [12] may add additional constraints on the planning of the campaign. Finally, robustness to contingencies must be guaranteed. The imperfect knowledge of the atmospheres and their random variability at high altitude make aerobraking campaigns risky activities which require heavy operational loads. Those loads can however be reduced when the spacecraft have the capability to sense and react to the encountered actual atmospheric properties, in particular by measurement of the drag deceleration to infer the next pericentre time and to execute corridor control manoeuvres [1], and monitoring of the temperatures to trigger emergency pericentre raising manoeuvres [5].

The different phases of a campaign can be decomposed into [9]:

- the initiation, where the altitude of the pericentre is decreased until reaching the top of the atmosphere
- the walk in, where the atmospheric conditions (absolute value and variability of the density) and the behaviour of the spacecraft are probed, and the pericentre altitude is further decreased so as to reach the target dynamic pressure corridor
- the main phase, where the thermal constraints are usually preponderant, and the pericentre altitude is controlled such as to remain within the target dynamic pressure corridor; the adjustments (raising or lowering) depend on the observed atmospheric density (day/night transitions, sand storms), and on the decrease of the relative velocity as the apocentre is lowered.
- the walk out, where the apocentre altitude has nearly reached its target value; if the eccentricity of the orbit is so low that the spacecraft spends a consequent portion of its orbit in the atmosphere, the active constraint becomes the minimum time of life in case of emergency, the satisfaction of which requires a gradual increase of the pericentre altitude.
- the termination, when the pericentre altitude is raised above the atmosphere, and the orbit adjusted to the nominal science orbit.

We recall hereafter the essential equations for the analysis. The acceleration from the air drag can be expressed as:

$$\vec{a}_{drag} = -p_{dyn} C_d \frac{S}{m} \frac{\vec{V}}{\|\vec{V}\|} \tag{1}$$

where C_d is the drag coefficient (2.2 was used), S the surface exposed to the flow (10.4 m^2), m the mass of the spacecraft (650 kg), $\vec{V}$ the spacecraft velocity relative to the atmosphere; p_{dyn} is the dynamic pressure:

$$p_{dyn} = \frac{1}{2} \rho \vec{V}^2 \tag{2}$$

where ρ is the mass density of the atmosphere, which can be locally (for given altitude range, latitude, longitude, local time, ...) expressed by:

$$\rho \approx \rho_0 e^{-h/H} \tag{3}$$

where ρ_0 is a constant, H the scale height, h the altitude. Naming r_p and V_p the pericentre altitude and tangential relative air velocity, and neglecting the atmospheric winds against the orbital velocity, the total imparted change in velocity after a passage in the atmosphere is then:

$$\Delta V = p_{dyn} \frac{C_d S}{m} \frac{\sqrt{2\pi H r_p}}{V_p} \tag{4}$$

The change in orbital period can be approximated by:

$$\Delta P = -\frac{3}{\sqrt{h + R_V}} (2\mu)^{-1/6} \left(\frac{P}{\pi}\right)^{2/3} P \, \Delta V \tag{5}$$

For Venus Express, typically $\Delta P \approx 5min \ll P \approx 1day$. Finally, the pericentre time deviation from what it would be if the initial period would be conserved is after n pericentres can be approximated by:

$$\Delta t_{per} = \Delta P \frac{n(n+1)}{2} \tag{6}$$

This is however without considering the inherent variability of the atmosphere density from one passage to the next. When considering for instance a certain variability, as well as other random variations such as attitude control thruster actuations, then by naming $\sigma_{\Delta P}$ the standard deviation of the change in period, the standard deviation in the pericentre time after n passages is:

$$\sigma_{\Delta t} = \sigma_{\Delta P} \sqrt{\frac{n}{6}(n+1)(2n+1)} \tag{7}$$

3 Venus Express campaign design

3.1 Context

Venus Express inherited from its very similar precursor Mars Express of a dedicated aerobraking spacecraft mode, to be used in case of misperformance of the planetary insertion burn to reach the nominal orbit. This need proved to be unnecessary for both missions, therefore the aerobraking mode had never been tested before the end of life campaign.

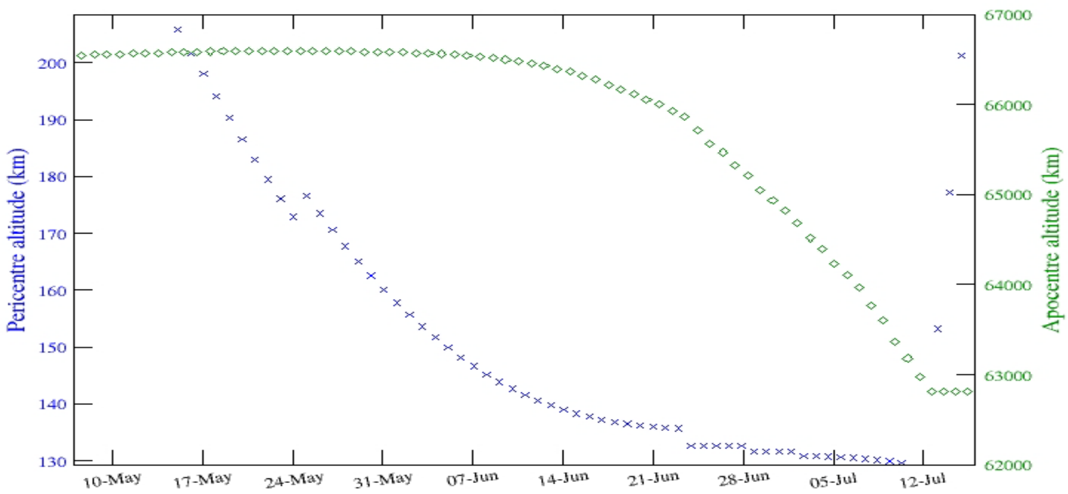

Figure 2: Evolution of the pericentre and apocentre altitudes over the campaign.

