# VENUS EXPRESS SOLAR ARRAYS ROTATION EXPERIMENTS TO MEASURE ATMOSPHERIC DENSITY

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***Abstract:*** *The European Space Agency probe Venus Express successfully completed in October 2010 its last and most ambitious Aerodynamic Drag Experiment Campaign to date. The campaign was designed to provide as much information as possible about the upper level of the atmosphere of Venus, at height varying between 165 and 185 km from the surface. At these altitudes, the spacecraft experiences a disturbing aerodynamic torque that must be compensated by the Attitude Control System by varying the angular momentum of the onboard reaction wheels. By studying the 8 Hz telemetry data gathered around pericentre, the values of the atmospheric density and of the accommodation coefficient can be deduced.*

***Keywords:*** *Venus Express, Aerobraking, Atmospheric Density, Accommodation Coefficient.*

## 1. Introduction

This paper describes the preparation and execution of the six-week drag experiments campaign carried out by Venus Express in September-October 2010. The main focus is the justification of the operational constraints under which the experiments were executed, as well as the depiction of the safety precautions adopted in order not to jeopardise the mission. The drag experiments campaign succeeded in providing meaningful data that can be reduced and exploited to improve the available atmospheric models. The main results of the campaign are that the values of the atmospheric density on Venus seem to present oscillations from day to day, but tend to increase from night to day. At 165 km of altitude, along the terminator, the estimated accommodation coefficient is equal to 0.886±0.02 and the estimated scale-height of an exponential atmospheric model fitting the data gathered during this campaign is equal to 5.34±0.71 km.

## 2. The Aerodynamic Drag Experiments (ADE) Campaigns

### 2.1. The Venus Express Mission

Venus Express (VEX) is the first mission of the European Space Agency (ESA) to Venus. It was launched on November 9$^{th}$ 2005 and performed Venus Orbit Insertion on April 11$^{th}$ 2006: it has been studying the atmosphere, geology and plasma environment of the planet ever since. VEX operational orbit is a highly-elliptical, quasi-polar orbit, with a period of 24 hours. This orbit provides complete latitudinal coverage and represents a good trade-off for allowing both low-altitude, high-resolution observations of the northern hemisphere, and high-altitude observations of the global dynamics of the atmospheric phenomena over the southern hemisphere.

In 2008, the scientific community proposed to alter the operational orbit in such a way to allow medium-high resolution scanning of the southern hemisphere: for this reason, the option of lowering the apocentre by using aerobraking manoeuvres was investigated.
As part of this investigation, in 2009 Venus Express underwent several Aerodynamic Drag Experiment (ADE) campaigns, which aimed at providing an estimate of the atmospheric density in the range of altitudes between 175 and 200 km. The scheduling of the campaigns took into account that the operational orbit of VEX is heavily affected by the third-body perturbation due to the Sun: depending on the relative geometry the effect can be the raising of pericentre and lowering of the apocentre, or vice-versa. The drag campaigns were executed during periods of favourable evolution of the pericentre height, gently decreasing before the beginning of each ADE, and constant throughout each campaign, thus reducing the risk of experiencing a sudden dramatic increase in the atmospheric density. The "plateaus" in Fig. 1 highlight the periods in which it is safer to schedule a drag experiment campaign.

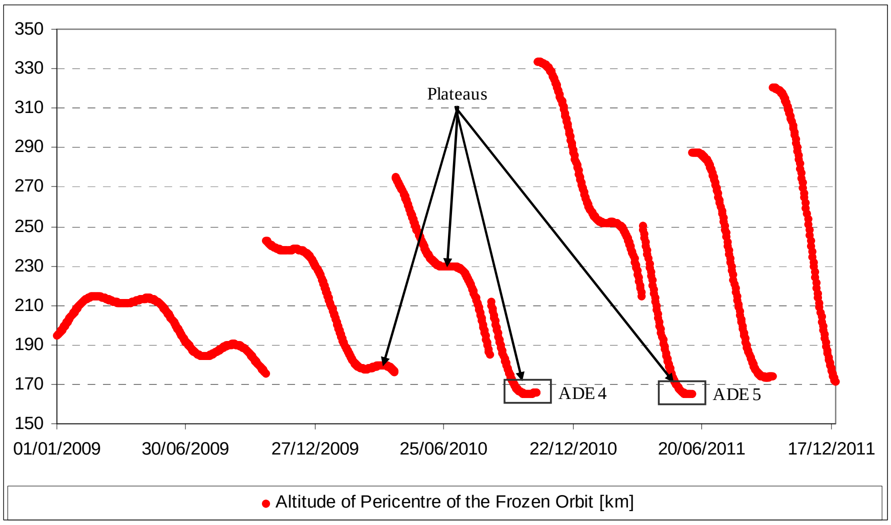


**Figure 1: Evolution of the Predicted Pericentre Height of the Venus Express Probe.**

During the campaigns executed in 2009, the atmospheric density was estimated by analysing the drag perturbation over the orbit, a method that requires several days of data gathering to provide meaningful information.
Part of the investigation consisted in the analysis of 8 Hz telemetry data, which provides readings for spacecraft rates and acceleration, the requested control torque and the angular momentum of the reaction wheels. The study of the data collected around pericentre showed that, while the atmospheric drag at the flown altitude was too low to be detected by the accelerometers mounted on the spacecraft, the torque of the aerodynamic forces led to a change in the reaction wheel levels.
This suggested the use of a new strategy for the drag experiments in 2010: whenever the pericentre height was such that the presence of atmosphere was not negligible, the solar arrays were moved in a non-symmetric configuration with respect to the relative wind.
By doing so, the drag experienced by each of the solar arrays would result in a torque that the Attitude Control System would compensate by varying the angular momentum of the onboard reaction wheels. The study of the evolution of the wheel levels around pericentre would allow an estimation of the aerodynamic torque acting on the spacecraft (neglecting the depointing caused by the drag). Since the geometry of the problem is fully known, the atmospheric density could be deduced from the aerodynamic torque. This method, which uses reaction wheels as almost-real-time sensors, not only allows detecting density variations, but also provides scientifically and operationally valuable data at the next contact with a ground station.
As soon as the details of the new experiments had been agreed upon, three new ADE campaigns, in February, April and October 2010 respectively, were scheduled.

### 2.2. The Design of the Experiments

Venus Express is a three-axis stabilised spacecraft of roughly cubic shape, with the High Gain Antenna (HGA) on the +*x* face, and the solar arrays on the ±*y* faces. Actuators can allow rotation of the solar arrays around an axis parallel to the *y* axis.

