VELOCITÉ

VEnus Lander and Orbiter for Characterising the Interior and TEctonics

Team Blue:
Julian BARTOLOMÄUS, Rumbidzai CHIMBUYA, Michaela ELLMEIER, Katarina LAUDAN, Anthony LETHUILLIER, Aisling MURPHY, Mariusz SANTORA, Andreas SCHAFFER, Krzysztof SOSNICA, Benoît SEIGNOVERT, Filippo SILVESTRUCCI, Teresa STEINKE and Nicole ZIBRID.

Tutors:
Ruth ZIETHE and Jaan PRAKS.

Mission target:
Venus

Expected launch:
December 6th, 2032

Duration:
5 years

Class mission:
L class – €1.6 B

Abstract:
Venus' dense atmosphere and hostile conditions on its surface make space observation a challenging objective. That is why little is known about the geological processes on the Venusian surface and our understanding of Venusian tectonics and volcanism is limited. Recent thermal monitoring by the Venus Express mission indicates active volcanism, at very low resolution. Our knowledge cannot be improved with available instrumentation currently in Venusian orbit.
To improve our knowledge of geological dynamics and surface activity, we propose a 5 year mission - VELOCITÉ - to Venus. The mission is designed to determine the precise nature and activeness of surface tectonics and volcanism on and help us understand evolution of Earth like planets. The proposed mission concentrates on surface dynamics and will give a closer look also into the interior structures of the planet. The surface dynamics measurements will be achieved by utilising a high resolution InSAR in combination with ground penetrating radar and gravity measurement system on the orbiting spacecraft (VISAGE) and a local scale in-situ measurement lander system (LOVE 1 & 2).

Keywords : Alpbach 2014, Terrestrial Planets, Venus, Tectonics, Volcanism, Inner-structure, InSAR, Lander

1 Introduction

The complex environment of Venus offers intriguing possibilities to study the planetary evolution of the terrestrial planets. Despite its similarities to the Earth (size, structure, bulk chemical composition) Venus *behaves* very differently from Earth. The slow retrograde rotation, the dense and hot atmosphere and the high surface temperature set it apart from its so-called sister planet Earth. Investigating Venus will help us to construct a unified scenario for terrestrial planet formation and evolution. This is a key issue in understanding the habitability and potential for life in Earth-like planets. Investigation of Venusian tectonic dynamics is, however, remarkably demanding: on one hand, the planet's dense atmosphere limits remote observations, and on the other hand, hostile conditions on the ground limit the life-time of ground scientific instruments. Moreover, studying the planet's interior requires large-scale satellite investigations, whereas the investigation of local features such as volcanic activity, tectonic processes and erosion require detailed small-scale observations, including in-situ studies.

There have been over 10 successful missions to Venus, among them a few designed to investigate the planet underneath the clouds. The first information about the surface was revealed by Venera 8 (1972) (Aleksandrov et al., 1988). Successive missions in the Venera program provided images (including the first colour images) showing uneroded rocks of sizes between 30-40 cm, large pancake domes, lava and other weathered rocks.

Venera 15 and 16 (1983) mapped the northern 25% of the planet at a resolution of 1 to 2 km. It was discovered that the planet is largely covered with lava fields and shield volcanoes, networked with linear ridges and coronae, with patches of a more ancient wrinkled terrain, called tessera (figure 1) (Aleksandrov et al., 1988; Showstack, 2008) Pioneer 12 (1978) and Magellan (1989) delivered radar images that led to the topographical maps (Woo et al., 1980).

Magellan mapped approximately 98% of the Venusian surface with Synthetic Aperture Radar (SAR) and delivered the first gravity data (Greeley et al., 1992).

More recently, the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument and the Venus Monitoring Camera (VMC) onboard the Venus Express satellite has obtained evidence of previous (and possibly ongoing) lava flows on the surface (Helbert et al., 2009).

Large changes of the sulphur dioxide in the atmosphere have also been observed, which may indicate volcanic eruptions (Yung et al., 2009). The debate about the Venusian tectonic state is ongoing.