In 2009, Venus Express began to perform so called aerodrag campaigns [10], where the spacecraft pericentre altitude went down to 160 km altitude with solar panels oriented so as to maximise the atmospheric drag torque, under nominal reaction wheel controlled attitude control mode. Although the effect on the orbital period was minimal, it allowed the scientists to obtain in-situ measurements, and radio science as well as attitude dynamics reduction permitted to obtain atmospheric density measurements at those altitudes [2][4]. The density was then characterized to have variations of 100% from day to day, accentuated at the transitions between the day and the night side. The measurements were compared to a state of the art atmospheric model, the Venus International Reference Atmosphere [6]. The drag coefficient C_d could also be estimated by a windmill-like solar panel orientation.

In 2011 after the first extension of Venus Express mission, it was discussed whether it would be scientifically worthwhile to lower the apocentre such that the orbital period is reduced from 24 hours down to 12 hours by means of aerobraking (equivalent to 250 m/s delta V). Because the aerobraking mode was never foreseen to be used nominally in the mission, aerobraking with Venus Express was only possible without being robust to contingencies. In particular any safe-mode could have led to the end of the mission, because the controllers of the safe hold mode were not designed to coupe with atmospheric torques at the aerobraking altitude. Furthermore, the ΔV due to attitude control pulses in safe-mode could have lowered the pericentre altitude further such that the thermal limit would have been exceeded by far. For this reason, ESA decided to postpone this exercise until 2014 or 2015 when the propellant would be close to run out, and to implement it as an end of life experiment, where the potential damages to the spacecraft would be more acceptable.

date	i °	Ω °	ω °	e	a (km)	h_a (km)	h_p (km)	P	V_p (km/s)
19/05	89.876	104.115	75.505	0.8418	39444	66597	186.6	23h59	9.793
24/07	89.803	103.881	75.064	0.8275	37687	62822	461.7	22h24	9.546

Table 1: Orbital elements of Venus Express before and after the aerobraking.

date	pericentre latitude	pericentre longitude	Earth elevation	Sun elevation
19/05	75.5	165	-87	-30
24/07	75.1	250	-19	-64

Table 2: Evolution of the pericentre sub-satellite point and of Sun and Earth elevations above the orbital plane. The middle of the plateau (Sun elevation of -87°) was on 27/06.

Let's consider the aerobraking relevant characteristics of the mission. Venus Express evolved on a highly eccentric orbit, with a 24h period, an apocentre above 66000 km and a pericentre altitude maintained between 250 and 400 km. Due to the Sun's third body gravitational effects, the pericentre altitude monotonously decreased (up to -5 km/day) and had to be regularly raised, with periodic stabilization seasons when the Sun was perpendicular to the orbital plane, a situation occurring every 4 months. As for the aerodrag experiments, those pericentre altitude plateaus were optimal for the main phase of the aerobraking because they permitted a cheaper corridor control in terms of manoeuvres. Finally, the June 2014 plateau was chosen since the most pessimistic fuel estimates predicted a depletion during the following pericentre raising manoeuvre.
The objectives of the campaign were on one side to maximize the dynamic pressure, while on the other side to minimize the operational load, namely the frequency of commanding cycles. For Venus Express, thermal studies [11] indicated that the spacecraft could withstand 3000 W/m2 (or 0.3 Pa dynamic pressure) without damage, excepted the front of the High Gain Antenna, which would approach its qualification limit, and Muti-Layer Insolation tape glue which could melt, but stand-offs would still maintain the foils in place. If not exposed to the Sun during the atmosphere crossing, the solar panels, with a temperature limit of 146 Celsius degrees, could even temporarily be exposed to 7000 W/m2 or 0.7 Pa. The structure would resist to at least 1.5 Pa.
The aerobraking attitude (see Fig. 1), aerodynamically stable, consisted to have -Z of the satellite and the back of the solar panels oriented towards the gas flow. A dedicated thruster actuated attitude control mode would maintain the angular error within 15° of the fixed reference attitude while damping excessive angular rates.

3.2 On-board and on-ground activities scheduling

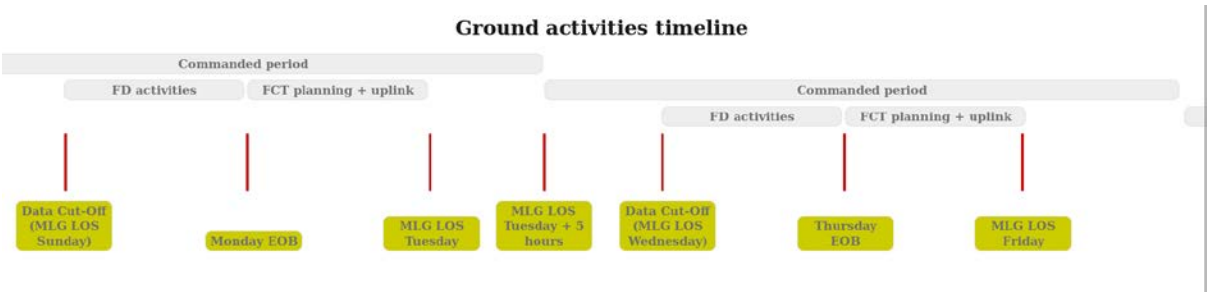

Figure 3: Weekly ground activities.