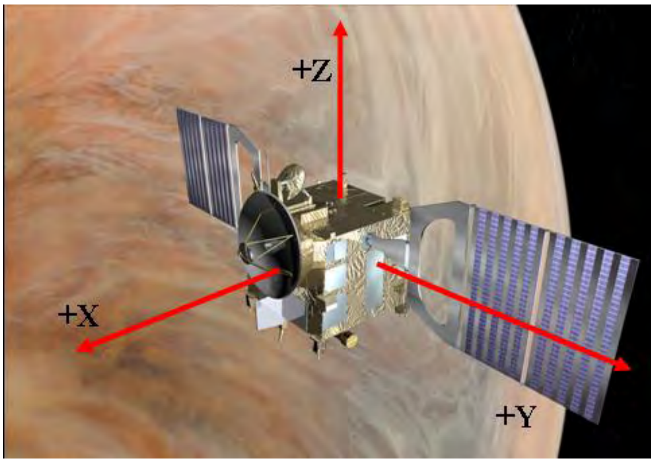


**Figure 2: Venus Express Spacecraft Frame.**

Since there are operational constraints over the Sun direction in spacecraft frame, in general during such an experiment the solar arrays cannot be perfectly perpendicular to the wind direction (i.e. the velocity normally has, in spacecraft frame, a component along *y*). We will refer to the angle between the vector normal to the solar array surface and the *xz* component of the velocity in spacecraft frame "sensitivity angle".

A full-featured drag experiment has a length of 8 hours. One hour before pericentre, the solar panels are commanded to the desired position, one hour after pericentre, the positions of the solar arrays are inverted; after four more hours, they are inverted again (to a configuration equal to the one at pericentre) until the end of the experiment. This strategy has been chosen for two reasons: first, when switching the configuration, the torque caused by the solar radiation pressure (SRP) changes sign, and therefore the accumulated SRP torque throughout the experiment is evanescent. Second, in the last two hours of the experiment, when the spacecraft is already far from pericentre and does not experience torques due to either atmosphere or gravity gradient, it is possible to gather data over the torque caused by the SRP alone, which will allow filtering out the SRP contribution when reducing the data collected around pericentre. If, for operational reasons, the flight dynamics timeline cannot allocate an experiment of eight hours, a shortened four-hour version of the experiment, is scheduled. In this case, the experiment lasts between one hour before pericentre to three hours after it, with just a single repositioning in the middle of the slot.

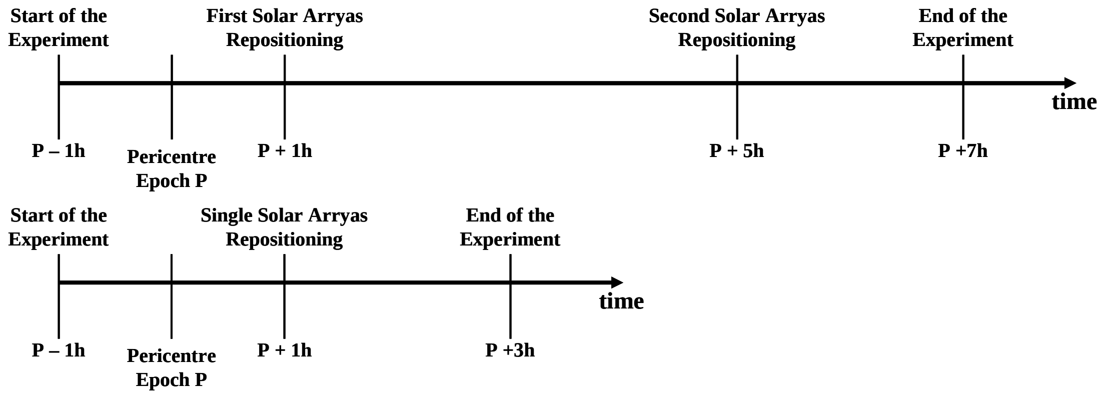


**Figure 3: Timeline of the Drag Experiments (Eight-Hour and Four-Hour Variants).**

It is worth noting that the time required by the solar arrays to reach any commanded position is less than two minutes, and therefore can be disregarded in the post-processing of the raw data.

### 2.2.1. Criterion for Choosing the Solar Arrays Rotation Angles

The routine operations for Venus Express are split into medium-term and short-term processing (from now on simply referred to as MTP and STP respectively). During the medium-term processing, checks are run to ensure that the proposed flight timeline is feasible from the operational point of view; in short-term, the commands are actually prepared and sent to the spacecraft, about one week before the first execution time. The scheduling of the drag experiments is done in MTP, while the preliminary choice of the sensitivity angles is made in MTP and later confirmed or amended in STP.

The experiments are designed taking into account two fundamental parameters: the predicted aerodynamic torque experienced by the spacecraft (based on the available atmospheric model) and the predicted power input. The solar arrays rotation angles are decided in such a way that the predicted aerodynamic torque, mapped onto the reaction wheels assembly, does not saturate the operational torque capacity of any of the four wheels. In order to take into account the uncertainties over the atmospheric density, which has been formerly demonstrated to vary with latitude and illumination conditions, a safety factor of 10 has been introduced.

For every sensitivity angle, there are two possible positions of the solar arrays, one offering the solar cells to the wind, and the other offering the back side. Among these two options, the one maximising the power input and minimising the solar aspect angle (i.e. the angle between the direction normal to the solar array surface and the Sun direction) is always chosen. As soon as the configuration of the spacecraft throughout the experiment is decided, simulations are carried out in order to guarantee that the repositioning of the solar arrays is power-wise feasible and does not translate in loss of performances of the probe.

During the short-term processing, the most recent information about the atmosphere, as provided by the telemetry data dumped daily by the probe, are updated in the simulation, and the solar arrays rotation angles are confirmed or amended. In this last case, the criterion for choosing the new angles is that the predicted torque over any reaction wheel must be below 10% of the maximum torque capacity at any time, and that at any time the predicted power output must be above the power output predicted in MTP.

In what follows, the operational constraints are described in further details.