First, Venus could be highly active volcanically and possibly tectonically, today, releasing radiogenic heat as well as affecting atmospheric chemistry (Solomon,

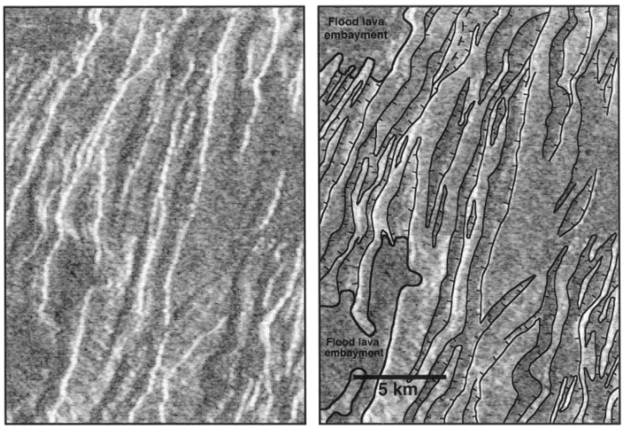

Fig. 1— *SAR image and map of ribbon terminations at southwestern Fortuna Tessera, hatched lines delineate trough walls with ticks on the trough side; thick lines mark extent of lava flow embayments. From Hansen (1998).*

1993); the second possibility is that Venus was tectonically active with associated widespread volcanism and perhaps lithospheric overturning before 500 My ago but then went into a period of inactivity that continues to this day (Turcotte, 1993).

Clear evidence of the planet's geophysical processes is required to resolve such questions. However, no data has been obtained regarding the temporal dynamics of the surface; indeed, very little data has been collected from the surface at all. Therefore a key objective for a new mission to Venus is to investigate such surface characteristics and processes via in-situ measurements on the ground.

These questions mentioned above have motivated the VELOCITÉ mission, described hereafter. The aim of VELOCITÉ is to enhance our knowledge about Venus' current geologic activity and interior structure. It is intended to investigate the nature of its tectonics and volcanic activity. Data will be collected that enable us to draw conclusions about the near-surface layer as well as the deep interior like the planet's core.

2 Mission overview

The VELOCITÉ mission is capable of coupling large scale and small scale investigations on the planet. This mission is therefore designed with the goal of addressing following topics.

2.1 Objectives

Studying the near-surface geological activity and the interior structure will allow us to substantially broaden our knowledge of the current status of evolution and dynamics of Venus.

2.1.1 Venusian geological activity

Tectonic activity shall be investigated through observations of vertical surface displacements, large-scale mass redistributions, and surface temperature variations. Gravity field changes supported by the topography model will allow investigation of crustal density and crustal thickness changes, crust-mantle interactions, and atmospheric-induced erosion processes affecting the crust. The key issue for such studies is the repeatability of the observations. The observation must thus be capable of detecting both short-time dynamic variations as well as long-term observations providing information on seasonal and secular tectonic changes.

2.1.2 Venusian inner structure and dynamics

The interior structure, including in particular size and shape of the Venusian core, will be studied through observation of rotational parameters, i.e. length-of-day, precession, nutation, and polar motion in conjunction with variations in low-degree gravity field parameters and the reaction of Venus to tidal forces. Decoupling of atmospheric angular momentum and gravity field variations induced by near-surface mass redistributions in the length-of-day variations will provide crucial information on the planet's moment of inertia. Observing seismic parameters and the complex permittivity of the upper layer shall substantially improve our knowledge of the composition, structure, and thickness of Venus' upper layer, as well as mutual interactions between the interior layers.

2.2 Measurement requirements

Only stringent requirements imposed on state-of-the-art measurement techniques will allow us to meet the sophisticated and demanding goals of this mission.

