# European Space Agency
# Research and Science Support Department
# Planetary Missions Division


## *Venus Express*

## VEX Science Cases


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## CHANGE RECORD SHEET

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| Oct. 2004 | 1 | A | | Initial Version |
| 26 June 09 | 2 | 0 | All | Changed writing from future to present tense. Spell Checked Document. Numerous minor editorial changes. |
| | | | 4.12 | Added Case 11: Calibrations |
| | | | 4.1 | Added Case 0: Other Types of Observations |
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| | | | | |
| | | | | |

# Content

# Tables



# Figures

# 1. Introduction

## 1.1 Purpose

The Venus Express mission is based on re-use of the Mars Express spacecraft and available instruments at Venus. The use of the Mars Express bus with minor modifications in the much harsher environment at Venus causes difficulties mainly related to the thermal requirements to the spacecraft and payload. This justified a need for careful planning of observations in order to effectively use the spacecraft and payload resources and capabilities and to maximize the science return of the mission.

The purpose of this document is to describe typical modes (called “science cases”) of the Venus Express observations in orbit, to summarize scientific requirements to the spacecraft and ground segment, and to analyze their capabilities to meet the mission science goals. This document describes 11 basic science cases as they were defined in the document “Science Cases Definition and Study Assumptions” [RD 1] and presents the results of their analysis performed by Astrium in the framework of the project Critical Design Review (CDR) [RD 2]. So it summarizes the mission planning activity done by the time of CDR [March-April 2004].

Also Section 6 of this document describes the proposals to modify and combine the basic science cases in order to fully exploit the spacecraft resources and to increase the overall mission science return. The Venus Express science cases, their modifications and combinations presented in this document are currently being used as building blocks to construct the mission Science Activity Plan (SAP) [RD 3].

## 1.2 Scope

This document will discuss the basic science observation types, or “cases”, used in the Venus Express planning.

## 1.3 Referenced Documents

RD1 VEX-T.ASTR.-TCN-00665, issue 2, 26.08.03, Science Cases Definition and Study Assumptions

RD2 VEX-T.ASTR.-TCN-00932, issue 1, 27.02.04, Synthesis of Science Cases Analysis

RD3 Venus Express Science Activity Plan

## 1.4 Acronyms

CDR Critical Design Review

EOL End of Life

LTAN Local Time at Ascending Node

OT Orbital time (time starting at pericenter)

SAP Science Activity Plan

# 2. Venus Express Mission Timeline

The Venus Express was launched on 9 November 2005. The spacecraft arrived at Venus on 11 April 2006. The first capture orbit was an eccentric polar orbit and lasted 9 days. Several manoeuvres over the period 15 April-6 May 2006 lowered the spacecraft into its operational orbit: a 24-hour elliptical, quasi-polar orbit. The pericenter altitude is 250 km and the apocenter altitude is 66000 km.

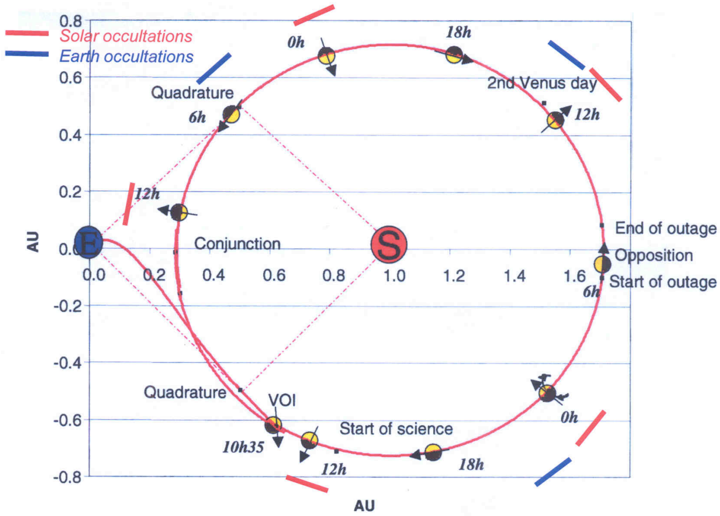


**Figure 1: Venus Express Orbital Mission Timeline**

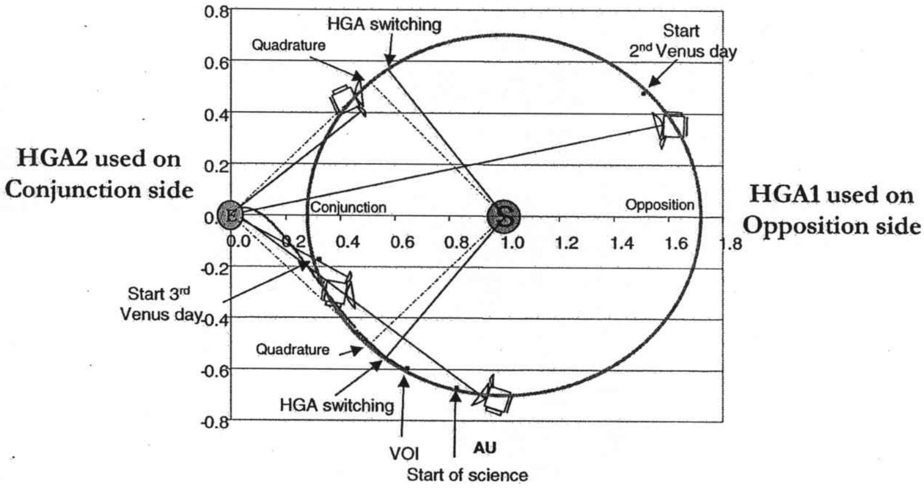


**Figure 2: Venus Express Communications Strategy**

Figure 1 and Figure 2 show the mission timeline and communication strategy. The position of the satellite orbit plane with respect to the Sun and Earth and revolution direction are marked with an arrow in Figure 1. The solar and Earth occultation "seasons" are approximately shown by red and blue bars.

Two high gain antennas onboard the spacecraft provide communications with the Earth (Figure 2). The big antenna (HGA1, 1.3m dish) is used for telecommunications when the angle Earth-Venus-Sun is less than 90 degrees. Between the quadratures in inferior conjunction when Venus is between the Sun and the Earth, the spacecraft is flipped so that the telecommunication with the Earth are performed via the smaller antenna (HGA2, 0.7m dish). This strategy keeps the Sun permanently between +Z (nadir looking platform) and +X (HGA1 axis) directions during telecommunications and to avoid Sun illuminating the –X wall occupied by payload radiators.

# 3. Venus Express orbit

The Venus Express orbit (Figure 3) has the following parameters:

- Pericenter altitude 250 km
- Apocenter altitude 66000 km
- Period 24 h
- Inclination ~90 deg
- Pericenter latitude 80 deg

Spacecraft altitude, latitude of the sub-spacecraft point and other orbital variables are shown in Figure 4 through Figure 7.