### 2.2.2. The Constraint over the Maximum Aerodynamic Torque

The prediction of the aerodynamic torque in spacecraft frame is carried out taking into account the attitude of the probe, the predicted position of the centre of mass and the predicted value of the atmospheric density. The prediction of the aerodynamic torque disregards the contribution of the cubic body of the spacecraft, and takes into account only the contribution of the solar arrays. The aerodynamic force acting on each solar array can be expressed as a function of the so-called *accommodation coefficient* $\alpha$, a priori unknown, which is used to model the exchange of kinetic energy between the molecules of the atmosphere and the surface they bounce upon. The model assumes that a fraction $\alpha$ of molecules performs perfectly inelastic impacts and transforms all its kinetic energy in heat that the spacecraft will absorb, while a fraction $(1-\alpha)$ performs perfectly elastic impacts and bounces over the surface of the spacecraft. So the aerodynamic force experienced by each solar array can be written as:

$$\vec{F}_{\pm} = -\rho_{(h,\varphi,\Psi)} A \left|\vec{v} \cdot \vec{n}_{\pm}\right| \left[\alpha \vec{v} + 2(1-\alpha)(\vec{v} \cdot \vec{n}_{\pm})\vec{n}_{\pm}\right] \tag{1}$$

where

- the subscript ± indicates that this expression is valid for the solar array on either the $+y$ or the $-y$ face,
- $\rho_{(h,\varphi,\Psi)}$ is the predicted atmospheric density as a function of
  - the altitude $h$ of the spacecraft,
  - and latitude φ of the spacecraft,
  - the Sun-Venus-spacecraft angle Ψ, which provides information over the illumination conditions,
- $A$ is the area of each solar array,
- $\vec{v}$ is the velocity vector in spacecraft frame (the velocity of the molecules with respect to Venus is neglected),
- $\vec{n}$ is the vector normal to the surface of the solar array, expressed in spacecraft frame,
- $\alpha$ is the accommodation coefficient.

The torque caused by this aerodynamic force depends on the position of the centre of mass of the spacecraft. This depends on the position of the solar arrays and on the masses of liquids stored in the tanks of the bi-propellant chemical propulsion system onboard the Venus Express. The mass properties of the solar arrays can be calculated analytically. The distribution of the masses of the pressuring gas in the tanks is deduced from the values of pressure and temperature, as provided by the telemetry data, while the volume of oxidiser and fuel in the tanks is obtained by subtraction. Once the volume of the liquids in the tanks is known, the position of the centre of mass and inertia matrixes of the liquids can be interpolated by using reference tables obtained in laboratory conditions. Once the position of the centre of mass of the spacecraft in spacecraft frame, $\vec{r}_{CoM}$, has been estimated, the arm of the aerodynamic forces acting on the solar arrays can be calculated, since the position of the centre of pressure of each of the solar arrays, $\vec{r}_{CoP_\pm}$, is know a priori. So the aerodynamic torque in spacecraft frame can be written as:

$$\vec{T}^{SC}_{AERO} = \sum_{\pm}\left(\vec{r}_{CoP_\pm} - \vec{r}_{CoM}\right) \times \vec{F}_\pm \tag{2}$$

The torque in spacecraft frame can be mapped over the reaction wheels assembly by calculating the pseudo-inverse matrix $\hat{P}_S \in \Re^{4\times3}$ of the reaction wheels alignment matrix $\hat{M} \in \Re^{3\times4}$, whose columns are the rotation axes of the reaction wheels in spacecraft frame:

$$\hat{M} = \begin{bmatrix} 0.577096 & 0.577096 & -0.577096 & -0.577096 \\ -0.577096 & 0.577096 & 0.577096 & -0.577096 \\ 0.577858 & 0.577858 & 0.577858 & 0.577858 \end{bmatrix}$$

Therefore, the torque in RW frame is calculated as follows:

$$\vec{T}^{RW}_{AERO} = \hat{P}_S\left(\hat{M}\right) \cdot \vec{T}^{SC}_{AERO} \tag{3}$$

The first operational constraint for the drag experiments is:

$$\max_i \left|\vec{T}_{AERO,i}^{RW}\right| < \frac{T^*}{10} \quad (4)$$

being $T^*$ the maximum torque capacity of the wheels, equal to 0.04 Nm.

### 2.2.3. The Constraint over the Attitude

In order to provide an independent estimation of the atmospheric density, it was decided to schedule radio-science experiments (i.e. one-way and two-way Doppler measurements) during all pericentre passes in which a drag experiment was executed. This decision translated into the operational requirement of having the high-gain antenna pointing to Earth during the drag experiments.
An Earth-pointing attitude is usually referred to as a “GSEP block” in the flight dynamics timeline, where the acronym stands for Gyro-Stellar on Ephemeris Phase. In GSEP attitude, there are constraints over the remaining degree of freedom (i.e. the rotation of the spacecraft around the high-gain antenna axis) because Venus Express operates under strict limits for the Sun direction in spacecraft frame. A so-called “permanent illumination box” (PIB) has been defined during the phase of mission design in order to establish the zone in which the sun direction could dwell without endangering the spacecraft. This zone is shown in Fig. 4 hereafter.

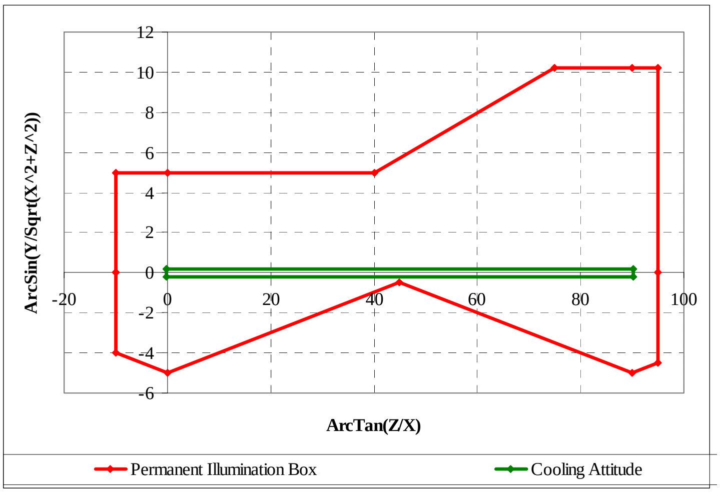


**Figure 4: Definition of Permanent Illumination Box and Cooling Attitude.**

The Sun direction is allowed to exit this box for short periods of time, like during slews or short scientific pointings. After every set of observations carried out within the PIB, or after any single activity in which the sun direction exited it, VEX must spend a certain pre-calculated time in what is usually referred to as “cooling attitude”. This is done in order to allow the heat accumulated through solar illumination and payload operations to be dissipated, and to begin the new set of observations in a configuration re-initialised from the thermal point of view.
Typically, the attitude during GSEP blocks, like the one in which the experiments were executed, is a cooling attitude. Since the heat radiators are located on the $\pm y$ faces of the spacecraft, thrusters and main engine on the $-z$ face and star trackers on the $-x$ face, this attitude requires the Sun direction to have:

1. vanishing $y$ component (a tolerance of ±0.2 degrees is applied for the angle between the Sun direction in spacecraft frame and the $xz$ plane),
2. positive $x$ and $z$ components.