The elevation model of the surface shall be known with 15 m accuracy, whereas geological events such as volcano eruptions and tectonic displacements can be detected by determining relative displacements with at 1 cm level accuracy. High-degree gravity field variations in conjunction with elevation changes will provide remarkable information on tectonic-induced inner mass redistributions and interactions between the crust and mantle. Therefore we require the gravity field model expansion up to degree 250 of the spherical harmonics (with the spatial resolution of 70 km), knowledge of geoid temporal changes to an accuracy of 5 cm, and the accuracy of C_{20} of 10^{-11} (of fully normalized spherical harmonics). Surface and near-surface volcanic activities can be investigated by mapping the temperature of selected surface areas with 1 K accuracy. The rotational parameters should be determined with the accuracy of 0.2 arc seconds with a temporal resolution of 8 hours. These measurements will enable the study of subtle polar motions and variations in day length induced by a possible precession of the oblated core. To study possible dynamic volcanic activities and features such as lava chambers, the upper layer structure should be investigated to a depth of 1000 m, with an accuracy of 15 m.

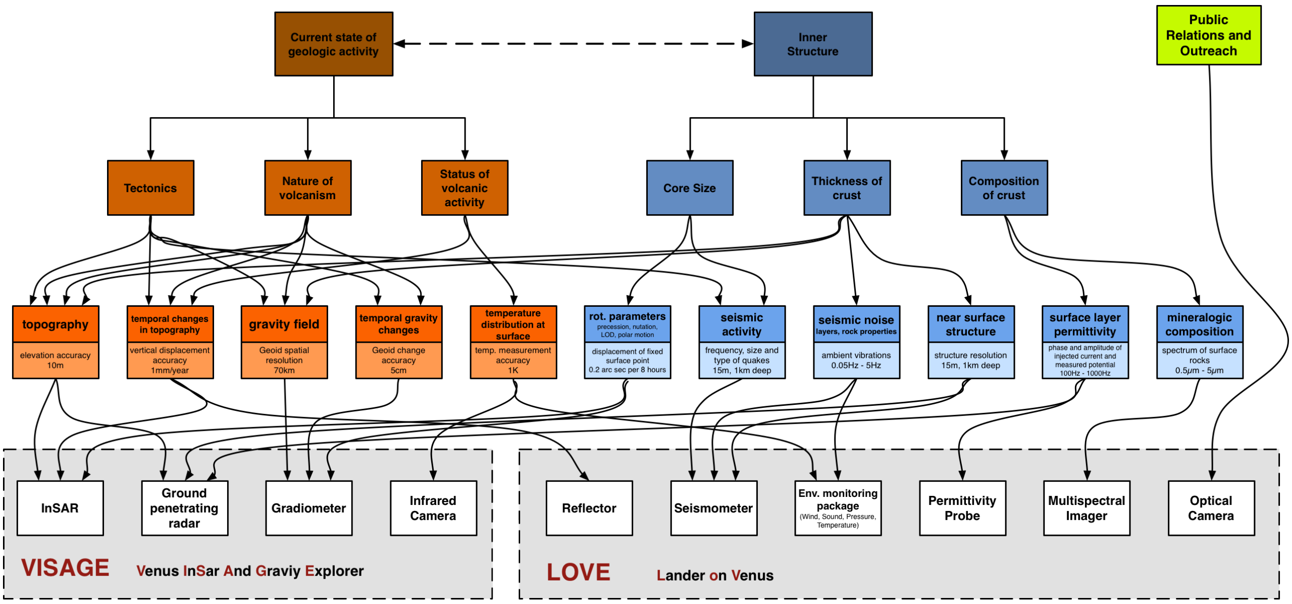

Fig. 2— *Flowchart showing connection between scientific objectives, mission requirements and instruments*

3 Mission Design

The VELOCITÉ mission comprises an Venus satellite and two landers with the major goal of aerospace and in-situ geophysical studies. The satellite has been named ***V**enus **I**n**SA**R **A**nd **G**ravitational **E**xplorer* (VISAGE), whereas the probe has been called ***L**ander **O**n **VE**nus* (LOVE). The orbiter is designed to carry a high resolution L-band SAR to carry out accurate surface topography and variability measurements by utilizing interferometric measurement setup from a dedicated orbit. VISAGE will provide information of the tomography, gravity field, and inner structure by orbiting in a circular orbit at the altitude of 280 km and inclination of 50°. The major goal of both LOVE landers is to study and register seismic noise and the near-surface permittivity using the in-situ probe. The overall life-time of the VISAGE mission is designed to be five year, whereas the operational life-time of LOVE is limited to a few hours due to severe atmospheric conditions on the Venusian surface.