The originally designed timeline of the activities around a pericentre passage [8] is shown in Fig. 2 (the pericentre time is marked in red). A perfect knowledge of the pericentre time is assumed there, since 200 s is the duration of the atmospheric pass. Following this strategy would have required one commanding session with updated navigation for every orbital revolution, which was not affordable. Therefore, a timeline taking into account the uncertainties on the knowledge of the predicted pericentre times had to be designed.

Figure 4: Original timeline of activities around the pericentre

During the plateau, the orbit was such that the solar arrays would get no power while in aerobraking attitude. Thorough power analysis by the Flight Control Team showed that, since there would be no eclipses, by switching off all unnecessary units, while keeping only 2 instruments on, the maximum time in aerobraking attitude was 8400 s. This imposed a constraint on the maximum aerobraking mode duration of 6900 s (the solar arrays receive power during the slews but not in the rest of the phases), and on the maximum uncertainty of the pericentre time of 6700 s. For a scale height of 3.5 km, a constant altitude of pericentre, a target dynamic pressure of 0.4 Pa, and a standard deviation of 20 %, this allowed to cover up to 7 pericentres in a single commanding cycle. Along the one month main phase of the campaign, where the 24h hours period could not be reduced by more than 2h, this would allow 6 days between the data cut-off and the execution of the last commands. Leaving 1/2 day for the data downlink, one day for the preparation of the commands and 1/2 day of margin for the up-link (2 different ground station contacts), two commanding cycles per week sufficed (instead of one during the nominal mission).

On the other hand, in case of safe mode, the automated sequence would point the solar panels towards the Sun. This would mean that very little drag would be imparted to the spacecraft. Hence, defining a sequence of commands robust to both the maximum expected dynamic pressure and an absence of atmosphere would allow the spacecraft to be recovered in case of safe mode by the Flight Control Team without the need for an update of the timing of commands by the Flight Dynamics Team.

Figure 5: Final timeline of activities around pericentre.

The final pericentre timeline is shown in Fig. 5, where the commanded pericentre time is again marked by a red line. Pericentre times were scheduled based on a no-drag propagation, ensuring that the last commanded pericentre would take place, in the worst case, 6700 seconds after the actual pericentre, and in case of safe mode during any pass, still inside the aerobraking mode window.
Due to this simplified approach for the command timing, a consistent rule had to be specified to ensure that commands for all pericentres would get their chance to be uploaded during the proper station pass. Taking into account that the actual pericentres could take place as much as 6700 seconds earlier than commanded, and adding some margin, all activities up to Malargue End-Of-Track + 5 hours were included in the on-going commanding period.

Notice that having a timeline with such big margins added some inefficiencies on the aerobraking itself. Since the S/C would enter aerobraking mode (a very coarse attitude control mode with a 15 degree deadband) long before the atmospheric pass, the attitude would naturally drift away (due to SRP and gravity gradient torques), reaching the atmosphere with a depointing in the order of 15 degrees. However, this reduces the drag by only 4%, so this small downside could be neglected. Another deficiency yet was the associated increased fuel consumption.

Figure 6: Timeline of activities around the apocentre.

The full orbital timeline was completed by the apocentre part, which included a wheel off-loading in an attitude such that the ΔV was perpendicular to the orbital plane (to avoid influencing the pericentre altitude) and a slot for eventual pericentre raising or lowering manoeuvres (see Fig. 6). The rest of the orbit was spent in an Earth pointing power optimised attitude.

3.3 Campaign organisation

All the phases of the campaign were actually organised so as to minimise the departure from the nominal operations. During the plateau preceding the campaign, the pericentre altitude had been raised such that the next plateau would occur around 130 km. Therefore, the initiation consisted in waiting until the natural decay of the pericentre altitude brought it to 180 km where the campaign officially started. The walk in phase also took advantage of the naturally decelerated decay of the pericentre altitude to probe the atmosphere and adjust the foreseen dynamic pressure at the middle of the plateau to the target dynamic pressure using a conservative scale height. The evolution of the pericentre lighting conditions (from day to night side) and the change in altitude required regular updates of the atmospheric model. Pericentre altitude tuning manoeuvres were implemented in order to target the desired dynamic pressure. Those manoeuvres took place at the first apocentre included in the planned sequence of activities of a cycle in order to provide measurements on the new atmospheric conditions before the next commanding cycle. Although wheel controlled spacecraft modes could have been used up to 0.3 Pa [8], to simplify the main phase sequence of commands was already applied from 180 km downwards. In this campaign, there was no walk out as such since the orbit was not circularised enough to activate life time constraints. The termination phase consisted in a series of manoeuvres raising the pericentre up to an altitude of 460 km, during which there were chances that the spacecraft would run out of fuel.

4 Flight Dynamics task repartition

4.1 Attitude monitoring and telemetry processing

There was no contact with the spacecraft during the passage in the atmosphere, however the essential data was recorded on-board and regularly downlinked, during the daily pass. The usual low frequency housekeeping telemetry was screened as usual to monitor the behaviour of the attitude control system in all phases, including the aerobraking mode. Note that since the temperatures were not determinant for the dynamic pressure corridor control, they were not monitored by the Flight Dynamics Team, but by the Flight Control Team, as during the nominal mission.