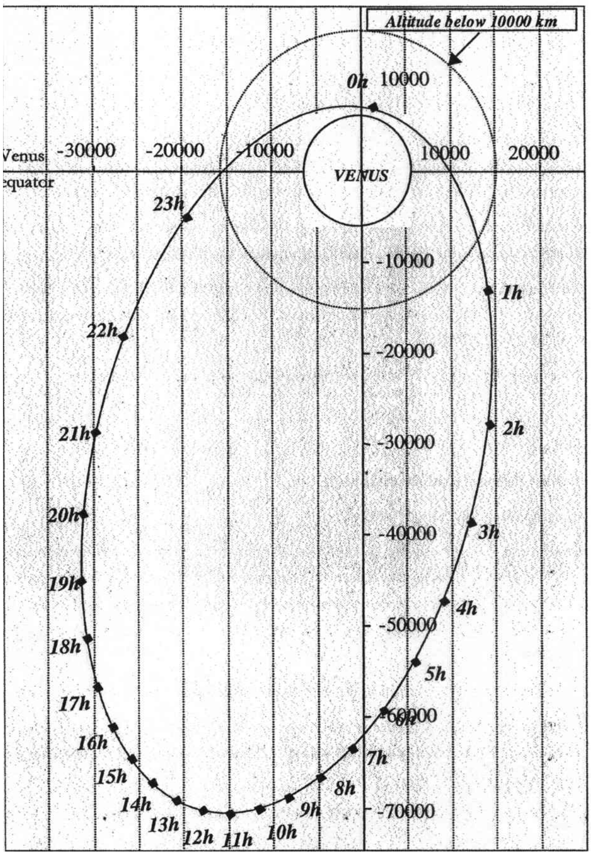


**Figure 3: Venus Express orbit. Ticks mark orbital time starting from pericenter**

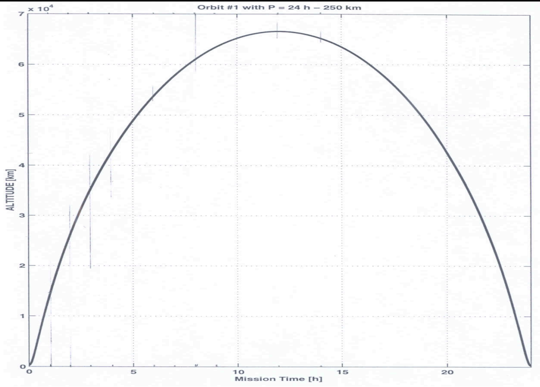


**Figure 4: Spacecraft altitude above the Venus surface versus time from pericenter**

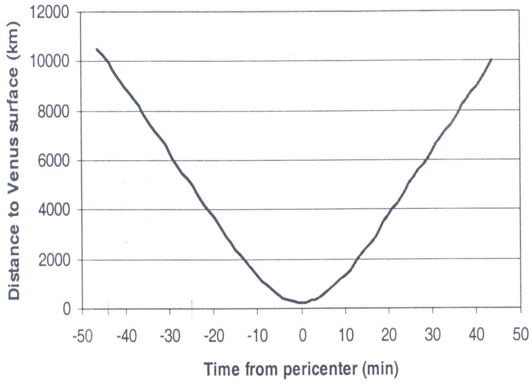


**Figure 5: Spacecraft altitude above the Venus surface versus time around pericenter**

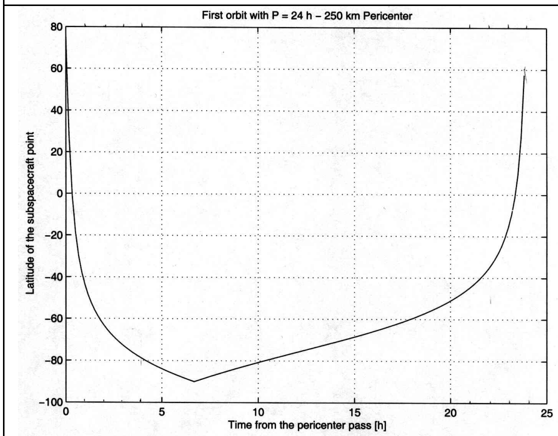


**Figure 6: Sub-spacecraft latitude versus time from pericenter**

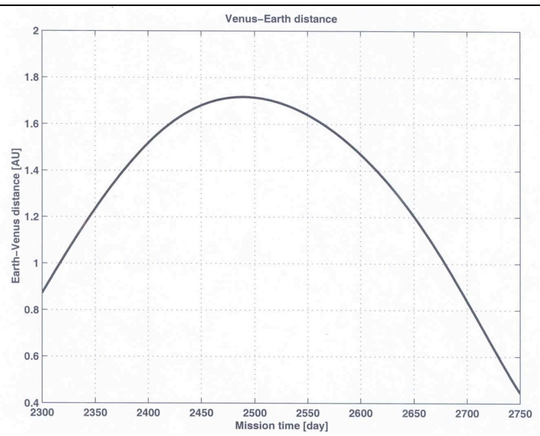


**Figure 7: Venus-Earth distance during the nominal mission.**

# 4. Venus Express Basic Science Cases

The Venus Express orbit is divided into three parts:

1. observations,
2. Earth pointing with telecommunications, and
3. Earth pointing without telecommunications.

The communications with the Cebreros ground station take place in each orbit between 2 and 10-11 hours orbital time (OT) (see Figure 3). The duration of telecommunications is at least 8.5 hours. The possibility to increase the downlink duration depends on the visibility of Venus from the Cebreros station and on the ground segment resources available. The remaining 15-16 hours are used for observations. Out of observation and telecommunication phases the spacecraft will point the HGA to the Earth but without telecommunications. It should be emphasized that the Venus Express mission goals can be achieved only by combinations of pericenter observations that give a close view of the planet with off-pericenter observations that provide a global picture of Venus.

This section describes 12 typical Venus Express modes of observations (called “science cases”). They are different in goals, geometry of observations and experiments involved. These basic types are considered as building blocks of the mission Science Activity Plan (SAP). The science cases were studied by Astrium in the framework of CDR. Results of this analysis will be described for each case.

## 4.1 Case #0. Other Types of Observations

Some instrument observations are used for calibration purposes. In these cases, the Case #0 can be used for the data products resulting from the calibrations.

For example:

- VIRTIS H and M:

  - observations of an internal source with protective shutter closed.
- VMC:
  - Earth pointing;
  - Wheel Off Loading (WOL);
  - Orbit Maneuver.
- Spicav:
  - Dark Current calibration where observation is made with shutter closed.

The observations are made when the spacecraft is in a suitable attitude which meets the spacecraft and instrument thermal constraints.

## Case #1. Observations in Pericenter

This case was defined by ESA and Astrium as the spacecraft "sizing case", i.e. the one that defines the spacecraft design and its resources.

*Science goals.*

- High spatial resolution spectroscopic and imaging survey of the Northern hemisphere;
- Moderate spatial resolution observations of low latitudes;
- plasma and magnetic field observations in the planet vicinity.

Payload operations.

The +Z looking experiments (PFS, SPICAV, VIRTIS, and VMC) perform observations during 96 minutes around pericenter (Figure 4.1) that correspond to spacecraft altitude of less than 10,000 km (Figure 6). ASPERA and MAG operate along the entire orbit. Cooling of the instruments will be done before entering the pericenter arc if needed. The breakdown of data production rate and power consumption is estimated in Table 1 and summarized in Section 5.

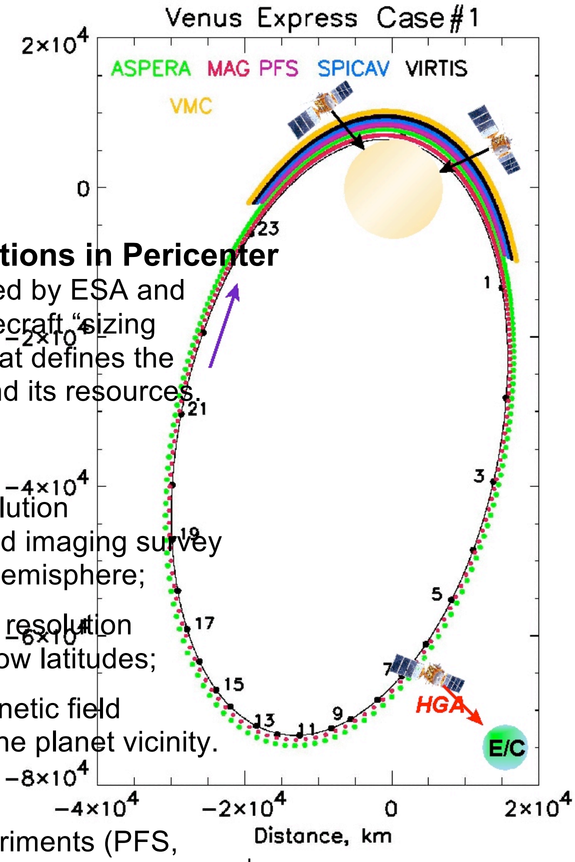


**Figure 3: Case #1. Pericenter observations.** Black ellipse shows the orbit with ticks representing hours of the orbital time starting at pericenter. Colored dots and lines mark orbital sectors with the instruments ON.

Spacecraft operations.

During the pericenter pass the spacecraft will keep +Z axis (that is co-aligned with the optical axes of PFS, SPICAV, VIRTIS, and VMC) in the local nadir direction. The Y axis will be kept in orbital plane with velocity face (+Y or –Y) selected so that to keep the –X wall in the shadow. Out of pericenter phase the spacecraft will keep the HGA Earth pointing. The telecommunication phase is typically placed between 2 and 11 hours orbital time (OT) when in the visibility of the Cebreros antenna. Some modifications of Case #1 are described in Section 6.

*Results of the CDR study*.

No constraints on implementation of Case #1 were identified except for that the data traffic on the OBDH bus was above critical limit of 85 kbps for the whole pericenter pass and exceeded maximum limit of 100 kbps for 2 minutes around pericenter. This caused specific SPICAV polling problem that resulted in data loss by the experiment.

The overload of the OBDH bus results from simultaneous operations of four instruments (ASPERA, MAG, PFFS and SPICAV).

## 4.2 Case #2. Off-Pericenter Observations

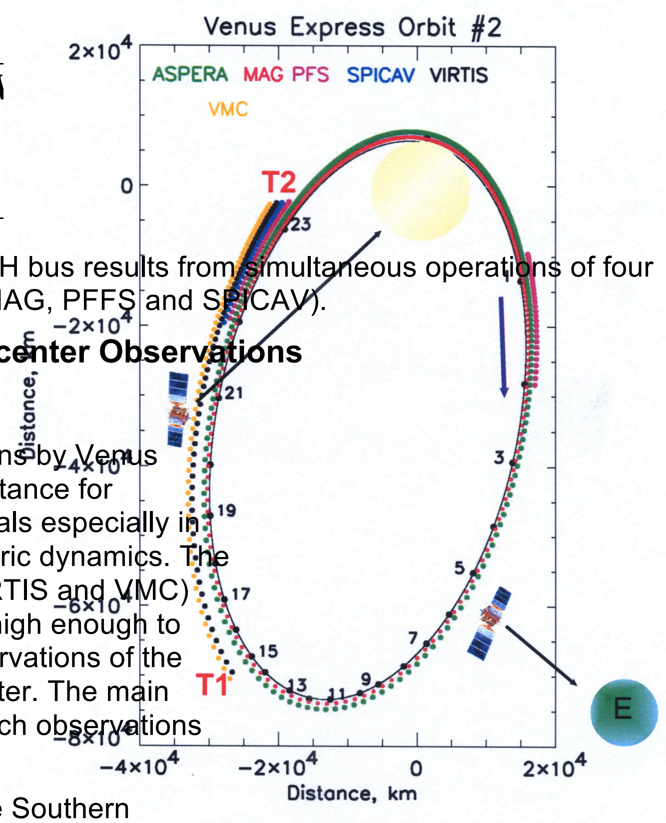

**Figure 9: Case #2. Off-Pericenter Observations**

Science goals.