3.1 Orbiter Payload

To fulfil the demanding scientific requirements, VISAGE combines two main state-of-the-art systems that have been successfully applied for Earth observation missions and previously proposed for Venus research, namely a precise Interferometry Synthetic Aperture Radar (InSAR) (Meyer and Sandwell, 2012; Ghail et al., 2012) and a gravity field system comprising a high-accuracy gradiometer.

3.1.1 SAR System

We have selected L-band radar with a range angle of 25° and the swath of 70 km to pass trough the atmosphere of Venus. The L-band frequency provides optimal penetration through the atmosphere and allows orbital configuration where the optimal baseline 7.7 km (Meyer and Sandwell, 2012) can be achieved between subsequent orbits. The SAR antenna has right- and left-looking modes capable of measuring displacements on either side with a nominal resolution of 15 m at 25 cm wavelength. This configuration will allow for multiple observations of same area with the repetition interval of 92 minutes. The same area will thus be registered several times (up to 12 times per year), allowing for derivation of the short-term temporal surface displacements as well the long-term displacements. Moreover, the radar will be operating in the low (100 m/px) and medium (50 m/px) as well as high-resolution mode (15 m/px) as a trade-off between the data volume and obtaining the best resolution. Preference is given to promising geological active areas.

A side-looking radar with synthetic aperture provides high-resolution phase and intensity maps of microwaves reflected by surface structures. Two or more SAR images can be used to generate maps of surface deformation and digital elevation models, making use of differences in the phase of the waves returning to the satellite. This technique can effectively measure sub-cm changes in deformation over a timespan of hours to years. Application of method was suggested by Meyer and Sandwell (2012). It has already been widely applied for geophysical studies, e.g., earthquakes, volcanoes, landslides, and in subsidence and structural stability analyzes. Different surface reflectivity properties will provide additional information, e.g., about the roughness and possibly the composition of most external layers.

In addition to the elevation models and surface displacements, SAR shall provide a precise geodetic network that will be used for the monitoring of Venusian rotation. The network will be established through the so-called persistent scatterers, i.e., selected objects on the ground (e.g., stable large rocks) providing consistent and stable radar reflections back to the satellite. This technique uses a multi-image approach in which one searches the stack of images for stably reflecting objects, i.e., the aforementioned persistent scatterers. The scatterers may be the size of a pixel or sub-pixel that shall be present in every image in the stack. The stable geodetic network on the Venusian surface will allow a transformation between the surface-fixed reference frame and the inertial reference frame defined by a satellite orbit.

A geodetic network based on persistent scatterers will allow achieving an unprecedented accuracy of precession, nutation, and length-of-day parameters, as well as the polar wobbling of Venus. The parameters are crucial in investigating the moment of inertia, size, shape of the Venusian core, and even the possible precession of the core. However, this requires separation of the different perturbations imposed on the length-of-day parameter and pole coordinates, namely the contribution from excitation of the polar motion (with a major contribution from the atmospheric angular momentum) and the surface mass redistributions (which can be identified by variations in the low-degree gravity field).

Moreover, the analysis of displacement via the ground geodetic network will provide information on the tidal forces deforming the solid crust. Thus, both the tide-induced surface displacements and the tide-induced gravity field changes can be recovered (the latter by using the observations of satellite perturbations and accelerometer data).

3.1.2 Penetrating Radar

We have selected a 15 m resolution penetrating radar with the deep ranging capability of 1000 m. The radar will be supported by two booms of 10 m length each, using the carrier frequency 20 Mhz and 85 μs pulses with a repetition frequency of 700 Hz, similar to the one onboard SHARAD mission on Mars (Seu et al., 2004).

Penetrating Radar shall provide two kinds of observations, on one hand the absolute height measurements (through the altimetry observations) and on the other hand, imaging of underground sub-surface layers. Ground penetrating radar uses high-frequency radio waves that are transmitted into the ground. When the wave hits a boundary with different dielectric constants, the receiving antenna records variations in the reflected return signal. The principles involved are similar to reflection seismology, except that electromagnetic energy is used instead of acoustic energy, and reflections appear at boundaries with different dielectric constants instead of acoustic impedances. The depth range of the penetrating radar is, however, strongly limited by the electrical conductivity of the ground, the transmitted center frequency, the radiated power and the water content underground. In the Earth sciences this method is used to study, e.g., bedrock, soils, groundwater, and ice. Using a penetrating radar can thus provide substantial information about underground tectonics and volcanic processes on Venus.

