REVIEW OF VENUS EXPRESS MISSION ANALYSIS

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ABSTRACT

This paper summarizes the main results of the mission analysis of the 2005 launch window of Venus Express. The operational orbit is a polar eccentric orbit with about a 1 day period. The orbit is well suited to study the atmosphere, the plasma environment and for remote observations.

The launch window using the Soyuz+Fregat launcher is open for 30 days with the use of 10 launch programs. The capture at Venus will be done with the main engine into a 6.2 days orbit using about the 70% of the fuel budget and the reduction of the apocenter with a main engine manoeuvre plus one or two manoeuvres with the reaction control thrusters.

The operational orbit is perturbed by the Sun gravity pull such that the argument of the pericenter decreases and the pericenter altitude increases. During the mission lifetime the pericenter altitude will be controlled in a band from 250 to 400 Km.

Abbreviations and Symbols

V_∞	Hyperbolic Velocity Modulus
δ_∞	Hyperbolic Velocity Declination
α_∞	Hyperbolic Velocity Right Ascension
A-T	Along-Track
C-T	Cross track
R	Radial
r	Position Vector
v	Velocity Vector
deg	degrees
T	Thrust
ME	Main Engine
RCT	Reaction control thrusters
I_{sp}	Specific Impulse (seconds)
LP	Launch Program
ΔV	Delta-V
ω	Argument of pericenter
σ	Standard deviation
Ω	Right Ascension of the Ascending Node

1. INTRODUCTION

The Venus Express mission was proposed in March 2001 as a response to the ESA "Call for Ideas" on how to reuse the design of the Mars Express spacecraft. Out of a number of proposals, ESA finally selected Venus Express in November 2002. What made Venus Express especially attractive was the reuse of many of the spare instruments developed for the Mars Express and Rosetta missions.

Venus Express will perform remote surface and sub-surface studies and special emphasis will be given to the atmospheric studies to improve our knowledge of the composition, circulation and evolution of the atmosphere and how the surface and the solar wind interacts with it [1].

Venus Express will be launched with a Soyuz+Fregat launch vehicle from Baikonur in the period late October-November 2005. The interplanetary arc between the Earth and Venus will last about 5 months. The operational orbit around Venus has been selected as a polar orbit with an orbital period near 24 hours, which maximises the data and telemetry recovery from the ground station planned for the mission in Cebreros (Spain). A detailed report of the Venus Express mission is in [2] and of the mission analysis in [3].

2. INTERPLANETARY TRAJECTORY

2.1 Transfer Earth to Venus

The transfer arc between the Earth and Venus has been optimised according with the launch vehicle performances and the capture manoeuvre at Venus. A launch window with Soyuz+Fregat from Baikonur is available for launches at October/November 2005 and arrivals at April 2006.

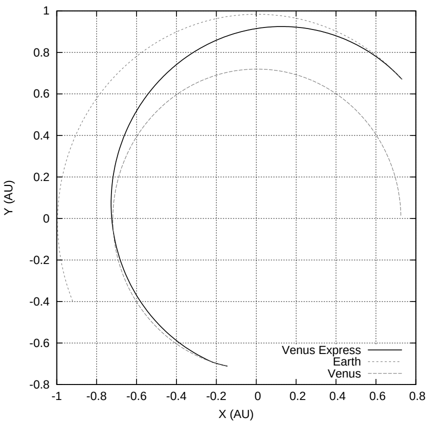

Fig. 1. Orbits of Venus Express, Earth and Venus projected onto the ecliptic

The characteristics of the direct transfer arc do not depend very much on the launch day. The trajectory is close to a Hohmann transfer, but covering slightly more than half a revolution, Fig. 1. As the spacecraft flies inside Earth's orbit, an inferior conjunction will occur at the beginning of January 2006 difficulting down-link communications. The periods of visibility from Cebreros during this arc have a duration of about 7 hours that increases to about 10 hours when the spacecraft is arriving to Venus.