Off-pericenter observations by Venus Express are of key importance for achieving the mission goals especially in what concerns atmospheric dynamics. The imaging instruments (VIRTIS and VMC) have angular resolution high enough to provide high quality observations of the planet even from apocenter. The main scientific objectives of such observations are the following:

- Global view of the Southern hemisphere;
- Global spectro-imaging of the planet with emphasis on atmospheric dynamics;
- Plasma and magnetic field investigations from a distance.

Payload operations.

The +Z looking experiments observe Venus on ascending branch of the orbit between 15h and 23 h OT from a distance ranging from 66,500 km (apocenter) and ~10,000 km (beginning of the pericenter arc) (Figure 9). VIRTIS and VMC continuously observe the planet. SPICAV observations consist of 5 min slots evenly distributed between 15 and 23 hours OT. Broad field of view of PFS limits observation range to a distance of <25,000 km from the planet. So in Case #2 PFS observes only between 22 and 23 hours. ASPERA and MAG operate along the entire orbit. Exact duration of observations and their position in orbit (i.e. location of the points T1, T2 in the Figure 4.2) should be defined for each orbit and each experiment taking into account particular science goals and available spacecraft resources. Note also that the definition of Case #2 made above was deliberately “purified” for the study of thermal aspects. Modifications of Case #2 that seem to be more realistic and more applicable to actual observations in orbit are described in Section 6.

Spacecraft operations.

The spacecraft keeps the +Z axis nadir pointed. The Y axis is kept normal to the Sun direction (yaw steering) to optimize batteries charging and to avoid sun illumination on the +/-Y walls. The –X wall (with cryogenic radiators) is always kept in shadow. From time to time (typically once per hour) the solar arrays will be re-oriented around Y axis to optimize generated power. This attitude will also provide comfortable thermal environment for the payload (ASPERA in particular).

CDR study.

Obvious limitations result from the sun illuminating the –Z wall (propulsion system) in case of Venus day side observations (Sun shines from the left in Figure 4.2). The analysis was carried out for 3 values of local time at ascending node (LTAN): 0h (night side), 12h (day side), and 18h (terminator). (The orbit ascending node corresponds to ~23:30 OT in Figure 9). No thermal constraint was identified for 0h and 18h LTAN. For LTAN=12h (day side observations) the following duration times were determined:

1. Maximum observation time if the session starts at 15 hours OT equals 5h 30 min;
2. Maximum observation time if the session ends at 23 hours OT equals 3h;
3. Minimum time needed for the spacecraft to relax (cool down) to the reference thermal conditions is 1h30min.

A second limitation results from the overload of the OBDH bus due to simultaneous operations of ASPERA, MAG, PFS, and SPICAV. However, since in this case there is no requirement of simultaneous operations, the problem could be easily solved by switching on PFS and SPICAV in turn.

## 4.3 Case #3. Global Spectro-Imaging From Apocenter by VIRTIS

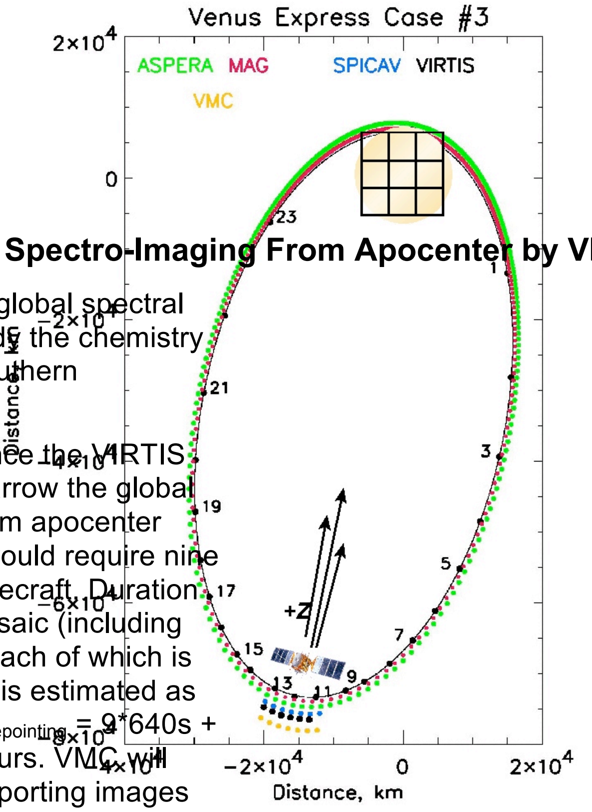


**Figure 10: Case #3. Global apocentric spectro-imaging by VIRTIS.**

*Science goals.* VIRTIS global spectral mosaic of Venus to study the chemistry and dynamics of the southern hemisphere.

*Payload operations.* Since the VIRTIS field of view is rather narrow the global mosaic of the planet from apocenter vicinity (> 60,000 km) would require nine re-pointings of the spacecraft. Duration of complete VIRTIS mosaic (including spacecraft re-pointing each of which is assumed to be ~1 min) is estimated as follows: $T = T_{imaging} + T_{repointing} = 9*640s + 8*60s = 6240s = 1.7$ hours. VMC will take a sequence of supporting images with a time step of about 10 min. SPICAV is operated in Nadir mode during 5 min for each spacecraft pointing. This orbit type should be repeated in the next 5-6 orbits in order to reconstruct the pattern of atmospheric dynamics. ASPERA and MAG operate during entire orbit.

*Spacecraft operations.* During observations the +Z axis is near Nadir pointed, and the Y axis is kept normal to the Sun direction (yaw steering) to optimize the SA power and to avoid sun illumination of the Y radiators. The –X face is kept in the shadow. During this session spacecraft performs 9 re-pointing about 4 degrees each.

*Results of the CDR study.* The Case #3 is covered by Case #2. It was concluded that Case #3 was compatible with all spacecraft resources and is therefore feasible at any date of the mission without constraints.

## 4.4 Case #4. VeRa Bi-Static Radar Experiment

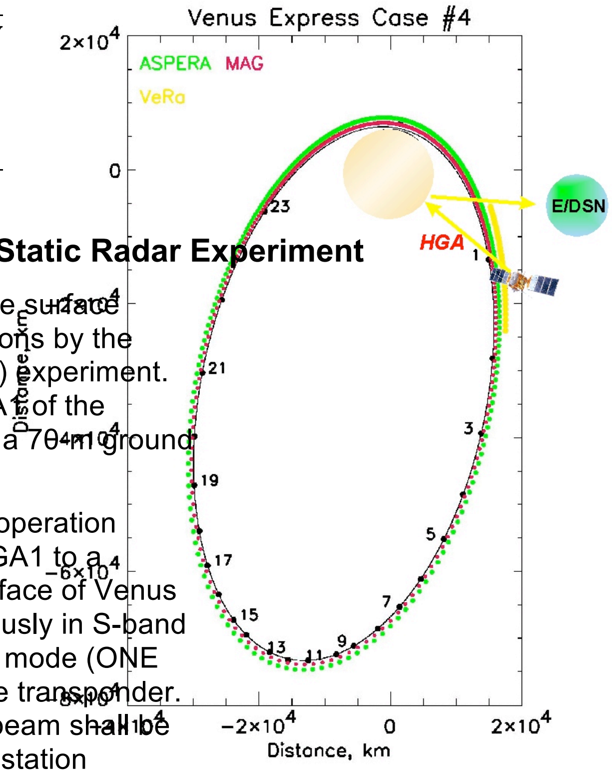

Figure 11: Case #4. VeRa bistatic sounding.

*Science goals.* Study of the surface properties of selected regions by the VeRa bi-static radar (BSR) experiment. The transmitter is the HGA1 of the spacecraft, the receiver is a 70-m ground station on Earth.

*Payload operations.* The operation consists in pointing the HGA1 to a specified target on the surface of Venus and in emitting simultaneously in S-band and X-band in carrier only mode (ONE WAY-mode) with the same transponder. The reflected microwave beam shall be received at a 70m ground station (specular reflection). These observations require the 70 meter DSN antenna because of higher signal-to-noise capabilities. Preferable conditions for the bi-static sounding are defined as follows:

1. Venus is close to Earth (approximately between quadratures);
2. the spacecraft is close to Venus;
3. signal that reaches the Earth is not corrupted by solar coronal plasma noise.

The preferred season for bi-static sounding is close to quadrature. Bi-static sounding is carried out between 00:30 and 1:45 OT. Selection of surface targets will be provided by the VeRa experiment team. Each observation sequence consists of the following steps:

1. ground station pre-calibration (~ 15 min);
2. Spacecraft slew pointing the antenna toward the selected target on the surface (~30 min);
3. Observations (~30 min);
4. Spacecraft slew back towards the preferred pointing (earth or nadir);
5. Post-calibration of the ground station (~15 min). This sequence is based on the Mars Express BSR experience. The other instruments except for ASPERA and MAG will not operate during the VeRa bi-static sounding.