3.1.3 Gravity System

The gravity system consists of a GOCE-like gradiometer that measures the second derivatives of the gravity field potential, and an accelerometer which is sensitive to low-frequency perturbing accelerations acting on a satellite orbit. The gradiometer comprises 3-axis pairs of accelerometers sensitive to high-frequency gravity variations. It will detect the high-degree gravity field model and gravity field changes associated with mass redistributions, underground density changes, and large-scale tectonic and volcanic activities. The detail gravity field model with conjunction of topography model allows for derivation of crustal thickness, temporal variations in the crust, and various mantle-crust interactions. The low-degree gravity field changes will be determined using the observed orbit perturbations supported by an accelerometer (in order to recover the perturbing forces for the periods without direct visibility and connection to the Earth). The low-degree gravity field perturbations, including the *geocenter* coordinates of Venus (center of mass), oblateness parameter C_{20}, parameters describing the excitation of polar motion induced by mass redistributions (C_{21}, S_{21}), parameters describing tidal longitudinal displacements (C_{22}, S_{22}), and a parameter describing differences between hemispheres induced by seasonal effects (C_{30}), will provide the information on large-scale surface changes and, e.g., the liquidity of the core.

3.1.4 Infrared Camera

In addition to geodetic instruments an infrared camera will be used to determine the temperature at the surface, which gives a distinct indication of atmospheric, tectonic, and volcanic activities.

3.2 Orbit for InSAR data acquisition

For the satellite, a circular orbit at 50° inclination with respect to the Venusian equatorial plane is selected. This configuration will allow dense mapping of the Venusian surface, including the major volcanic and suspected tectonic activity, with maximum repeatability of SAR imagery and improved spatial resolution. Inclination of the orbital plane allows achieve the critical baseline for L-band InSAR measurements. In total about 67% of the surface can be investigated during the mission, excluding the polar and near-polar regions. The life-time of the mission is at least 5 years, thus the orbital altitude of 280 km has been chosen as a trade-off between the maximum sensitivity to gravity field recovery (for low orbits) and a minimum impact of atmospheric drag (for high orbits). The revolution period at an altitude of 280 km is 92.6 minutes and the groundtrack orbit shift is 10.1 km.

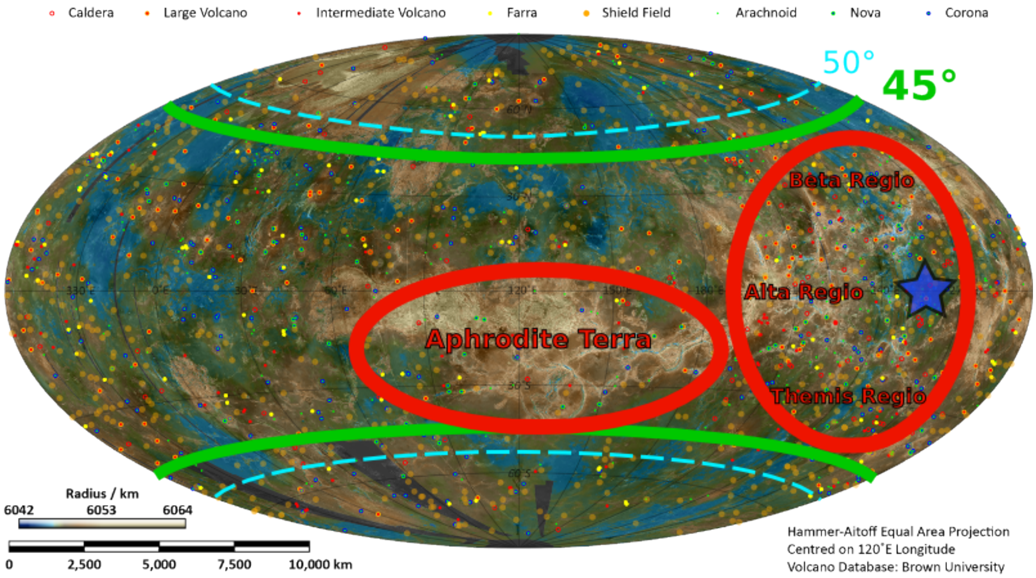

Fig. 3— *Location of interesting tectonic and volcanic areas. The blue star represent the landing site choose for LOVE landers.*