2.2 Launch Window

Fig. 2 shows a level lines plot of the 2005 Venus launch window as a function of the departure and arrival dates. The minimum of the departure hyperbolic velocity is about 2.77 Km/s. The arrival velocity is about 4.6 Km/s.

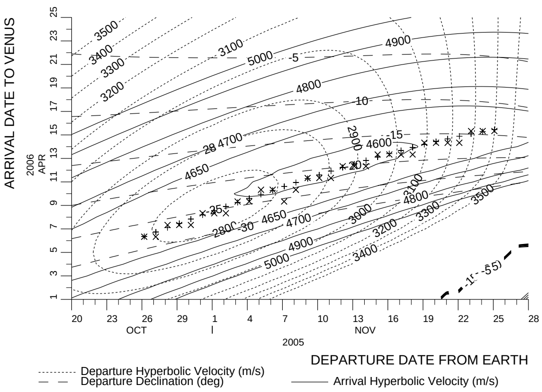

Fig. 2. Departure and arrival conditions for 2005 launch window

Due to the planning of the mission, the launch window for Venus Express begins the 26/10/2005 and ends the 24/11/2005, the last day that the Soyuz+Fregat launcher can provide the required departure hyperbolic velocity for the 1270 Kg payload mass – spacecraft plus launcher adapter. Therefore, a total of 30 launch opportunities are available.

A launch target for the Soyuz+Fregat launcher consists on the couple hyperbolic velocity modulus and declination at departure. In order to reduce the number of flight programs to be used, the optimum launch conditions for some launch days must be grouped. A correction manoeuvre a few days after departure is used to reoptimize the trajectory towards Venus.

An analysis of the launch window assuming correction manoeuvres of less than 30 m/s concluded with a strategy of 10 launch programs (LP). The characteristics of the launch window permit easily to group the days at the beginning, which are near the minimum ΔV region. However, for the last days coupled or dedicated launch programs must be used.

Table 1.Launch Programs

LP	Days per LP	Launch Days
1	10	25/10 to 04/11
2	7	05/11 to 11/11
3	3	12/11 to 14/11
4 - 6	2	15/11-16/11, 17/11-18/11, 19/11-20/11
7 - 10	1	21/11, 22/11, 23/11, 24/11

Fig. 3 shows the optimum launch conditions – V_∞ and δ_∞ - for each launch day and the grouping of these targets in LP. At the beginning, the differences of velocity modulus are small and the targets within one group differ mainly in the declination. For the last launch days, the launcher must provide additional 50 m/s every day and the grouping with correction manoeuvres below 30 m/s is not possible.

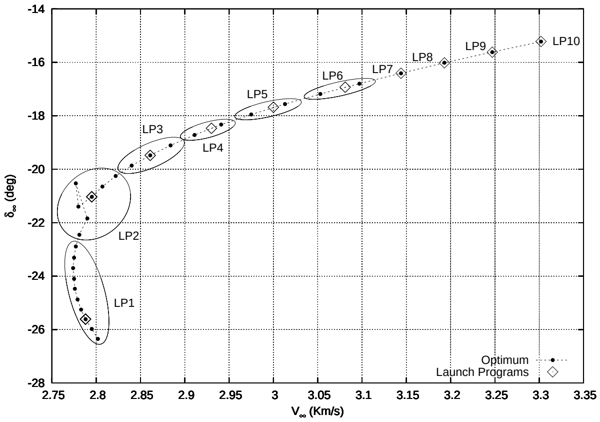

Fig. 3. Modulus vs. Declination of the hyperbolic velocity for the 2005 launch window with grouping of launch programs

2.3 Navigation and Guidance

A manoeuvre launcher correction injection is required to correct the injection dispersion of the launcher. The following table presents the assumed 1-σ launcher injection errors for the analysis of this correction.

Table 2. Launcher injection errors

	A-T	C-T	R
r (Km)	12.8	2.7	1.0
v (m/s)	1.0	5.6	14.9
	V_∞	δ_∞	α_∞
v_∞ (m/s, deg)	3.9	0.055	0.070

During the LEOP phase, Venus Express will be tracked by the ESA ground stations of New Norcia and Cebreros. Range and Doppler measurements from these ground stations will be used for orbit determination. After two days of measurements the precision in the determination is below 1 Km for r and 1 cm/s for v .