The aerobraking mode controller, which had not been foreseen to be used outside the atmosphere, nevertheless performed well, effectively keeping angular rates and attitude error

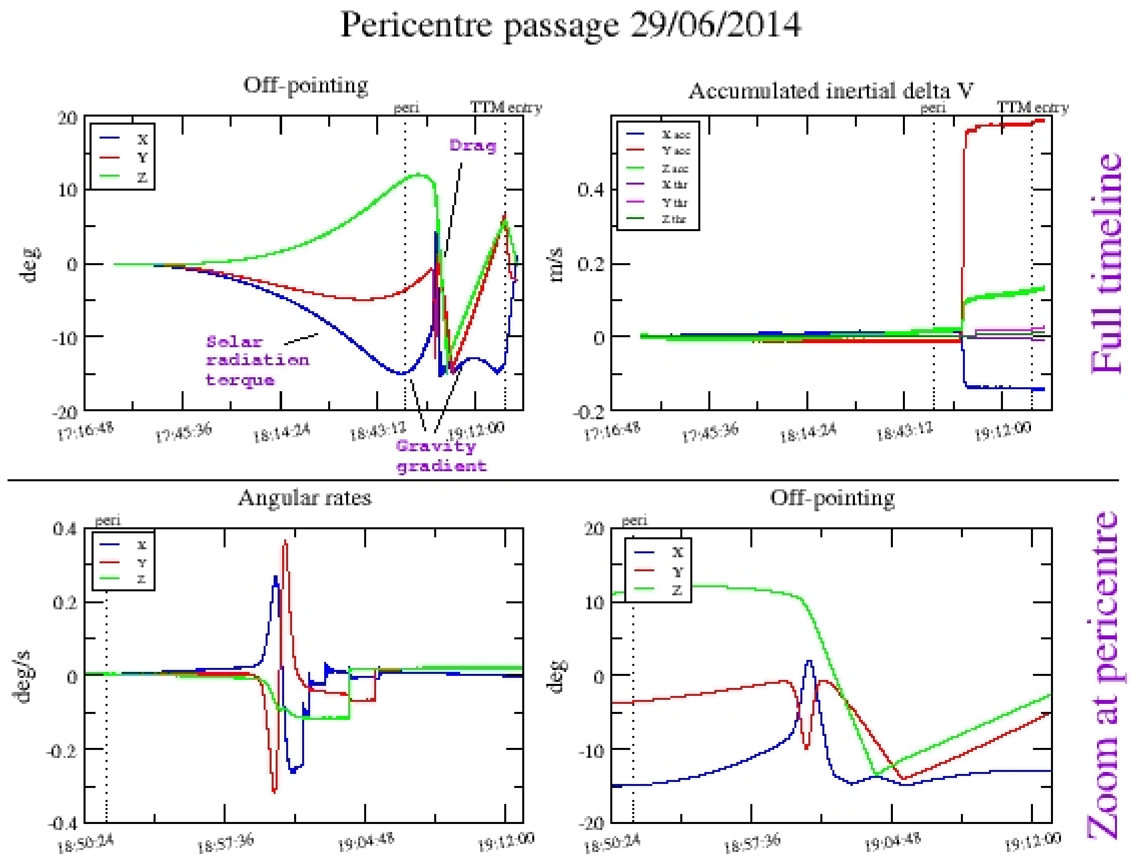

Figure 7: Attitude evolution for the thruster controlled part of an orbit: aerobraking and thruster tranquillisation (TTM) modes. The top right plot provides the accumulated measured linear acceleration as well as the thruster reconstructed contribution. "peri" marks the predicted pericentre time, while high angular rates (bottom left) and accumulated linear acceleration (top right) spot the actual one. The top left plot represents the off-pointing to the reference attitude.

within bounds. As depicted on Fig. 7, the aerobraking phase started with a long period during which the dynamics were dominated by the Solar radiation induced torque, then gravity gradient became predominant until the atmosphere was entered. At this point, the atmospheric drag induced torque drove the satellite into stable, but non damped oscillations for a short time (actually the period of the oscillations depends on the maximum dynamic pressure, which was never high enough to have more than one oscillation). Symmetrically, after leaving the atmosphere, the spacecraft attitude drifted again, subjected to gravity gradient and solar radiation pressure, finally converging at entry into the tighter control modes. As expected, the behaviour of X and Y axes showed a similar oscillation in the atmosphere, while the Z axis encountered very low drag torques. The fact that the oscillations were not centred around the origin comes from the fact that the centre of mass of the spacecraft was not perfectly aligned with the centre of pressure in the reference attitude. Such alignment calibration, initially foreseen in the design of the aerobraking mode to reduce the oscillations, was finally not performed since high angular errors could not be avoided anyway at entry into the atmosphere.