Modifications of the Case#4 are described in Section 6.

*Spacecraft operations*. The spacecraft keeps HGA1 pointing to local nadir. The Y axis is kept close to normal to the Sun direction (yaw steering) to optimize the solar array power and to avoid Sun illumination of the Y radiators. The –X face is kept in the shadow.

*Results of the CDR study*. Between the 2007 quadratures the LTAN changes from 6h to 22h. Analysis shows no limitations for the LTAN between 6h and 18h that corresponds to first quadrature in June-July 2007. For 18-22 h LTAN the limiting factor is overheating of the HGA2. The case was studied for the worst case of LTAN=22h. General conclusion is that Case #4 is clearly covered by the sizing case except for LTAN=18-22h when the duration of bi-static sounding should be decreased to 15 min.

## 4.5 Case #5. Stellar Occultation by SPICAV.

Stellar occultation technique is an effective tool to study the upper atmosphere from orbit. It will be applied at Venus for the first time.

*Science goals.* Study of the composition and structure of the upper atmosphere of Venus by SPICAV, VIRTIS and VMC in stellar occultation geometry (Figure 12).

*Payload operations.* Stellar occultation can be observed from any portion of the orbit. Although dark limb in stellar occultation is preferable, the observations of the day limb are also foreseen. The list of bright stars provided by the SPICAV experiment is used in the development of the Science Activity Plan.

The observation includes two stellar occultation at the entrance and exit limbs

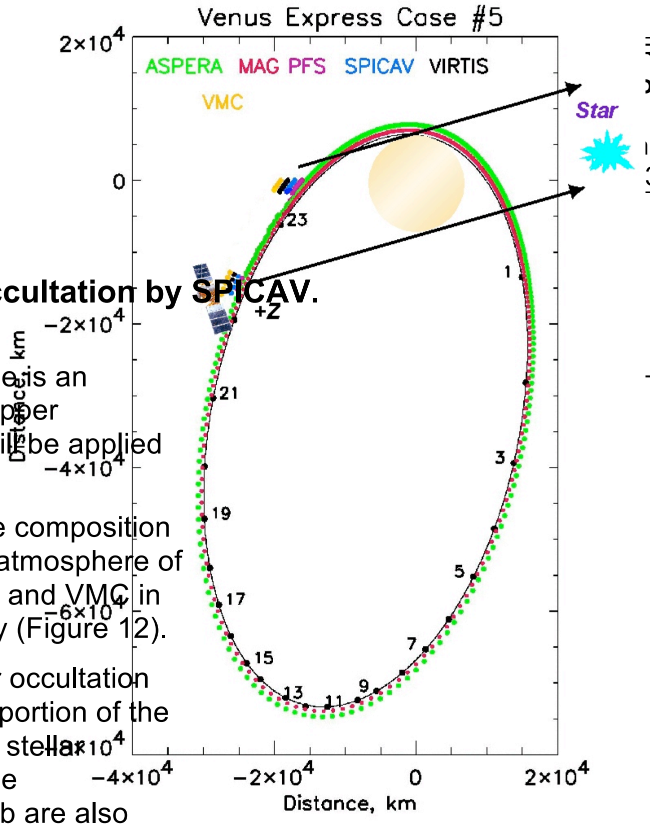


Figure 12: Case #5. SPICAV stellar occultation.

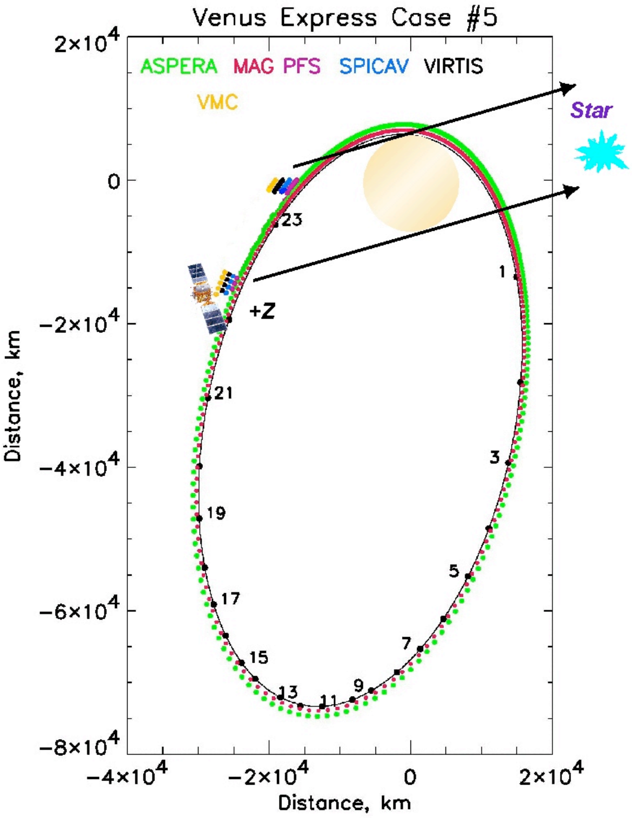


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Figure 12). Each occultation phase lasts for 5 min. The entire session starts at 22:15 and ends at 23:15 OT. SPICAV, VIRTIS, and VMC are ON for this period and take measurements during occultation phases. Modifications of the Case #5 are presented in Section 6.

*Spacecraft operations*. In stellar occultation the spacecraft +Z axis should point to the selected star before entering the limb and keep inertial pointing during the entire observation session, i.e. till the end of observations on the exit limb. The +Z axis was assumed to be in orbital plane. The Y axis is kept normal to the Sun direction (yaw steering). The –X wall is kept in shadow. The angle between +Z axis and sun direction must exceed 30° for proper SPICAV and VIRTIS operations.

*Results of the CDR study*. In many respects this case is covered by the sizing case. Similarly to Case #2 the limitation results from the illumination of the –Z wall when the LTAN is between 6h and 18 h. For the worst case of LTAN=12h the session duration should be reduced to 45 min. No other constraints were identified by the analysis.

## 4.6 Case #6. Sola
## Occultation by SP

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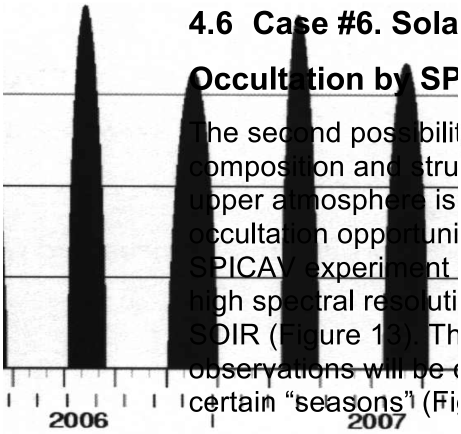



ure 14: Solar occultation seasons. ...
ipses duration is given in hours.

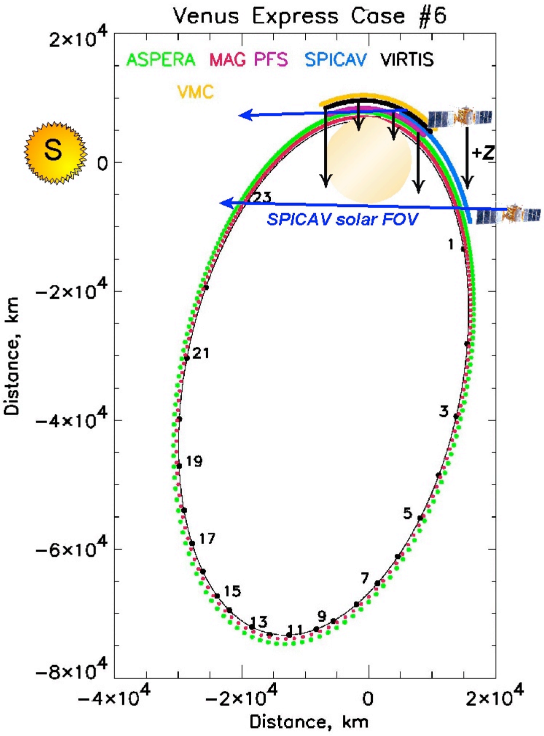



**Figure 13. Case #6. Spicav/SOIR solar occultation.**

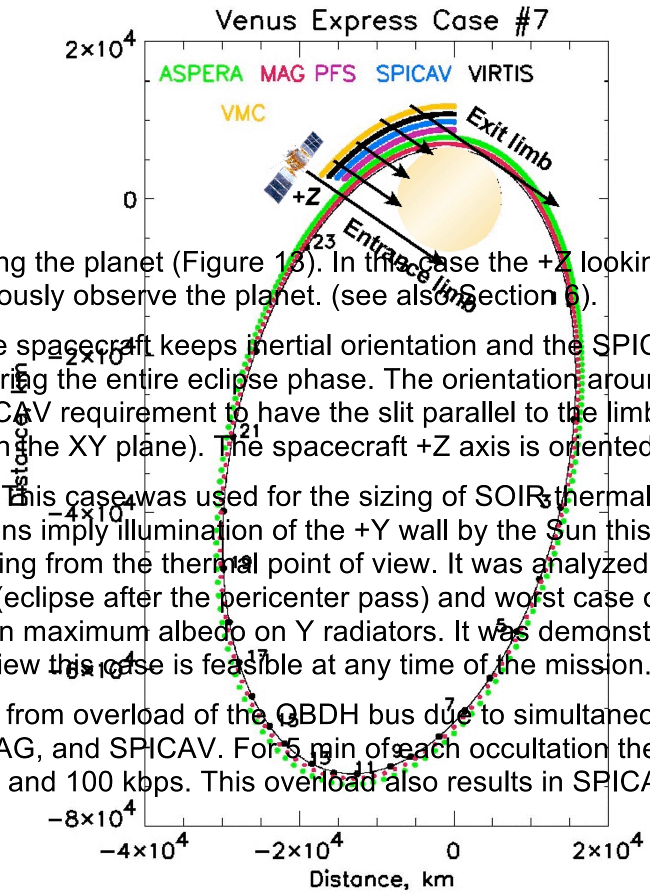
*Science goals*. Study composition and structure of the upper atmosphere of Venus by SPICAV/SOIR in solar occultation geometry.