A manoeuvre has to be implemented between the days 4 and 7 to correct the launcher dispersion. A study by means of Monte Carlo simulations of this launcher correction manoeuvre has shown that the 99 percentile is about 15 m/s. In order to obtain an accurate arrival to Venus, a guidance strategy has been analysed which considers three small trim manoeuvres, two of them at the arriving part of the transfer 40 and 10 days before the capture manoeuvre. The accumulated ΔV for these trim manoeuvres has been estimated below 5 m/s.

3. CAPTURE AND ORBIT INSERTION

The spacecraft arrives to Venus in a hyperbolic trajectory with an inclination of 90° and pericentre about 500 Km, which would give the possibility to put the spacecraft over the North with a high pericentre latitude or over the South with low latitude. In order to optimise the scientific return, the pericentre is selected on the northern hemisphere. The change of the argument of pericentre during capture and orbit insertion can only be done at a high ΔV cost.

The ESOC study "Use of Weak Stability Boundary Trajectories for Planetary Capture" has analysed multiple capture strategies for Venus Express into polar orbits. The main result [4] is a wide range of possible ω-Ω combinations improving the mission flexibility at practically no ΔV cost, but with the drawback of very long transfer times to the operational orbit from 100 to 200 days.

The Venus Express propulsion system consists on a main engine – ME (Isp=314s, T=410N) and the reaction control thrusters (RCT), which can be used together to produce a ΔV (Isp=280s, T=11.2N after capture). The main engine can only be used when the fuel left in the propellant tanks is more than 60.1 Kg. As a requirement, the altitude of the spacecraft over Venus shall be at any moment higher than 250 Km.

The mission baseline consists then on a large capture manoeuvre with the ME in the anti-velocity direction that inserts the spacecraft into a high eccentric capture orbit, with a period of more than 5 days. The third body perturbation of the Sun on such an orbit has a tremendous effect for the pericenter altitude, which increases in more than 150 Km in only one orbit. This effect increases when the orbital period increases.

A small correction manoeuvre (< 5 m/s) is needed at the apocentre of the capture orbit to limit this increase of the pericentre height. Optimum captures require orbit periods from 6.5 to 8.5 days. On the other hand, the correction at apocentre can be avoided with smaller capture orbits (4.5-5.8 days) that are less perturbed. A 6.2 days capture orbit (apocentre radius 260000 Km) provides a good solution for the whole launch window.

The reduction of the apocentre radius to the operational orbit (about 66600 Km) is carried out with another ME manoeuvre up to the limit of propellant that can be used with the ME. Finally, one manoeuvre with the RCT or a pair of manoeuvres in order to limit the gravity losses, is needed to reach the operational orbit.

This capture manoeuvre extends in true anomaly from about –90º to 90º with a total ΔV of about 1280 m/s, of which a 12.5% is due to the gravity losses. The first apocentre reduction with the ME is about 280 m/s with very low gravity losses. Taking into account the LP correction and the ΔV reserved for navigation, the operational orbit can be achieved with these 2 ME manoeuvres for the launch days 09/11 and 13/11. In the rest of the cases at least 4 m/s and up to about 30 m/s must be provided by the RCT in order to insert Venus Express into the operational orbit.

4. OPERATIONAL ORBIT

4.1 Orbit Evolution

The main perturbation acting on a spacecraft around Venus is the third body effect of the Sun. The perturbations due to the non-sphericity of Venus can be disregarded.

The third body effect on eccentric orbits is well known and has been extensively studied in the literature. For the Venus Express operational orbit, the main effects of the Sun perturbation are over the pericenter altitude and the argument of the pericenter (ω). The effect on the semi-major axis is negligible and the period from pericenter to pericenter is slightly perturbed. The inclination of the orbit has variations smaller than 0.2º for 1000 days and Ω diminishes at a rate of less than 0.1º every 100 days.