A second set of telemetry parameters were processed and used as input by the orbit determination team. It consisted in a selection of some dynamic housekeeping parameters recorded at the frequency at highest frequency (8 Hz) for the thruster controlled phase of each orbit:

1. angular rates from gyroscopes on 3 axes, for attitude reconstruction

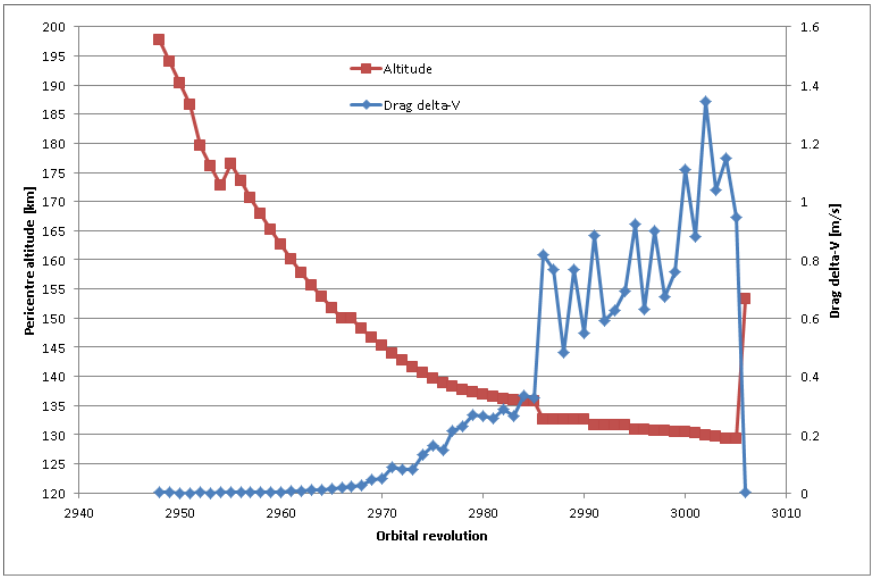

Figure 8: Reconstructed altitude and drag ΔV per pericentre.

2. non gravitational acceleration on 3 axes from accelerometers, for the drag estimate; the measured acceleration was projected in inertial frame and integrated over the passage in the atmosphere after compensation of the bias; the pericentre time was obtained at the time when half of the delta V was reached; the a priori standard deviation of the total was 16 mm/s over the 200 s of passage in the atmosphere.
3. attitude control thrusters actuations, combined and projected into discrete ΔVs in inertial frame; they had an a priori accuracy of 20 %.

Angular rates and thruster actuations were also used to cross-check by attitude dynamics reduction the orbit determination period estimates at the beginning of the walk in, were the signal to noise ratio of the accelerometers was still very low.

4.2 Orbit determination

During aerobraking operations, the orbit determination (OD) was performed in a similar way as for routine operations: based on 2-way Doppler data from ESA deep space antennae (Cebreros and Malargüe), using the ESOC's interplanetary orbit determination system [13], with an observation arc spawning from data cut-off (time of latest available measurement) to 9-10 days in the past. In each OD the set of estimated parameters were: spacecraft position and velocity at certain epoch, scale factor for the Solar radiation acceleration, calibration factors for wheel-off-loadings and orbit control manoeuvres, plus parameters for calibrating the drag acceleration per pericentre passage.
For aerobraking operations, two additional inputs from S/C telemetry were fed in the OD system: integrated accelerometer data during aerobraking mode (ABM) as a measurement of the atmospheric drag, and reconstructed thruster pulses during ABM and TTM (thruster transition mode).
During operations, three different OD configurations were used, each one modelling the atmospheric drag in the following way:

- ACC: using the integrated accelerometer data, modelled as an impulsive ΔV at the central time, estimating a calibration in 3-axis per pericentre.
- ATM: using the S/C drag model and the applicable engineering atmospheric model, estimating a scale factor per pass.
- DV: modelling the integrated drag as an estimated impulsive ΔV at each pericentre time.

In each commanding cycle, the results of the three configurations were compared (in terms of

observation residuals, estimated parameters, estimated orbit), in order to select the solution to be used for orbit reconstruction and to provide the estimated spacecraft position and velocity at data cut-off, that subsequently was used for orbit prediction and manoeuvre optimization.
Additionally, the estimated drag scale factors from the ATM runs, interpreted as a scale factors of the density provided by the operational atmospheric model, were consequently used to update this atmospheric model. Figure 8 shows the reconstructed altitudes and the estimated drag ΔV for each pericentre passage during the whole aerobraking phase.

4.3 Operational atmospheric model management

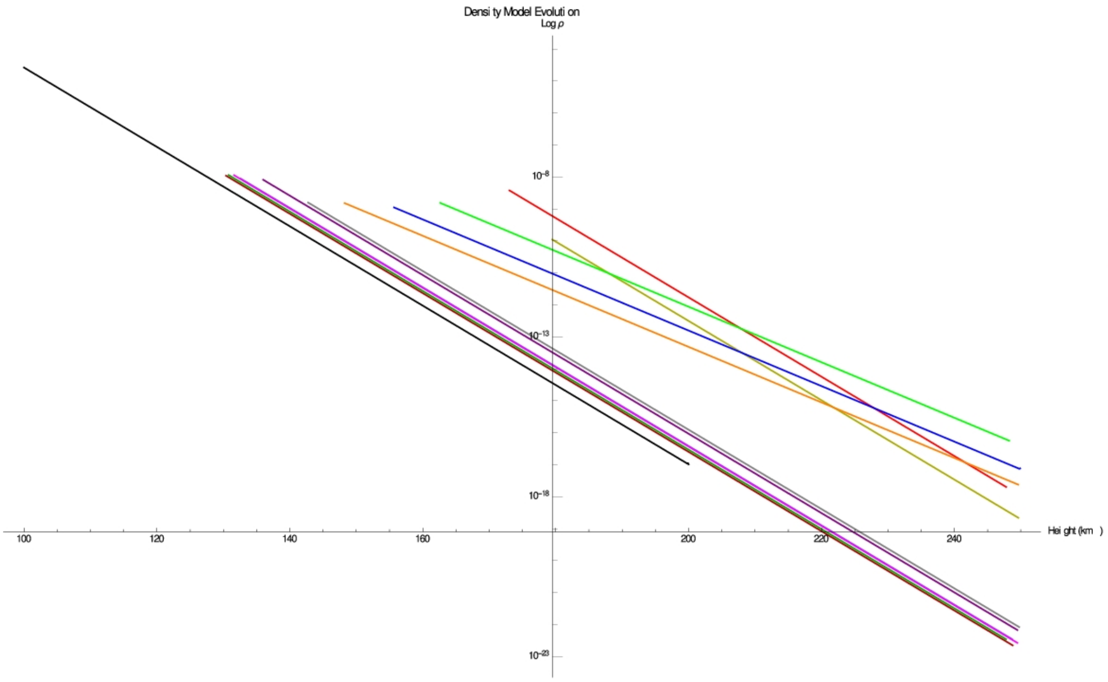

Figure 9: Operational atmospheric density models.