These conditions fully determine the attitude of the spacecraft during the Earth-pointing phase, and represent the second operational constraint for the drag experiments.

### 2.2.4. The Constraint over the Maximum Heat Flux

During the preparation of the ADE 4 campaign, it was agreed that the heat flux generated by the impacts of the molecules with the surface of the spacecraft had to be negligible with respect to the heat generated by solar illumination and payload operations. In order to have a quantitative constraint, it was decided to limit the heat flux caused by the atmosphere to the heat flux considered negligible in the definition of the "cooling attitude" mentioned in the previous section.

$$Q_{Negligible} = Q_{Earth} \frac{d_{Earth}^2}{d_{Venus}^2} \sin(\varepsilon) \tag{5}$$

being:

- $Q_{Earth}$ the solar constant at one astronomical unit,
- $d_{Earth}$ and $d_{Venus}$ the mean orbital distance of the planets from the Sun,
- ε equal to 0.2 degrees, as from the previous section.

The value of $Q_{Negligible}$ is about 9 $W/m^2$ and can be substituted in the equation of the dynamic pressure in order to compute an upper limit for the atmospheric density below which the heat flux between molecules of the atmosphere and spacecraft is negligible:

$$\alpha \frac{Q_{Negligible}}{v_{peri}} = \frac{\rho_{Max}}{2} v_{peri}^2 \tag{6}$$

being:

- $v_{peri}$ the spacecraft velocity at pericentre with respect to Venus, which is in the order of magnitude of 10 km/s (the velocity of the molecules with respect to Venus is neglected),
- α is the accommodation coefficient, equal to one in the worst-case scenario.

Therefore the third and last operational constraint for executing the experiments is that the predicted atmospheric density must be below $18 \cdot 10^{-12}$ $kg/m^3$.

### 2.2.5. Additional Operational Constraints

In order to ease the post-processing of raw data, two further operational constraints have been introduced: during an interval of 30 minutes around pericentre, no eclipses must occur, since the SRP is difficult to estimate in penumbra regions, and all payload operations must be discontinued, in order not to provide additional vibrations. Furthermore, in order to minimise depointing (and therefore to provide less noisy data), all throughout the experiments the spacecraft mode is required to be FPAP (Fine Pointing Accuracy Phase), which provides a response to the environmental torques much faster than the one of a normal Earth-pointing phase.

## 2.3. The Experiment Campaign in September and October 2010

The fourth aerodynamic experiments campaign, carried out throughout September and October 2010, has been the most ambitious to date: the altitude of the pericentre reached values as low as 165 km, an all-time minimum for Venus Express.

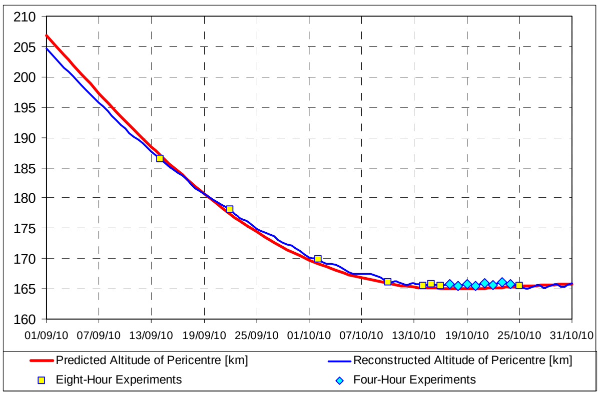


**Figure 5: Altitude of the Pericentre during ADE Campaign 4.**

Four experiments were performed during the descending phase, and other twelve during the plateau. The experiments in the descending phase were performed in order to monitor the evolution of the density but, even in the days in which no experiments were scheduled, the 8 Hz telemetry was switched on in a time interval of ±15 minutes around pericentre in order to register any deviation from the predicted behaviour of the reaction wheels.

It is worth noting that the oscillations of the pericentre altitude during the plateau are due to wheel off-loading manoeuvres which provide, as a side effect, a small delta-V that is used for orbit control.

### 2.3.1. The Geometry of the Problem

In this specific campaign, the effect of the increase of the atmospheric density over the aerodynamic torque was mitigated by the evolution of the attitude, which was becoming less and less favourable to the experiments towards the end of the campaign (i.e. the *y* component of the velocity in spacecraft frame was becoming predominant). This effect was due to the fact that the attitude of the spacecraft in GSEP is defined through a cross product between the spacecraft-to-Earth and spacecraft-to-Sun directions: since in October 2010 Venus was approaching inferior conjunction (Sun-spacecraft-Earth angle approaching 180 degrees), these two directions were almost collinear, and thus a slow change in the relative geometry brought to a fast change in the direction of the vector resulting from the cross product, and consequently in the evolution of the attitude.

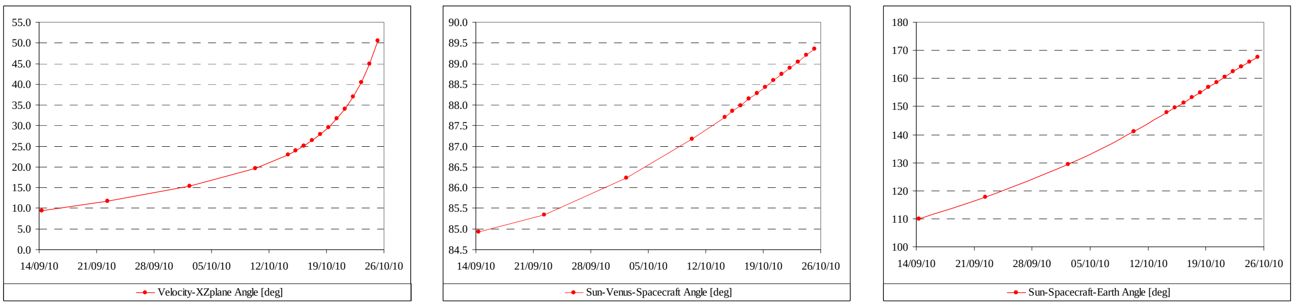


**Figure 6: Evolution of the Angle between the *XZ* Plane and the Flow in Spacecraft frame (right), the Sun-Venus-Spacecraft Angle (centre), and the Sun-Spacecraft-Earth Angle (left).**

Other guidance options more favourable to the experiment geometry have been considered and subsequently discarded, since they were not feasible from the thermal point of view.