For a polar orbit like the one of Venus Express, the secular effect of the Sun on the eccentricity depends on the value of the argument of the pericenter referred to the orbital plane of Venus around the Sun (ω'), which is about 2 degrees smaller than the equatorial ω. For ω'>90º, the eccentricity decreases and the pericenter increases. Just the opposite occurs for ω'<90º. However, the secular variation of ω' is always negative in a region from about 40 to 130 degrees.

The initial argument of pericenter of the operational orbit depends on the launch day and is between 102 and 114 degrees. Then ω diminishes about 9º in 1000 days and the pericenter altitude tends to increase continuously during the extended mission lifetime as the change of behaviour at ω'=90º has not been reached. Fig. 4 shows the initial argument of pericenter of the operational orbit and the value after 1000 days in orbit.

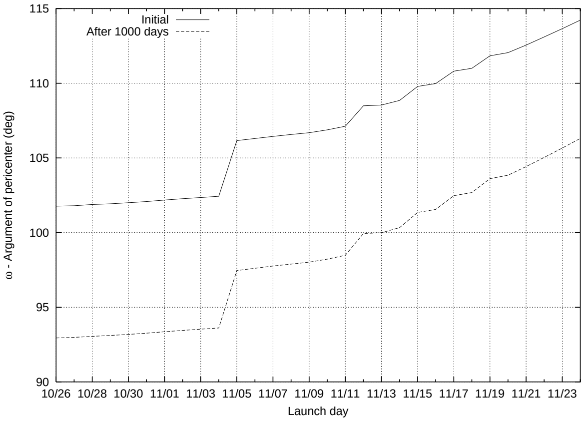

Fig. 4. Argument of pericenter of the operational orbit as a function of the launch day

4.2 Orbit Maintenance

In order to perform the observations of the atmosphere and the surface near the pericenter of the orbit, the pericenter altitude has to remain controlled in a band from 250 to 400 Km. As the gravity pull of the Sun tends to increase the pericenter altitude, a series of correction manoeuvre must be implemented whenever the altitude becomes higher than 400 Km.

The correction of the pericenter altitude can be achieved by means of two manoeuvres Apocenter-Pericenter, however the phasing with the ground station would be shifted and a small period drift would be needed to correct this shift before the next series of manoeuvres.

A series of three manoeuvres Apocenter-Pericenter-Apocenter corrects the pericenter altitude and maintains the pericenter time and therefore the phasing with the ground station with no ΔV cost. An intermediate orbit of pericenter altitude at 325 Km maintains the pericenter time after the three manoeuvres, even when an integer number of waiting orbits are used between them.

In addition to the manoeuvres to control the pericenter height, at least two manoeuvres must be given to maintain the visibility phasing from the nominal ground station in Cebreros. There is a period of about 150 days when the relative movement of Venus to the Earth induces a drift in the visibility and the orbital period must be diminished by about 200 seconds to follow such drift. This requires a ΔV of 2 m/s for 1000 days.

The total number of manoeuvres to correct the pericenter altitude needed during the 1000 days of the extended mission lifetime depends strongly on the pericenter argument of the initial operational orbit and is therefore a function of the launch day. When a manoeuvre to control the pericenter height and a manoeuvre to control the visibility phasing need to be performed within a few days, they can be mixed in an Apocenter-Pericenter correction saving about 1.5 m/s.

For the first day of the launch window, 24/11/2005, a total number of 5 manoeuvre corrections of the pericenter altitude, Fig. 5, and 52 m/s are required to control the orbit for 1000 days. For the last day, however, the number of manoeuvres is 15, Fig. 6, and the ΔV 162 m/s.