The atmospheric model update was one of the main drivers of the operations. For every commanding period, an atmospheric model update was performed based on the latest navigation data with the following objectives:

- Improving the prediction accuracy
- Checking that the standard deviation of the dynamic pressure was within limits

If the standard deviation was found to be outside the allowed boundaries, a pericentre raising manoeuvre commanding would be triggered.
An exponential atmospheric model was used with a nominal scale height of 3.5 km. Figure 9 shows the evolution of the atmospheric models used throughout the campaign. The time evolution is implicit in the height-range covered by the different models. It is clearly visible that, at high altitudes, the predictability of the atmosphere is bad due to both poor modelling and big errors since the effect is still small. Using a globally exponential atmospheric model in the first passes resulted in oversized densities at lower altitudes, reason why the scale height of the model was increased to prevent planning spurious and unnecessary manoeuvres. Once measurements from deeper layers of the atmosphere were gathered, the model slowly converged. The first big gap between models corresponds to the increase in reliability of the retrieved data, whereas the second and smaller one corresponds to the pericentre entering the night side. The black line show the model used during the Long Term Planning (operational

design phase) of the campaign.

4.4 Manoeuvre optimisation

4.4.1 Operational Procedure

During nominal long term planning operations, a reference trajectory was published some months in advance to allow the scientist to plan their instruments pointing. This reference trajectory included all deterministic manoeuvres for orbital phasing and Pericentre Raising. Then, during short term planning operations, a strategy of reaction wheels off-loadings (WOL), the procedure consisted in using non balanced WOLs to correct the orbital perturbations and keep the phasing error between the real orbit and the reference orbit within 20 minutes. The interplanetary FD software optimized the direction of the Delta-V produced by each WOLs to minimize the phase difference between both orbits.

During aerobraking operations, no science pointings were implemented. Due to the unpredictability of the atmosphere of Venus, it was then agreed not to follow a reference trajectory. Hence, there was no need to define a WOLs strategy, their Delta-V was defined perpendicular to the orbital plane to limit their impact on the pericentre altitude. However, it was still necessary to compute stochastic manoeuvres to keep the dynamic pressure within the spacecraft limits.

Although there was no reference trajectory to follow, the long term planning orbit targeted the main phase of the aerobraking during the plateau season. The pericentre altitude was defined to target a dynamic pressure of 0.4 Pa based on a low density atmospheric model (Venus night side). Once this season was finished, a group of deterministic Pericentre Raising Manoeuvres (PRM) was implemented to leave the aerobraking region.

During short term planning operations, the orbit was numerically propagated 15 days into the future using the latest operational atmospheric model. Then, the dynamic pressure was computed for all the atmospheric passes and if the maximum nominal dynamic pressure was predicted to be violated during the first 9 days, a PRM was implemented.

The PRM was fixed at the first non commanded apocentre. The manoeuvre direction was fixed to be in the spacecraft velocity and the magnitude was left free in order to fix the dynamic pressure to the maximum allowed (0.4 Pa, increased in the course of the campaign) at the time when the violation occurred.

Afterwards, the following flight rules were applied:

- If the manoeuvre magnitude was 2 cm/s or less, its magnitude was fixed to 2 cm/s.
- If the manoeuvre magnitude was 1.6 m/s. The manoeuvre needed to be split in different ones at consecutive apocentres.

The first rule was considered due to the manoeuvre performance. The second one, due to the low fuel available on the spacecraft, 1.6m/s is what was available for orbit control manoeuvres with almost empty tanks.

Once the nominal trajectory was completed, a new orbit was computed based on a free propagation of the nominal one, but without or with a very thin atmosphere. This second orbit was used to schedule the exit of aerobraking mode for each orbit, as explained in section 3.2.

4.4.2 Detailed short Term planning operations

During the first aerobraking sessions, the atmospheric profile was updated with the first real data calibrations. Since the new atmospheric profile was much denser than the previous one (see atmospheric profile difference between LTP and first calibrated on Fig. 9), the S/C was predicted to re-enter Venus at the end of June. Hence, a Pericentre Raising Manoeuvre had to be commanded (see manoeuvre on the 24^{th} of May in Tab. 3).