*Payload operations*. Each orbit within occultation season will have two observation phases: one at eclipse entry and one at exit. The SPICAV/SOIR operates during both phases. SPICAV solar port (in the +X/+Y quadrant, 60° from +Y axis) points to the Sun. The SPICAV slit (which is parallel to the spacecraft X axis) should be parallel to the limb. ASPERA and MAG will operate during the entire orbit. All other experiments are either OFF or in sleeping mode. (Note that in some configurations the SPICAV solar occultation pointing requirements would not exclude the +Z axis crossing the planet (Figure 13). In this case the +Z looking instruments can simultaneously observe the planet. (see also Section 6).

*Spacecraft orientation.* The spacecraft keeps inertial orientation and the SPICAV solar port pointing to the Sun during the entire eclipse phase. The orientation around the sun axis is dictated by the SPICAV requirement to have the slit parallel to the limb. (In other words the limb should be in the XY plane). The spacecraft +Z axis is oriented south.

*Results of the CDR study*. This case was used for the sizing of SOIR thermal control. Since the SOIR observations imply illumination of the +Y wall by the Sun this case was considered rather demanding from the thermal point of view. It was analyzed for the worst case of LTAN=12 h (eclipse after the pericenter pass) and worst case of pericenter argument of 92° resulting in maximum albedo on Y radiators. It was demonstrated that from the thermal point of view this case is feasible at any time of the mission.

The only constraint results from overload of the OBDH bus due to simultaneous operations of ASPERA, MAG, and SPICAV. For 5 min of each occultation the data rate is in the range between 85 and 100 kbps. This overload also results in SPICAV polling problem.




## 4.7 Case #7. Limb Observations.

**Figure 15: Case #7. Limb observations.**

*Science goals.* Study of the composition and structure of the atmosphere, ionosphere, and hazes in limb geometry by the +Z looking instruments (Figure 15).

*Payload operations*. The observations will be made close to pericenter. The +Z looking instruments will be switched ON before entering the limb and will observe the entrance limb, the planet, and the exit limb. At the distance to the limb of about 2000 km, they have the following spatial resolution: PFS – 70km; VIRTIS-H – 0.6x1.8km; VIRTIS-M – 1.4 km; VMC – 1.4 km.

The observation phase includes entrance and exit limbs and the planet between them. The whole session lasts from 23:30 till 24:00 OT. During the observation session

PFS, SPICAV, VIRTIS, and VMC operate simultaneously. ASPERA and MAG are ON during the entire orbit.

*Spacecraft operations*. Before entering the observation phase the spacecraft will be oriented so that the +Z axis points to the limb on one side of the planet. The spacecraft will keep inertial pointing so that the +Z axis would first scan the entrance limb, then it will traverse the planet, and finally will leave the disc at the exit limb

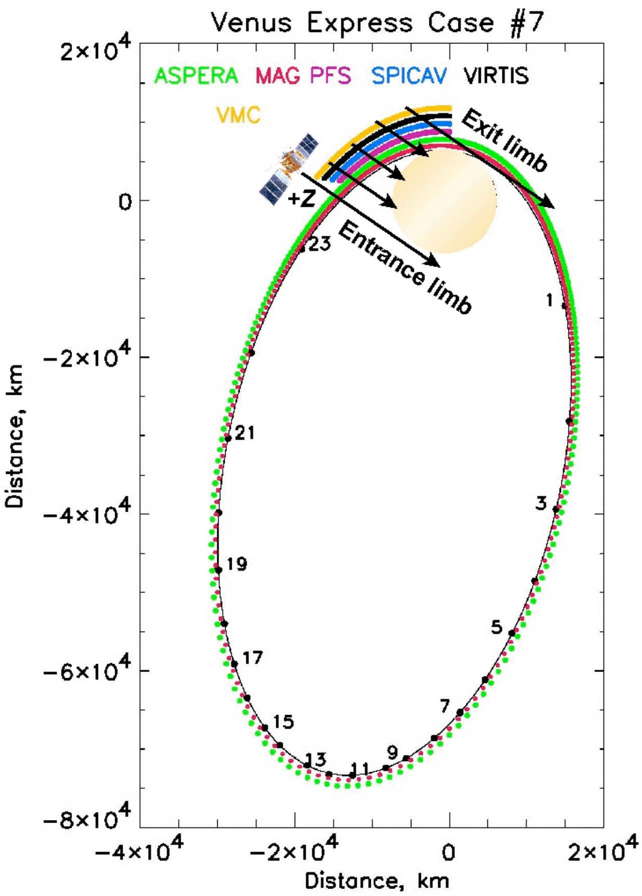



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Figure 15). The X axis is parallel to the limb thus fulfilling the pointing requirements of SPICAV (slit parallel to the limb) and VIRTIS (slit perpendicular to the limb). The –X face is kept in a shadow. The angle between the +Z axis and the Sun direction must be higher than 30° for proper SPICAV and VIRTIS operations.

Several important modifications of the Case are described in Section 6.

*Results of the CDR study*. The only limitation is too high traffic on the OBDH bus that is well above critical limit (85 kbps) for the entire observation phase and exceeds maximum of 100 kbps during 1 minute around pericenter. The OBDH overload causes a SPICAV polling problem. As in the other cases the problems result from simultaneous operations of ASPERA, MAG, PFS, and SPICAV.

## 4.8 Case #8. Earth Radio Occultation by VeRa.

*Science goals.* Study of the fine structure of the neutral atmosphere (density, pressure, temperature vertical profiles) and ionosphere (electron density) in the Earth occultation geometry.

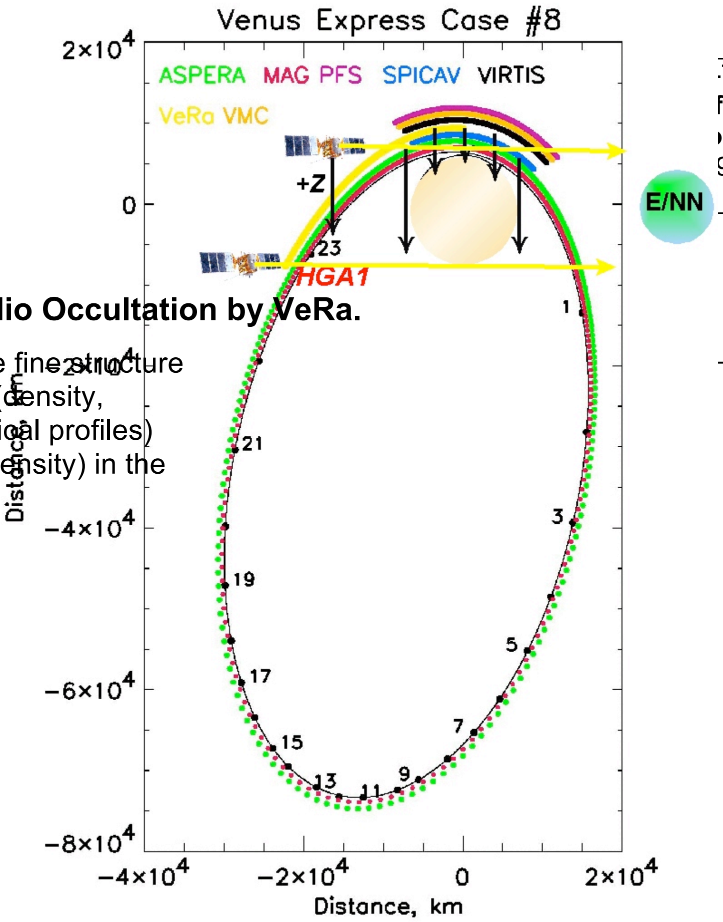


Figure 16: Case #8. VeRa radio occultations.