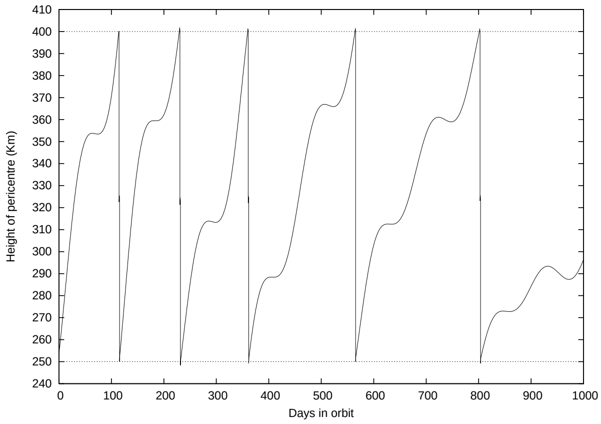

Fig. 5. Evolution of pericenter height - Launch 26/10

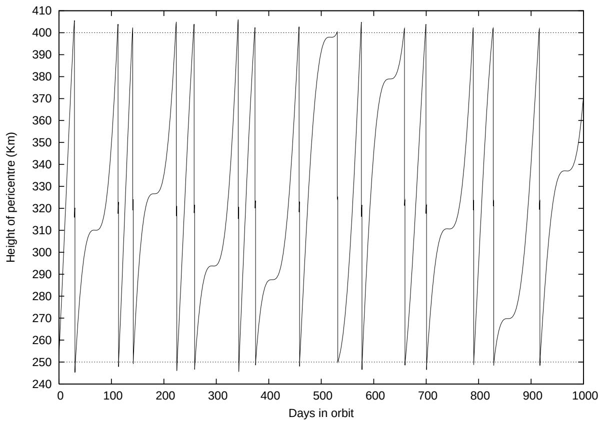

Fig. 6. Evolution of pericenter height - Launch 24/11

For a spacecraft dry mass of 670.9 Kg, Fig. 7 shows the ΔV required for maintenance of the orbit during the extended mission lifetime of 1000 days and the ΔV available for orbit maintenance considering the LP correction, the manoeuvres for navigation and the capture and apocentre reductions, and after discounting also the residual propellant (about 7.7 Kg) and the propellant reserved for attitude control in the operational orbit (10 Kg). At the moment, four launch days have negative ΔV budgets of less than 10 m/s at the end of the launch window. This means that the last correction of the pericenter altitude cannot be implemented and that the pericenter is controlled between 250-400 Km for less than 1000 days. The worst case is for launch at 24/11/2005 with 930 days.

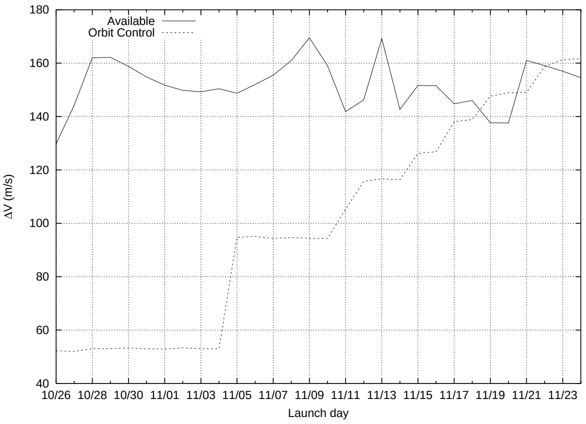

Fig. 7. ΔV available and required for orbit maintenance

That situation can change when the spacecraft dry mass including the mass to balance the center of gravity is better known. The design has been made with the worst case mass, but the estimations have a range of about 20 Kg. Any Kg of reduction of the dry mass will release 4.5 m/s available for the orbit maintenance.