It is also worth noting that performing the experiments in the plateaus highlighted in Fig 1., when the third-body disturbance over the altitude of pericentre and apocentre is minimised, implies that the pericentre is above the terminator: in this campaign, VEX was approaching the terminator from the day-side, and so the value of the density at a given altitude was expected to gently decrease at the increase of the Sun-Venus-spacecraft angle.

### 2.3.2. Safety Measures

The safety of the spacecraft has obviously been the supreme constraint of the Aerodynamic Drag Campaign. A great effort has been made to minimise the chances of putting the mission at risk, both by assessing the risks naturally associated with the manoeuvre, and by preparing appropriate countermeasures to be executed in case of need. This process has been made more challenging by the uncertainties over the values of density and accommodation coefficient, and by the tight available reaction-time.

The behaviour of the spacecraft in case of contingencies is predictable: a so-called “safe-mode” is automatically triggered. This spacecraft mode usually has the same Earth-pointing attitude of the GSEP mode, but performs attitude control using thrusters rather than reaction wheels (this is more expensive in terms of fuel consumption but much less in terms of power usage). At the triggering of the safe-mode, both solar arrays are automatically repositioned to minimise the solar aspect angle, and the wheels are spun down to zero: the resulting friction torque experienced by the spacecraft is compensated by the thrusters. Since Venus Express chemical propulsion system is unbalanced (i.e. all the thrusters are mounted on the $-z$ face of the probe), there is no way of providing a torque without providing also a delta-V. The direction of this delta-V is not easily predictable, since it depends on the spacecraft attitude and reaction wheel levels at the time of the triggering, but its magnitude is of the order of 1 m/s.

The worst-case scenario presents the safe-mode occurring a mere few hours before pericentre, giving no time for executing any recovering procedure before entering the atmosphere, with the delta-V firing in the direction opposite to the spacecraft velocity with respect to Venus. In these conditions the lowering of the pericentre due to the loss of kinetic energy can be about 10 Km: with scale-height (i.e. the altitude over which the density increases by a factor $e$=2.718...) of about 5 Km, this might translate in a raise of one order of magnitude in the value of the predicted atmospheric density. This risk has been considered acceptable for ADE 4 both in terms of heat flux and aerodynamic torque.

As previously mentioned, even in the days were no experiments were scheduled, the 8 Hz telemetry was switched on for a period of ±15 minutes around pericentre: as soon as the gathered data were dumped, a GO/NO-GO test based on the measured torque was performed. The commands for repositioning the solar arrays were, in fact, not included into the operational timeline, but were uploaded only after assessing the risks on a daily basis.

As a further precaution, the commands to execute pericentre-raising orbital correction manoeuvres around apocentre (one manoeuvre per orbit throughout the campaign) were prepared and ready to be uploaded.

Furthermore, the mission Flight Control Team prepared a new two-phased safe-mode recovery strategy which allowed the execution of one of the pre-calculated OCMs in a very short time (within one single slot of communication with the Cebreros ground station). The first phase contained only the few essential steps to put the spacecraft in the conditions of executing a manoeuvre (e.g. recovery of time correlation, spacecraft memory and TM/TC link, …). The second phase contained all recovery steps which were not to be executed necessarily before the escape manoeuvre. The escape manoeuvre would be uploaded and executed between phase 1 and phase 2. The following scheme displays the adopted rationale.