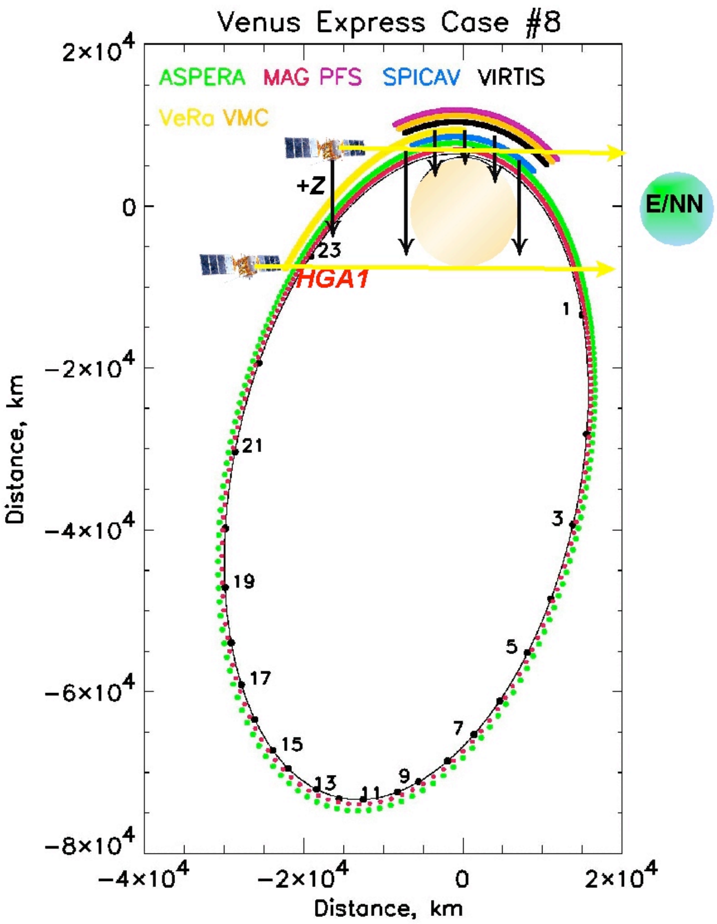


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Figure 16). This type of observations will be possible in specific seasons only (Figure 17).

*Payload operations*. The VeRa operations consist of pointing the HGA1 to Earth and emitting simultaneously in one-way S-band and X-band carrier-only mode with the same transponder. This operation is done during New Norcia and DSN antennae visibility (Cebreros is only an X-band station).

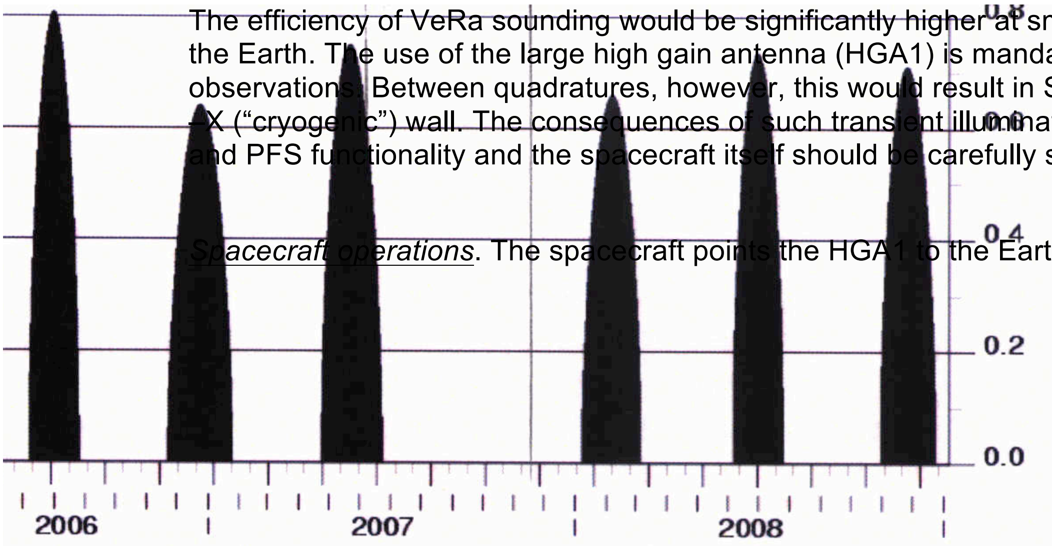
The VeRa operations includes :

- one calibration phase (Earth pointing without correction);
- a 1st operating phase with attitude correction profile and, depending on the detailed orbit geometry, a slew maneuver;
- a slew maneuver;
- a 2nd operating phase with attitude correction profile;
- lastly, another calibration phase

PFS, SPICAV, VIRTIS, and VMC are OFF during the Earth occultation. ASPERA and MAG are ON entire orbit.

The efficiency of VeRa sounding would be significantly higher at small distances from the Earth. The use of the large high gain antenna (HGA1) is mandatory for these observations. Between quadratures, however, this would result in Sun illumination of the +X (“cryogenic”) wall. The consequences of such transient illumination for the VIRTIS and PFS functionality and the spacecraft itself should be carefully studied.

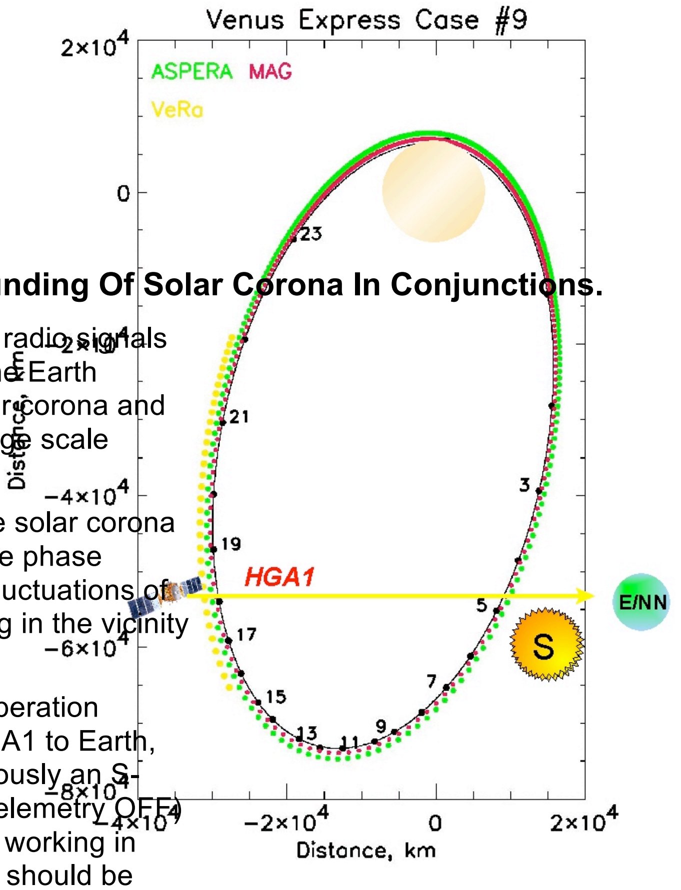
*Spacecraft operations*. The spacecraft points the HGA1 to the Earth before entering




**re 17: Earth occultation seasons. Occultation duration is given in hours.**

observation phase. A specific slew maneuver to compensate for atmospheric refraction and to keep contact with the ground station is required at both entrance and exit limbs. Attitude profile during observation is specified by the PI. The S/C +Z axis points toward the planet so that the +Z looking instruments can perform observations of the planet in the same session. The only limitation to this is available power.

*Results of the CRD study*. No constraint was identified except for that a slew maneuver of ~ 50° in 2 min 30 sec required to go from the first attitude profile to the second one exceeds the AOCS capability. Compliance can be reached by fine tuning of the attitude profile.




## 4.9 Case #9. VeRa Sounding Of Solar Corona In Conjunctions.

In superior conjunction the radio signals sent by the spacecraft to the Earth propagate through the solar corona and can be used to study its large scale structure (Figure 18).

Figure 18: Case #9. VeRa studies of the solar corona.

_Science goals._ Study of the solar corona properties by measuring the phase changes, path delay, and fluctuations of the radio signal propagating in the vicinity of the Sun.

_Payload operations_. The operation consists of pointing the HGA1 to Earth, and transmitting simultaneously an S-band and X-band carrier (telemetry OFF) with the same transponder working in coherent mode. The uplink should be kept in S-band (instead of X-band). Thus the solar corona study should done during New Norcia visibility (Cebreros is an X- Band Only Ground station). Science operation starts at 16:00:00 and ends at 22:00:00.

Note that current spacecraft configuration implies the uplink in X band (not S band) that is required by the TC link onboard monitoring (TLRAP) which deals only with X-band reception configuration of the TT&C subsystem.