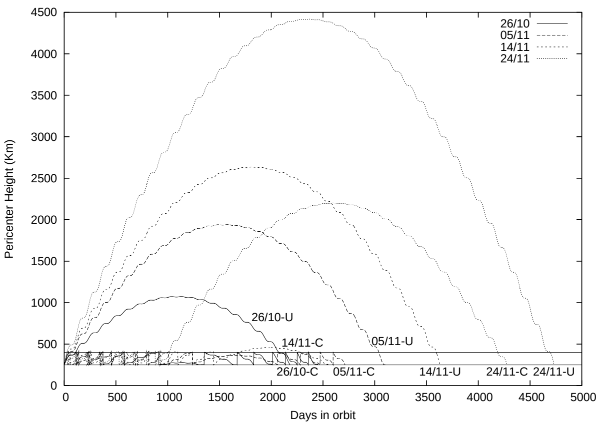

Fig. 8. Long-term evolution of the pericenter altitude

When analyzing the long-term evolution of the orbit, the argument of pericenter always falls below 90 degrees inverting the rate of change of the pericenter altitude. The precise day from which this inversion occurs is a function of the initial pericenter argument, which is given for every launch day, and of the ΔV available for pericenter control. Fig. 8 presents the predicted evolution of the pericenter altitude for different launch days for the controlled orbit taking into account the available propellant and also for a fully uncontrolled orbit. The satellite will end in any case with an entry into the dense Venus atmosphere. For 05/11 is the first launch day that the mission with pericenter control will end before a mission without control. For 14/11 is the first launch day that the capacity to control the pericenter ends when the pericenter height is still steadily increasing.

4.3 Surface Coverage

As the orbit of Venus Express is almost polar and Venus rotation is very slow, the ground tracks are almost meridional lines. The orbital plane is almost inertially fixed and the rotation of Venus makes the nodes of the orbit to cover all the longitudes with a repetition period of 225 days.

Observations will be taken for altitudes below 2000 Km. The spacecraft will enter this observation phase at latitudes of 45-60 degrees which decrease slightly with time and will exit at latitudes of 10-30 degrees, increasing with time. This period of observations will have a duration of about 26 minutes.

The latitude of the sub-satellite point of the pericenter will increase with time following the decrease of ω, Fig. 9. The elevation of the Sun over this point, which determines the illumination conditions of the surface, has a periodic variation with a slight diminution of the amplitude with the mission time.

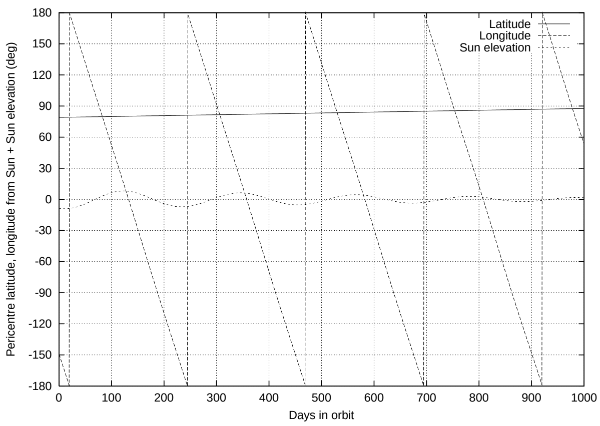

Fig. 9. Evolution of the latitude and longitude and the Sun elevation from sub-satellite point of the pericenter

Fig. 10 shows the period of day and night in the sub-satellite points during the observation phase. At the beginning of the mission the spacecraft enters in the observation phase during daylight and then in the night region before the pericenter until the end of the observation. After about 90 days in orbit, this reverses and the pericenter is observed with daylight. During the mission lifetime day and night at the pericenter are alternating with periods of about 90 to 120 days.

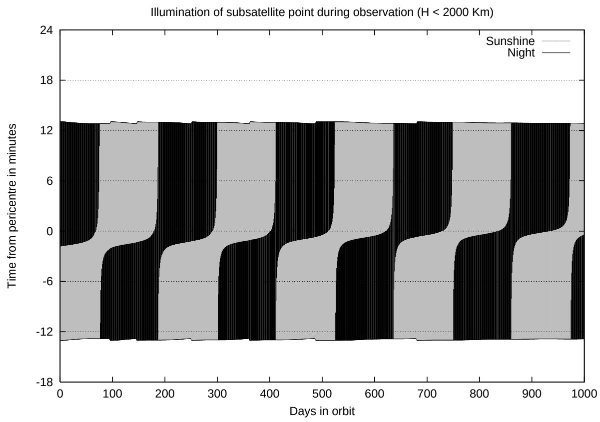

Fig. 10. Illumination conditions day-night of the sub-satellite points during the observation phase