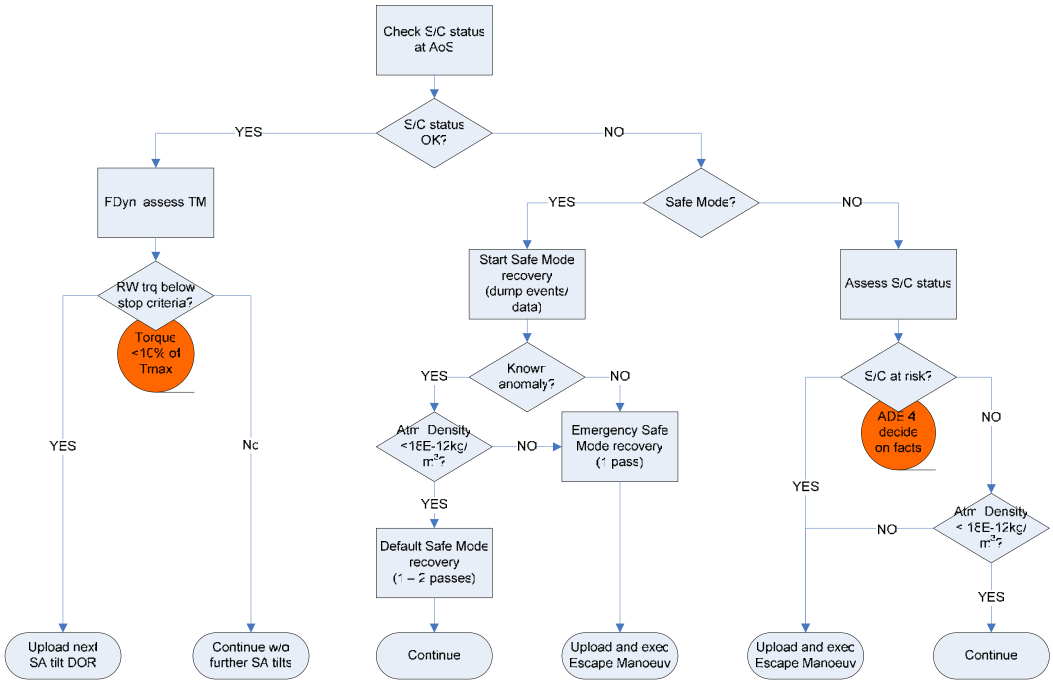


**Fig 7: Spacecraft Contingency Strategy in case of Anomaly, from [1].**

### 2.3.3. The Solar Arrays Rotation Angles

The first four experiments of ADE 4 campaign have been carried out in the so-called "full sensitivity" configuration, with a solar array perpendicular to the *xz* component of the velocity in spacecraft frame, and the other one edge-on, thus maximising the aerodynamic torque. These experiments aimed at providing data over the evolution of the atmospheric density at the decreasing of the altitude. The positions of the solar arrays were inverted (i.e. the panel edge-on with respect to the flow was a different one) from experiment to experiment, in order to give the possibility of filtering out the contribution of the main spacecraft body to the aerodynamic torque.
The subsequent three experiments have been executed in a configuration mimicking a windmill, with the two solar arrays forming with the incoming flow angles of +45 and -45 degrees respectively. This configuration generates an aerodynamic torque with a component along the direction of the incoming flow: the magnitude of this component depends on the accommodation coefficient, therefore the windmill experiments are especially suited to gather data to estimate this parameter.
The last nine experiments of the campaign were classified as full sensitivity experiments in the medium term processing but, since the values of the atmospheric density estimated in the first four experiments were systematically higher than the predicted ones, the solar arrays configuration commanded in STP was a less demanding one. Right after the experiment on October 2, a quick estimation of the worst-case scenario atmospheric density has been done by fitting the data gathered in the previous experiments into an exponential model with 5 km scale-height, and new solar arrays rotation angles have been chosen according to the constraints defined in section 2.2.1.
The following table summarises the configuration adopted in the experiments throughout the campaign; the tabled physical variables are the following ones:

- $\varsigma^+$ (resp. $\varsigma^-$) is the angle between the normal to the solar panel on the +*y* (resp. -*y*) face and the *xz* component of the velocity in spacecraft frame,
- $\tau^+$ (resp. $\tau^-$) is the angle between the normal to the solar panel on the +*y* (resp. -*y*) face and the *x* axis of the spacecraft reference frame, measured positively towards +*z* (resp. -*z*).

**Table 1: Solar Arrays Configurations during ADE 4 Campaign.**

| Epoch of Pericentre | $\varsigma^+$ [deg] | $\varsigma^-$ [deg] | $\tau^+$ [deg] | $\tau^-$ [deg] |
|---|---|---|---|---|
| 14/09/2010 08:36 | 180.0000 | 90.0000 | 100.7866 | -10.7866 |
| 22/09/2010 08:30 | 90.0000 | 180.0000 | 15.6514 | -105.6514 |
| 02/10/2010 08:23 | 180.0000 | 90.0000 | 109.6842 | -19.6842 |
| 10/10/2010 07:34 | 90.0000 | 180.0000 | 20.8267 | -110.8267 |
| 14/10/2010 07:06 | 45.0000 | 135.0000 | -24.2870 | -65.7130 |
| 15/10/2010 06:59 | 135.0000 | 45.0000 | 65.6367 | 24.3633 |
| 16/10/2010 06:52 | 45.0000 | 135.0000 | -24.4470 | -65.5530 |
| 17/10/2010 06:45 | 45.0000 | 110.0000 | -24.4939 | -40.5061 |
| 18/10/2010 06:38 | 110.0000 | 45.0000 | 40.4426 | 24.5574 |
| 19/10/2010 06:31 | 45.0000 | 110.0000 | -24.5831 | -40.4169 |
| 20/10/2010 06:24 | 110.0000 | 45.0000 | 40.4607 | 24.5393 |
| 21/10/2010 06:17 | 45.0000 | 110.0000 | -24.3775 | -40.6225 |
| 22/10/2010 06:10 | 110.0000 | 45.0000 | 40.9841 | 24.0159 |
| 23/10/2010 06:03 | 45.0000 | 110.0000 | -23.3135 | -41.6865 |
| 24/10/2010 05:56 | 110.0000 | 45.0000 | 43.0015 | 21.9985 |
| 25/10/2010 05:49 | 45.0000 | 110.0000 | -19.4991 | -45.5009 |

## 3. Reduction of the Reaction Wheels Telemetry Data

Venus Express collected a fairly impressive amount of telemetry data throughout the fourth aerodynamic drag experiments campaign. The data have been post-processed by ESOC Flight Dynamics team, not in order to construct a model of the atmosphere of Venus, but in order to provide operationally meaningful information. The post-processing method is herein presented, in order to provide a reasonable first estimation of the values of atmospheric density and accommodation coefficient for the range of altitudes taken into consideration.
In order to estimate the aerodynamic torque, the other unwanted contributions to the total environmental torque acting on the spacecraft had to be filtered out. These contributions are assumed to be limited to the gravity gradient torque (since the experiments are executed at pericentre) and solar radiation pressure torque (because of the asymmetric configuration of the solar arrays).

### 3.1. Modelling of the Gravity Gradient Torque

When considering Venus a perfectly spherical body, the gravity gradient torque is given by:

$$\vec{T}_{\mathrm{GG}} = 3\mu \left\| \vec{r} \right\|^{-5} \left( \vec{r} \times \hat{I} \cdot \vec{r} \right) \tag{7}$$

being:

- $\vec{r}$ the vector from Venus centre to the spacecraft,
- $\hat{I}$ the inertia tensor of the spacecraft,
- $\mu$ the gravitational constant of Venus.

The maximum torque due to the gravity gradient is approximately $7*10^{-4}$ Nm, which is a non-negligible fraction of the aerodynamic torque.
Assuming that the SC is moving on a Keplerian trajectory, the integral in time of equation (7) can be written as follows:

$$\Delta\vec{L}_{GG}\left(t,t^*\right)= f_{GG,diag}\left(t,t^*\right)\cdot \Delta I_{diag} + f_{GG,12}\left(t,t^*\right)\cdot I_{12} + f_{GG,13}\left(t,t^*\right)\cdot I_{13} + f_{GG,23}\left(t,t^*\right)\cdot I_{23} \quad (8)$$

being:

- $t$ the time variable and $t^*$ a reference time before the pericentre (and after any eclipse), when the contributions to the torque of gravity gradient and atmospheric drag are considered negligible (i.e. altitude above 210 km),
- $f_{GG,XX}$ are functions that can be calculated analytically,
- $\Delta I_{diag}$ is the difference of the two diagonal terms of the inertia tensor that correspond to directions in the orbital plane, while $I_{XY}$ are non-diagonal terms of the tensor.

### 3.2. Modelling of the Solar Radiation Pressure Torque

The solar radiation pressure torque in the most asymmetric configuration can be as high as $2*10^{-4}$ Nm. Given that, in a typical drag experiment, the SRP torque is negligible in comparison to the aerodynamic torque, this contribution in first approximation will be considered constant throughout the experiment. Nevertheless, it is worth mentioning that no model of solar radiation pressure is needed to filter out this contribution, since the value of the SRP torque can be evinced from the reduction of the telemetry data gathered far from pericentre, as explained in section 2.2.

$$\Delta\vec{L}_{SRP}\left(t,t^*\right)=\left(t-t^*\right)\vec{T}_{SRP}^{Const} \quad (9)$$

### 3.3. Modelling of the Aerodynamic Torque

Once a time interval $t_1 \div t_2$ (being $t_1<t_{Peri}$, $t_2>t_{Peri}$ ), in which the aerodynamic drag is not negligible, has been defined, the accumulated angular momentum due to aerodynamic torque, $\Delta\vec{L}_{AERO}\left(t,t_1,t_2\right)$, which is the unknown of the problem, can be assumed to be null up to epoch $t_1$, constant after epoch $t_2$, and variable in between.