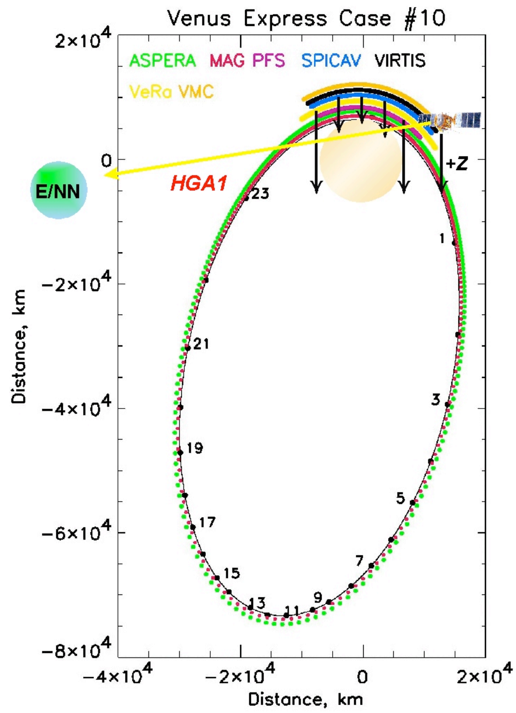
There are two different configurations (see Figure 1):

- Superior conjunction (Earth-Venus-Sun angle < 10 degrees)
- Inferior conjunctions (Earth-Venus-Sun angle > 170 degrees): for this particular case, a switching from HGA2 (used in communications) to HGA1 (used for VeRa operations) is necessary for the S-band uplink and downlink operations

Instruments on the +Z looking platform are not operating. ASPERA and MAG are ON for the entire orbit.

_Spacecraft operations._ The spacecraft keeps the HGA1 pointing to the Earth during the observations.

_Results of the CDR study._ Observations in superior conjunction have no limitations. Observations in inferior conjunction result in full sun illumination of the –X (cryogenic) wall. For this reason duration of experiment cannot exceed 2h 20 min. However acceptability of this case should be carefully verified by other experiments, especially PFS and VIRTIS.




## 4.10 Case #10. Study of … a.

*Science goals*. Study of the \

*Payload operations*. The ope
of pointing the HGA1 to the E
emitting simultaneously in S-
band in carrier-only mode wit
transponder working in coher
Science operations start at 2:
end at 00:15:00 OT. The +Z l
instruments (PFS, VIRTIS, S
VMC) operate simultaneously
axis crosses the limbs and th

*Spacecraft operations*. The o
are performed close to perice
spacecraft not in Earth occultation
condition. The spacecraft keeps the HGA
pointing to the Earth. The +Z axis points to
the planet so that the +Z looking
instruments can perform observations
simultaneously with VeRa.

**Figure 19: Case #10. VeRa gravitational studies.**

*Results of the CDR study.* Three factors limiting this type of observations were identified.

1). Peak power demand at DPU output (792W) slightly exceeds PDU capabilities (750W).

2). Illumination of the Y radiators limits duration of this case to 15 min.

3). Data traffic on the OBDH bus is always above the critical limit and for 2 minutes around pericenter exceeds maximum of 100 kbps. Overload of the OBDH bus causes SPICAV polling problem.

## 4.11 Case # 11. Planet Track Pointing

This pointing is used to track a planet, the Sun or the Earth-Moon point with the pointing axis specified in the spacecraft frame. The spacecraft Y-axis is oriented so that the power on the solar arrays is optimized (power-optimized pointing).

For pointing axes close to the spacecraft X-Z plane, and if the sun direction is not too closely aligned with the pointing axis, there are two possible attitudes with the Y-axis perpendicular to the Sun direction. The selection is made taking spacecraft thermal considerations into account. Normally the solution with no Sun on the -X face is chosen.

For pointing axes that are not in the spacecraft X-Z-plane, if the Sun is too closely aligned with the pointing direction, the Y-axis cannot be put perpendicular to the Sun direction. In this case the attitude is defined so that the spacecraft Y-axis is as close as possible to the plane perpendicular to the Sun

Note that for the special case in which the pointing axis is directed to the Sun, the Y-axis is oriented towards the spacecraft orbital North or South pole with respect to the Sun.

# 5. Summary of CDR Analysis of the Basic Science Cases

## 5.1 Spacecraft Resources

Table 1 summarizes the results of CDR study of the science cases.

## 5.2 Downlink Budget

The data rates and data volumes requested by the Venus Express experiments are put together in Table 2 and Table 3. Figure 20 compares the payload requests with expected downlink capabilities. The downlink data rate used in Figure 20 was confirmed by Astrium at the CDR. The downlink curve assumes 3dB margin and 8 hours of downlink.

Thin, colored vertical bars in Figure 20 show the downlink requests from experiments (see color legend in the upper right corner of the figure). The level of housekeeping data volume is shown by dark green bars. Thick red bars show the total downlink request (including spacecraft housekeeping) with numbers marking the science cases. Note that the science cases are arbitrarily positioned along the horizontal axis.

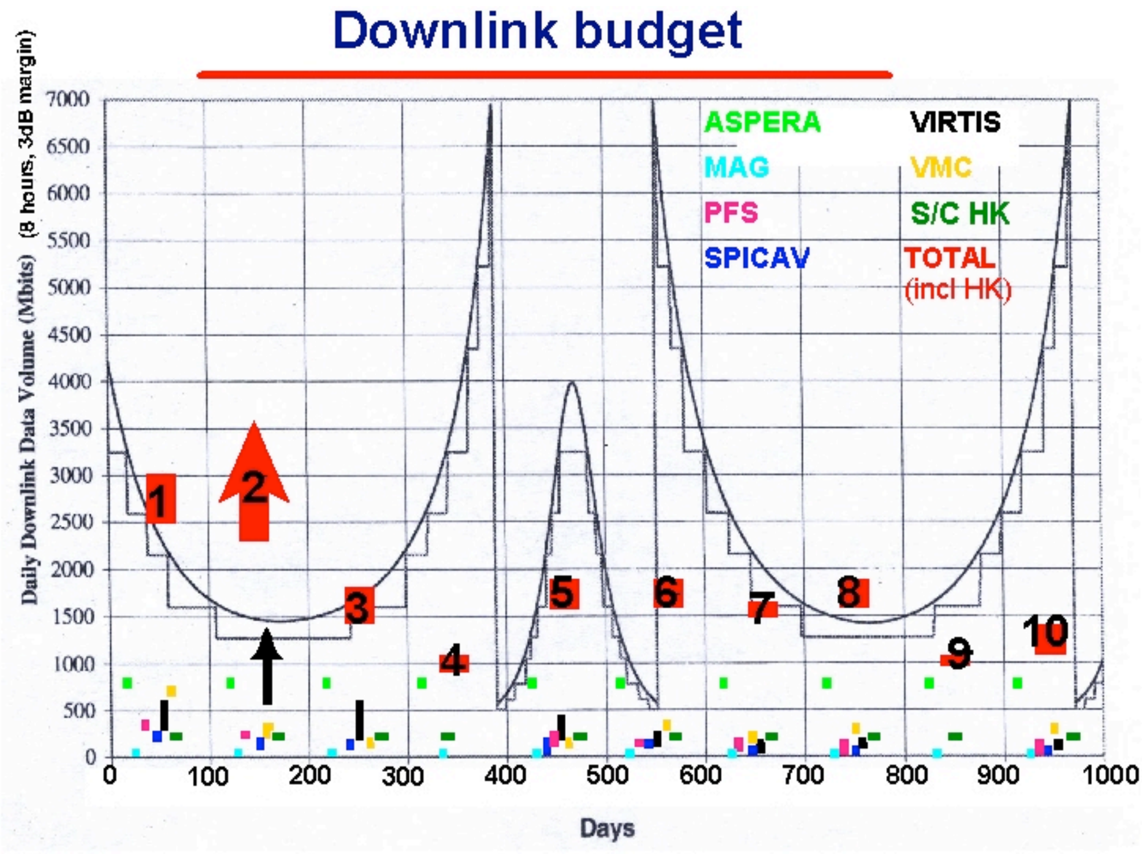



**Figure 20: Venus Express downlink budget**

Figure 20 leads to the following conclusions.

1. Volume of the solid state mass memory (SSMM) (~ 8 Gbits at EOL) is quite enough to store the data collected by experiments in one orbit.
2. The payload requests in the Cases #3-10 are within the downlink capabilities.
3. The payload requests exceed the downlink capabilities by a factor of 2 for the Case#1 (spacecraft sizing case) and Case#2 (off-pericenter observations). The situation gets worse at quadratures, just after the switch to the HGA2.
4. Keeping in mind that the combination of cases is highly desirable, deficit of the downlink budget strongly constrains the overall science return.
5. Certain measures could be used to balance the payload requirements and downlink capabilities:
    - Increase the duration of the downlink to Cebreros antenna;
    - Use additional ground stations (DSN) to increase the transmitted data volume.

- Keep the downlink via HGA1 as long as possible in the vicinity of quadrature (Note that at quadrature 30 minutes of downlink with HGA1 are equivalent to 7 hours of transmission with HGA2);
- Optimize experiments' observation modes (spectral and spatial resolution, data acquisition frequency, etc.);
- Use effective data compression.

# 6. Further Development of the Science Cases

Section 4 of this document described the Venus Express science cases as they were formulated and studied in the framework of CDR. Some of them were deliberately "purified" in order to study specifically selected aspects or resources. For instance, Case #6 (section 4.6, SPICAV/SOIR solar occultation) was used for sizing the SPICAV/SOIR thermal control. Case #8 (section 4.8, VeRa radio-occultation) was considered the most demanding case for the AOCS system and was formulated as a radio-occultation test case. This approach from the very beginning implied that some features of Venus Express science operations would be ignored. On the other hand, the CDR analysis proved that the spacecraft is a flexible system and that the "pure" science cases in many respects are well within the spacecraft capabilities. Thus, further development of the "family" of science cases that would include their modifications and combinations of several cases in one orbit appears to be quite possible. Their implementation in the Science Activity Plan would result in full use of the spacecraft resources and capabilities and would maximize overall mission science return.