4.4 Eclipses and Earth Occultations

During the extended mission lifetime the spacecraft will experiment nine seasons of eclipse. The maximum durations of shadow depends on the launch day, it will be 50 minutes at the beginning and 60 minutes at the end of the launch window. The eclipses after the pericenter are shorter. However, as the pericenter drifts towards the North Pole, the duration of the eclipses before and after the pericenter tend to become equal.

There are six seasons of Earth occultation. The duration of the maximum occultation is slightly longer than the maximum eclipses, Fig. 11.

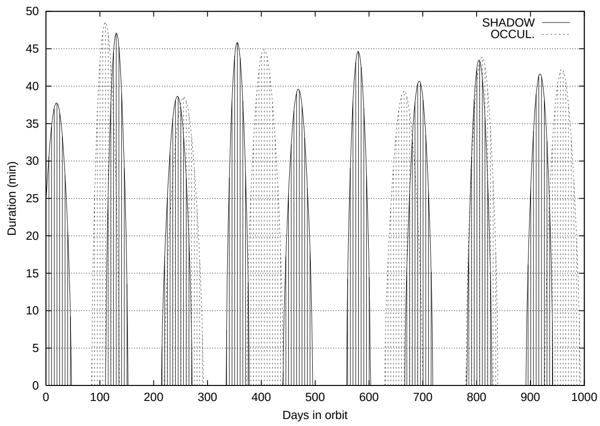

Fig. 11. Periods of eclipse and Earth occultation

4.5 Ground Station Coverage

Fig. 12 shows the visibility periods from Cebreros for a controlled operational obit. During almost the whole mission lifetime, the orbital period is slightly over 1 day as the visibility of Venus from the ground station occurs later every day. From about 430 to 580 days in orbit, there is a natural negative drift of the visibility caused by the relative movement of Venus with respect to the Earth. In order to follow this drift, the orbital period is reduced forcing to earlier apocenter passes each day.

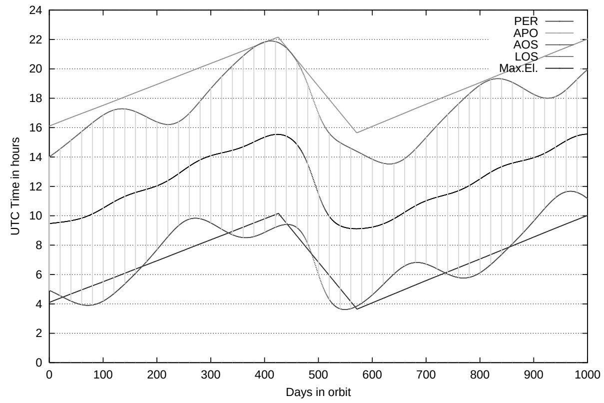

Fig. 12. Visibility periods from Cebreros

The beginning of the visibility can be chosen to occur approximately 2 hours at most after every pericenter. Then the download of the scientific data obtained in every pericenter pass can be maximised. The minimum duration of the visibility is about 6.5 hours.

5. CONCLUSIONS

The launch window for Venus Express with a direct transfer in 2005 covers a period of 30 days and requires 10 LP of the Soyuz+Fregat launcher. Correction of the launcher dispersion and navigation up to Venus can be done with about 20 m/s.

The use of the ME at Venus is limited to the capture and first apocentre reduction. One or two apocenter reductions must be implemented with the RCT. A capture orbit of 6.2 days gives the best performance.

The ω of the operational orbit is fixed by the arrival hyperbola for every launch day and is the determinant parameter for the number of correction manoeuvres to control the pericenter height during the extended mission lifetime. The last launch days have the higher rate of the pericenter growth and the available fuel will provide at least 930 days of orbit control.

6. REFERENCES

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