Type	Date	Delta-V	Target
PRM	2014/05/24	0.428 m/s	0.4 Pa at the pericentre on the 27th May
PLM	2014/06/23	0.177 m/s	0.4 Pa at middle plateau 29th June
PLM	2014/06/28	0.07 m/s	0.55 Pa at middle plateau 29th June
PLM	2014/07/02	0.05 m/s	0.55 Pa on the 3rd July 15
PRM	2014/07/11	0.02 m/s	Dynamic pressure < 0.6 Pa on the 12th July

Table 3. Manoeuvre characteristics commanded during the aerobraking campaign. PRM: Pericenter Raising Manoeuvre. PLM: Pericenter Lowering Manoeuvre

Here are the reasons of such differences between both successive atmospheric models (see also section 4.3):

- The previous atmospheric profile was used for the generation of the Long Term Products. It was based on the assumption that the pericentre would be on the night side. However, the first pericentres during aerobraking were on the day side.
- The calibration was computed using data from the upper layers of the atmosphere, but applied for the whole range of altitudes of the density profile. In reality, at the lower layers, the calibration factor (see section 4.2) was smaller.

During the following sessions, the atmospheric model was calibrated based on new data. At each session, the atmospheric profile was lighter than the previous one. The calibration factor became smaller as the altitude decreased. Then, on the commanding session of the 23rd June, it was necessary to implement a Pericentre Lowering Manoeuvre to target 0.4 Pa in the middle of the plateau (see manoeuvre on 23rd June in Tab. 3); otherwise, the dynamic pressure would have fallen below 0.4N/m2 as the pericentre moved from day to night.

In the plot of Fig. 10, the predicted maximum dynamic pressure is presented for different commanding sessions. The dark blue line represents the predicted evolution of the dynamic pressure on the commanding session previous to the implementation of the first pericenter lowering manoeuvre. The red line for the commanding session of the 23rd June and the yellow for the following.

In the next commanding session, the dynamic pressure was lower than the predicted one (yellow line of the plot), therefore the 0.4 Pa target could not be reached. As the aerobraking session was close to the end, a more aggressive approach was adopted: on the commanding session of the 26th of June a Pericentre Lowering Manoeuvre was implemented to target to 0.55 Pa (see manoeuvre on 28th June in Tab. 3).

In the following commanding session, 30th June, it appeared that the density was lighter than expected, so the 0.55 Pa was not to be reached. Hence, a new Pericentre Lowering Manoeuvre was implemented to target to 0.55 Pa on the 3rd of July (see manoeuvre on 2nd July in Tab. 3). The dynamic pressure prediction for the commanding session on the 26th and 30th June are shown in Fig. 10.

At the end of the aerobraking, at a pericentre altitude around 130km, the atmosphere was thicker than expected. Then, a Pericentre Raising Manoeuvre to target a dynamic pressure of 0.6 Pa at the last pericentre before the end of the aerobraking was implemented. This manoeuvre was very small, hence by spacecraft constraint the ΔV magnitude was imposed to 2 cm/s and the dynamic pressure decreased to 0.58 Pa (see manoeuvre on 11th July in Tab. 3). This manoeuvre was commanded during the 7th of July commanded session. However, in the commanding session of the 10th July, the expected dynamic pressure increased up to 0.75 Pa instead of 0.58 Pa. Nevertheless, since the commands were already on board, the risk was accepted and the commands from the previous session were kept.
After the last pericentre of the aerobraking, a series of deterministic Pericentre Raising Manoeuvres were performed to leave the aerobraking region.

5 Campaign outcomes

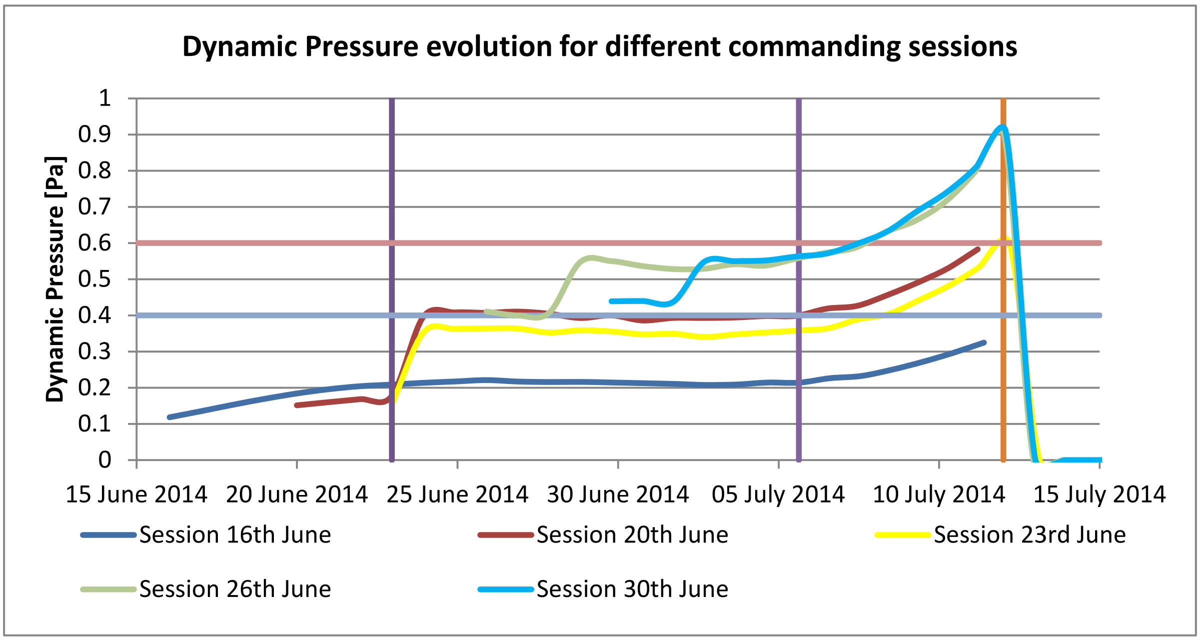

Figure 10: Dynamic Pressure evolution for different commanding cycles. Vertical purple lines represent the start and end of the plateau. Vertical orange line represents the end of the aerobraking.