### 3.4. Estimation of the Total Accumulated Angular Momentum

From what stated in the previous sections comes that a very good first approximation of the accumulated angular momentum can be expressed as follows:

$$\Delta\vec{L}_{SC}\left(t,t_1,t_2,t^*\right)=\Delta\vec{L}_{SRP}\left(t,t^*\right)+\Delta\vec{L}_{GG}\left(t,t^*\right)+\Delta\vec{L}_{AERO}\left(t,t_1,t_2\right) \quad (10)$$

The total angular momentum of the spacecraft, as reconstructed from telemetry data, can be expressed as the sum of the contributions of the body and of the reaction wheels:

$$\Delta\vec{L}_{SC}\left(t,t^*\right)=\hat{I}\left(t\right)\cdot\vec{\omega}_{SC}^{tm}\left(t\right)+\hat{M}\cdot\vec{L}_{RW}^{tm}\left(t\right)-\hat{I}\left(t^*\right)\cdot\vec{\omega}_{SC}^{tm}\left(t^*\right)-\hat{M}\cdot\vec{L}_{RW}^{tm}\left(t^*\right) \quad (11)$$

where $\hat{I}$ and $\hat{M}$ have the meaning aforementioned in the previous sections, while $\vec{\omega}_{SC}^{tm}$ and $\vec{L}_{RW}^{tm}$ are respectively the spacecraft rate and the reaction wheels angular momentum as read from telemetry. By performing a least-square of equation (10) to the telemetry data in equation (11) the accumulated angular momentum due to aerodynamic torque can be estimated.

### 3.5. Estimation of the Maximum Torque

A very good first approximation of the environmental torque can be expressed as follows:

$$\vec{T}_{SC}\left(t,t_1,t_2,t^*\right)=\vec{T}_{SRP}\left(t,t^*\right)+\vec{T}_{GG}\left(t,t^*\right)+\vec{T}_{AERO}\left(t,t_1,t_2\right) \tag{12}$$

The environmental torque can be reconstructed from telemetry, since it can be expressed as follows:

$$\vec{T}_{SC}(t)=\hat{I}(t)\cdot\dot{\vec{\omega}}_{SC}^{tm}(t)+\hat{M}\cdot\vec{T}_{RW}^{tm}(t)+\omega_{SC}^{tm}(t)\times\vec{L}_{SC}(t) \tag{13}$$

Since the spacecraft is in quasi-inertial attitude, $\vec{\omega}_{SC}^{tm}$ and $\dot{\vec{\omega}}_{SC}^{tm}$ are evanescent. This leads to:

$$\vec{T}_{AERO}(t)=\hat{M}\cdot\vec{T}_{RW}^{tm}(t)-3\mu\left\|\vec{r}(t)\right\|^{-5}\left(\vec{r}(t)\times\hat{I}(t)\cdot\vec{r}(t)\right)-\vec{T}_{SRP}^{Const} \tag{14}$$

The evolution in time of the estimated aerodynamic torque, as obtained by solving equation (14), is provided in the following plots.

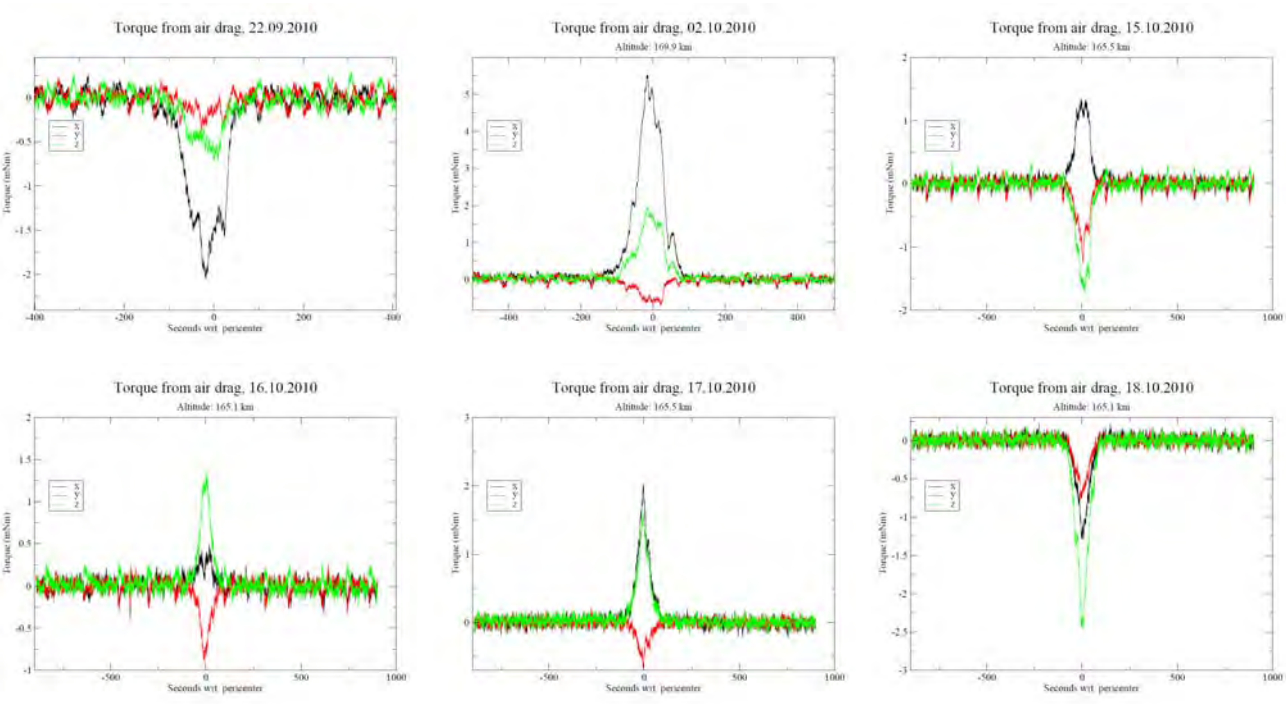


**Figure 8: Estimated Aerodynamic Torque during Different Experiments, from [3].**

### 3.6. Estimation of the Atmospheric Density and the Scale-Height

Before dipping into the calculation to estimate atmospheric density and scale-height, it is useful to define a reference torque $T_{ref}$ as the maximum torque that can be measured with the solar arrays parallel and assuming an accommodation coefficient α =1, and a sensitivity $\vec{s}(t)\in\Re^3$ that allows to compare different solar arrays configurations and spacecraft attitudes:

$$\begin{cases} T_{ref} = \left\| \vec{r}_{CoP_+} + \vec{r}_{CoP_-} \right\| \rho_{Peri} \, A v_{Peri}^2 \\ \vec{s}(t) = \vec{T}_{AERO}(t) / T_{ref} \end{cases} \tag{15}$$

where the symbols have the same meaning as in equations (1) and (2).
Now it is possible to define a time interval $\Delta t_{AERO}$ as the time interval in which VEX is affected by the presence of atmosphere: it can be expressed as the ratio between the magnitude of the accumulated angular momentum $\Delta\vec{L}_{AERO}$ and the magnitude of the maximum aerodynamic torque $\vec{T}^*_{AERO}$. By substitution in equation (15),

$$\rho_{Peri}\Delta t_{AERO} = \frac{\left\| \Delta\vec{L}_{AERO} \right\|}{\left\| \vec{r}_{CoP_+} + \vec{r}_{CoP_-} \right\| \cdot \left\| \vec{s}(t_{Peri}) \right\| A v_{Peri}^2} \tag{16}$$

On the other hand, in this same time interval VEX orbit can be approximated, within a reasonable tolerance, with a parabola. Therefore, under the assumption that the atmosphere is radial-symmetric around pericentre, and has a constant scale-height k, this interval can be expressed as a function of $\vec{a}_{Peri}$, the radial acceleration at pericentre:

$$\Delta t_{AERO} = \left( 2\pi k / \left\| \vec{a}_{Peri} \right\| \right)^{0.5} \tag{17}$$

The atmospheric density at pericentre, $\rho_{Peri}$, is found as a ratio between the results of equation (16) and equation (17). The entire process can be carried out using vector components rather than magnitudes: in this case the scatter in the result for different components indicates the uncertainty.
The results of this process are summarised in Table 2 hereafter.

**Table 2: Estimated Values of the Atmospheric Density.**

| Epoch of Pericentre | $\Delta t_{AERO}$ [sec] | $\rho_{Peri}$ [kg/m$^3$] |
|---|---|---|
| 22/09/2010 | 73.3 | $1.9*10^{-12}$ |
| 02/10/2010 | 79.3 | $4.4*10^{-12}$ |
| 10/10/2010 | 58.2 | $7.0*10^{-12}$ |
| 17÷25/10/2010 | 69.0±9.0 | $(7.5\pm1.7)*10^{-12}$ |

For the measurements on the days 17÷25/10/2010, the orbit is almost along the terminator and measured torques are therefore symmetric with respect to the pericentre: therefore for these measurements it is possible to estimate the scale-height: k = 5.34 ± 0.71 km.

### 3.7. Estimation of the Accommodation Coefficient

As previously pointed out, the estimation of the accommodation coefficient is done through the use of the telemetry data gathered during the so-called windmill experiments. In this configuration, in fact, the fraction of molecules that are specularly reflected by the solar arrays generates a torque around the flow direction, while the molecules that perform an inelastic collision generate a torque perpendicular to the wind-direction.

Therefore, the estimated accommodation coefficient is the one at which the angle between the expected torque and the measured torques is minimum, as shown in Fig 9. The fact that for all dates the angle reaches a distinct minimum for $\alpha \approx 0.9$ is evidence that this is indeed due to specularly reflected molecules.

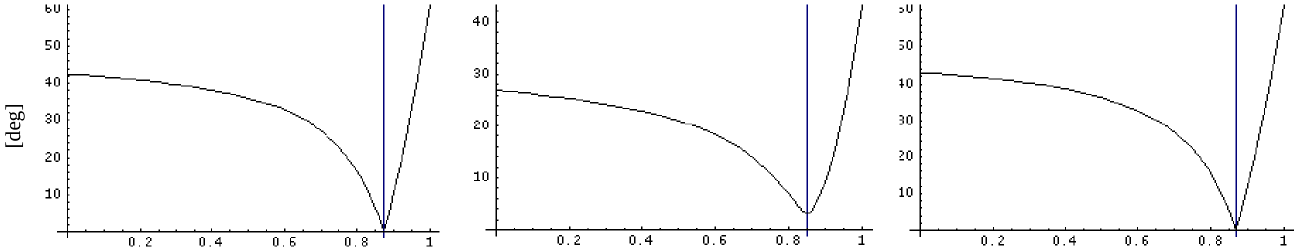


**Figure 9: Estimation of The Accommodation Coefficient for the "Windmill" Experiments Executed on October 14th (left), 15th (centre), and 16th (right), from [2].**

Overall, all measurements are reasonably close together such that the accommodation coefficient can be estimated by $\alpha = 0.886 \pm 0.02$.

## 4. Conclusions and Further Work

The fourth Aerodynamic Drag Experiment campaign completed by Venus Express in October 2010 has been the most challenging and ambitious to date. VEX performed flawlessly throughout the campaign, and provided telemetry data that can be used to build a new model of the atmosphere of Venus.

The first crude reduction of the telemetry data provided meaningful values for the atmospheric density ($\rho = 7.5 \pm 1.7 * 10^{-12}$ kg/m$^3$) and the accommodation coefficient ($\alpha = 0.886 \pm 0.02$) at 165 km of altitude and close to the terminator. The error of the density is not due to limitation of the sensitivity of the detection method, but due to real variation in the atmosphere. The scale-height is estimated to be $k = 5.34 \pm 0.71$ km.

During VEX extended mission, more slots have been allocated to perform new ADE campaigns at pericentre altitude as low as 165 km, in order to provide more data over the evolution of the atmospheric density with time, space and illumination conditions: the first of these campaigns will be performed in May 2011.

## 5. References


[1] Keil, N., "VEX AeroDrag Campaign #4 Operations Overview", VEX-ESC-TN-5820, unpublished.

[2] Müller, M., "VEX Atmospheric Drag Measurements", VEX-ESC-RP-5520, unpublished.

[3] Lauer, M., Kielbassa, S., Damiani, S., e-mails to the ESOC "Flight Dynamics Interplanetary Operations" account.