## 6.1 Modifications of Basic Science Cases

This section contains further modifications of basic science cases. For some of them it is easy to show that the modified cases are covered (in terms of required spacecraft resources) by those already studied at CDR. Some modifications require additional investigation.

### *6.1.1 Case #1a. Off-track pointing*

Case #1a differs from Case #1 by a constant angle off-track pointing of the +Z axis during the pericenter pass. This geometry can be used, for instance, in order to observe a site that is currently off-track. This could provide an opportunity of repeating observations of a specific place on Venus that otherwise would be not possible due to slow rotation of the planet.

### *6.1.2 Case #1b. Selected point tracking*

In this case the spacecraft +Z axis points to a selected point (latitude, longitude) on the cloud top or surface target for a period of its visibility from orbit. This would provide observations of a selected location at different viewing and phase angles that is of great importance for the study of the optical properties and structure of the cloud top. In this case the main effort would be to perform a spacecraft slew manoeuvre in the orbital plane to compensate for fast orbital motion.

### 6.1.3 Case #2a. Off-pericenter observations with modified instruments' timeline

The timeline of the payload's observations can be adjusted to the needs of experiments. Firstly, the original Case#2 was designed so that VIRTIS and VMC are continuously observing between 15h and 23h OT. However, usually 15 min of observation during 1 hour would be enough. This modification would significantly decrease produced data volume as compared to the original case #2 with continuous observations during 8 hours.

Secondly, PFS observations could be extended to the entire ascending branch of the orbit. This would provide possibility of averaging of great number of spectra (although with low spatial resolution) and to increase S/N ratio. This would be of particular importance for observations of week nightside emissions. Both modifications are incorporated in Case #2a and seem to be covered by the CDR study of Case #2.

### 6.1.4 Case #2b. Implementation of "pendulum" strategy

In original Case #2 the spacecraft keeps nadir pointing for 8 hours of observations. In the worst thermal case (LTAN=12h) sun illumination of the –X wall limits duration to 5h 30 min. After that the cooling time of 1h30min is required. In the current formulation, keeping the spacecraft nadir pointing for 8 hours is not feasible. One solution to this problem is to periodically change the spacecraft orientation from nadir pointing (~15 min) to an attitude with the Sun in the +Z/+X quadrant for intermediate cooling (~45 min).

### 6.1.5 Case 2c. Off-track pointing

Case #2c differs from the Case #2 by a constant angle off-track pointing of the +Z axis. This geometry can be used, for instance, in order to observe a site that is currently off-track. This could provide an opportunity of repeating observations of a specific place on Venus that otherwise would be not possible due to slow rotation of the planet. Similar pointing is described in Case #1a.

### 6.1.6 Case 2d. Selected feature tracking

In this case the spacecraft +Z axis points to a selected feature on the cloud top or surface target for a period of its visibility from orbit. Such pointing would be of great importance for the study of the cloud tops dynamics since it would allow following the motion and evolution of the cloud feature for up to 8 hours. In this case the main effort would be to provide the spacecraft slew in the direction perpendicular to the orbital plane in order to keep a selected cloud feature in the field of view of the instruments. The Venus atmosphere has an advantage of regular rotation, so that the spacecraft pointing in this case can be well predicted and pre-calculated. (Note the difference from similar Case #1b in which the spacecraft slew is mainly in the orbital plane.)

### 6.1.7 Case 3a. Selected feature tracking

This case is similar to that of Case 2d.

### 6.1.8 Case 4a. Bi-static sounding with extended duration

Duration of the bi-static sounding (Case #4) should be preferably extended on both sides. The sounding should be performed between 00:00 (pericenter) and 2h OT.

### 6.1.9 Case 4b. Specular reflection pointing

Efficiency of the bi-static sounding experiment will significantly increase if the spacecraft performs specific slew maneuver that would provide observation of a selected surface target (specular reflection pointing). The maneuver will be specified by the VeRa team for each particular observation.

### 6.1.10 Case #5a. Stellar occultation with +Z axis out of orbital plane

In the original Case #5 the +Z axis is kept in the orbital plane. In reality it would be difficult to exactly meet this requirement. So it is necessary to be prepared for observations with the +Z axis out of the orbital plane.

### 6.1.11 Case #5b. Stellar occultation with planet observations between limbs

In its original formulation the Case #5 consists of two observations of stellar occultation by SPICAV, VIRTIS, and VMC. Between the limbs, when the +Z axis scans the planet, the instruments do not take measurements despite the fact that they are ON. It is natural to keep the +Z looking experiments operating between the limbs as well.

### 6.1.12 Case #6a. Solar occultation with planet observations between eclipses

In its original formulation the Case #6 includes only SPICAV/SOIR observations of solar occultation. PFS, VIRTIS, and VMC are OFF. However, in some configurations the SPICAV solar occultation pointing requirements would not exclude the +Z axis crossing the planet (Figure 13). In this case the +Z looking instrument will be able to simultaneously observe the planet.

### 6.1.13 Case #7a. Limb tracking

In the original Case #7 the spacecraft is in inertial mode, thus providing limb observations in two locations on the planet. If the spacecraft performs a slew maneuver while keeping the +Z axis pointing to the local limb in the orbital plane, the +Z looking instruments can collect extremely valuable information on latitude variability of the upper cloud structure.

### 6.1.14 Case 7b. Observations of a side limb

Pointing to a side limb can allow observing the limb structure out of the orbital track or to select a favourable geometry (phase angle) of observations.

### 6.1.15 Case #8a. Radio occultation with planet observations by +Z instruments

Original Case #8 includes only VeRa radio-occultation. As a results PFS, SPICAV(nadir), VIRTIS, and VMC miss the opportunity of pericenter observations. However, by selecting an orientation of the +Z axis towards the planet (Figure 16) during occultation, by rotating the spacecraft around the +X (HGA1) axis, these experiments can be given a chance to simultaneously observe the planet.

### 6.1.16 Summary of Science Case Modifications

Table 5 summarizes proposed modifications of basic science cases, their effect on the science return, and preliminary conclusions about their feasibility.

## 6.2 Combinations of the science cases

The CDR analysis of the basic science cases (Sections 4 & 5) proved that the Venus Express spacecraft is a rather flexible system and that the basic science cases are in many respects well within the spacecraft capabilities. Using a "one-case-per-orbit" approach in the science planning would result in significantly underutilizing the spacecraft resources and reduction of the overall mission science return. In order to fully exploit available spacecraft potential, combinations of science cases were proposed. In some cases their analysis was based on CDR results and the conclusions are relatively straightforward. For some combinations additional studies were required.

Proposed combinations are attempts to merge two basic science cases in one orbit. The basic idea was to combine the science cases that utilize different spacecraft resources. For instance, the off-pericenter (case #2) and apocenter (case #3) observations that are rather demanding from the point of view of data volume could be naturally combined with the VeRa cases #4 and #8. Also VeRa solar corona study (case #9) can be easily placed in one orbit with any of near-pericenter observations (Cases 1,4,5,6,7,8,10).

Table 6 shows the matrix of possible combinations of basic science cases in orbit. The rows of the table correspond to the case that occurs first. The columns represent the case that follows. Abbreviations in the crossings give preliminary estimate of combination feasibility, and/or the potential source of constraints (T – thermal, Pnt – pointing conflict, AOCS, DV – data volume).

Below we consider several of the most important combinations that seem to be covered by the studied science cases and, hence, should be relatively straightforward in implementation. The proposal was to use these combinations from the very beginning of the mission. Table 7 gives a summary of these combinations emphasizing their impact on the science return and potential problems in their implementation.

### *6.2.1 Combinations (2+8), (3+8), (2+4), and (3+4)*

These are combinations that are implemented at different portions of the orbit and use different spacecraft resources. Hence, these combinations seem to be rather easy to implement. At the same moment they give great advantage to continue observations by the +Z looking instruments during radio-occultation seasons and bi-static sounding campaigns.

### *6.2.2 Combinations (2+6) and (3+6)*

The off-pericenter and apocenter +Z observations seem to be well combined with solar occultation except for the period of LTAN = 6-18 hours (dayside observations in case#2) when thermal constraints can appear. This combination would help to avoid "outages" in +Z observations during solar occultation seasons.

### *6.2.3 Combinations (3+1) and (2+1)*

Combining pericenter and off-pericenter observations in orbit could give the advantage of simultaneous observations of both hemispheres. These combinations, however, could have thermal and/or downlink limitations. The later could be resolved by splitting pericenter and off-pericenter activities between different experiments according to their specific scientific focuses.

### *6.2.4 Combinations (5 + 1) and (7 + 1)*

Combination of limb or stellar occultation cases with pericenter case #1 could result in AOCS limitations. The problem could be resolved by cancelling the exit limb, thus changing to the nadir orientation right after passing the entrance limb (or star occultation). This could provide balance between limb and nadir observations at one particular orbit.