5.1 Summary

The main technical objectives, namely six pericentre passes at a dynamic pressure of at least 0.4 N/m2, including at least 3 passes at a dynamic pressure of at least 0.5 N/m2, were fulfilled without degradation to the spacecraft. Large variability in density along-track and from day to day were observed, together with a steep gradient at the terminator. As shown on Fig. 11, as expected the measurements were initially closer to the day side atmospheric model, then evolved towards the night side model.
The average effect of the attitude control thruster pulses on an orbit was to impart 4 cm/s to the spacecraft, in a direction reinforcing the effect of the drag, reducing the period by 8 s, raising the pericentre altitude by less than 20 m. In total, the consumed ΔV represented about 10% of the drag ΔV.

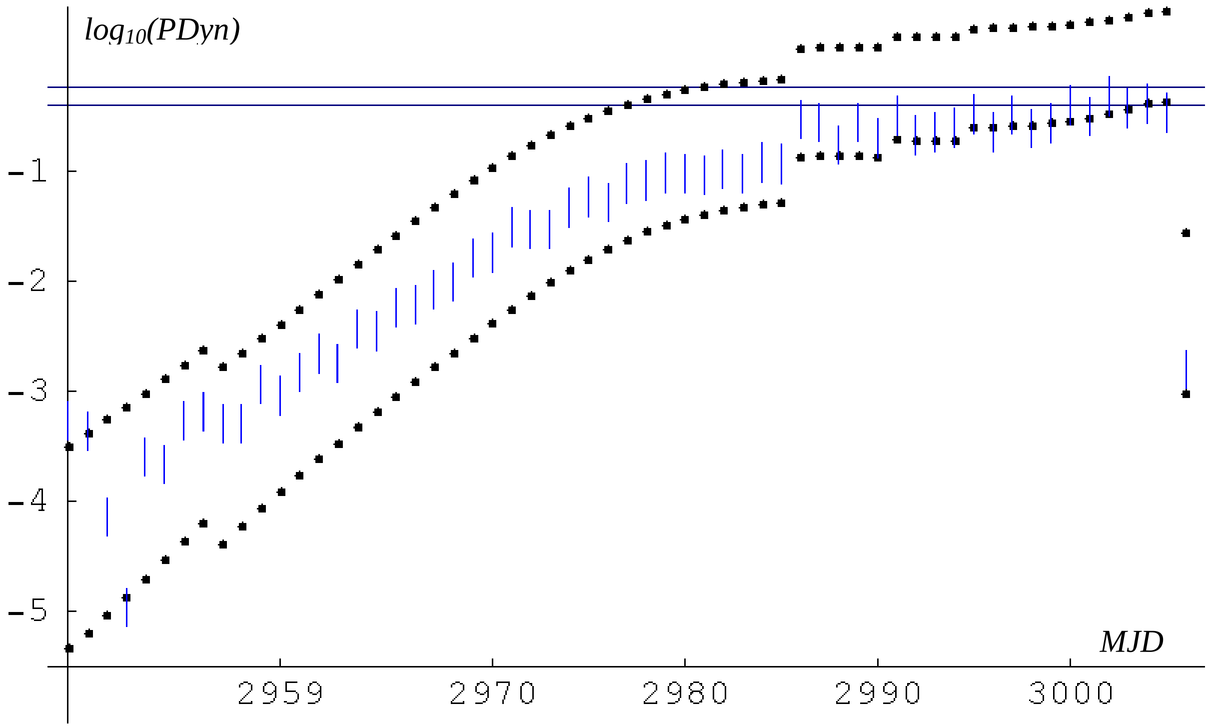

Figure 11: Decimal log of the estimated dynamic pressure with uncertainty (blue), together with noon (black, top) and midnight (black, bottom) VIRA models.

5.2 Perspectives

Because of the risks excepted for Venus Express aerobraking campaign, it is doubtful whether the used approach can serve as reference for a future mission which does aerobraking to reach during its nominal mission.

The first ESA mission to use aerobraking as a means of re-joining the scientific orbit will be Exomars, due to be launched early 2016. After Mars orbit insertion, the aims are to save a ΔV of 1160 m/s while lowering the apocentre height from 37000 km to 3800 km. Like Venus Express, this spacecraft will implement an aerobraking dedicated mode, however it will also be equipped with three essential autonomy features:

1. the actual pericentre time and drag ΔV will be used to predict the next pericentre time, and to synchronize the whole spacecraft timeline; indeed, especially during the walk out, the orbital period would be too small to accommodate for 2 hours in aerobraking mode that were used with Venus Express
2. the temperatures and accelerations will be monitored during the pass. In the case of a too high heat flux, dynamic pressure, heat loads or too low orbital period an autonomous flux reduction pericentre raising manoeuvre will take place. Then, the aerobraking will continue, but in a suboptimal regime. Unlike Venus Express, the aerobraking phase will take place before the exploitation phase, therefore the safety of the spacecraft must be ensured.
3. In a case of a Safe Mode triggering, the spacecraft will autonomously perform a Pop-up manoeuvre and raise the pericentre outside the atmosphere. Unlike Venus Express, thruster actuated attitude control will be force free, removing any impact on the pericentre altitude.

The corridor control activities (pericentre altitude tuning manoeuvres) will still be decided on ground depending on the results of the orbit estimation and the calibration of an atmospheric profile using radio-metric data.

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