3.3 Orbital Transfer

The selected launch date is 4th December 2032. Optimization of the transfer orbit is made for identifying the launch windows that could be used. The spacecraft journey from Earth to Venus will last roughly 160 days. Meanwhile, correction maneuvers will be performed in order to arrive at the desired point on the B-plane of Venus. This will dictate the shape of the insertion hyperbola that is characterized by the closest approach and the inclination. An orbital inclination of 50° (the same as for the final orbit) and 300 km altitude for the closest approach (see the blue orbit in figure 4) is selected. At the closest approach a braking maneuver is performed in order to reduce the speed and to be captured by the planet's gravitational attraction, which forces the spacecraft to leave the hyperbolic orbit and to enter a high-eccentricity elliptical orbit. After 8 hours from the closest approach, the spacecraft will reach the apoapsis, where the lander will be released with a separation maneuver. LOVE will follow a slightly deflected orbit that shall take the lander directly into the densest part of the atmosphere without any further revolutions. LOVE should land 8 hours later the the orbiter separation and initiate the communication directly with the Earth while performing geophysical experiments on ground. The orbiter will then continue its path and begin the aerobraking (purple line in figure 4). Small brakes will be performed at apoapsis in order to decrease the pericenter if the initial drag is insufficient for initialising aerobraking. Whenever the orbiter passes through the atmosphere the speed is reduced and the apoapsis is lowered. After 200–300 revolutions, which would take from 3 to 9 months, the spacecraft will be sufficiently slow and the orbit will be almost circular. Subsequently, correction maneuvers will be performed to fix the altitude and eccentricity and finally become operative in the designed science orbit (yellow orbit in figure 4).

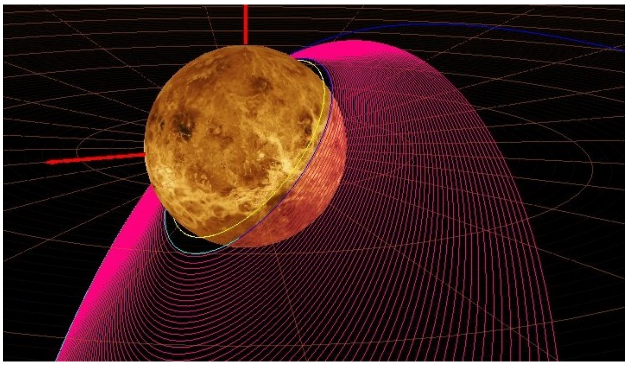

Fig. 4— *Venus approach orbit: the arriving hyperbola (blue) the aerobraking (purple) and the final scientific orbit (yellow).*

3.4 Lander Payload

The lander system LOVE 1 and LOVE 2 links in-situ investigations of the upper surface to orbit measurements. All active measurement systems have been adopted from previous space missions. Only the reflector design has not been tested. While LOVE 1 carries the full payload, LOVE 2 only carries the radar reflector and the seismometer allowing seismic networking.

3.4.1 Seismic Network

The main objective of the seismic network is to constrain seismic properties and structures of the upper layer. Along with the permittivity probe it is capable to give fine constraints on the surface rock properties and composition. To distinguish between seismic signal/noise and atmospheric noise precise pressure and wind speed measurements are essential. It has been Lognonne and Mosser (1993) suggested that a strong seismic background noise might exist due to the strong seismic energy coupling of the Venus atmosphere and interior. The possibility of detecting a seismic event in a two hour measurement on Venus' surface is likely very small. Adopting the same seismic activity than on Earth there is a 70 % change of detecting a Venus quake in 24 h (Lorenz, 2012). However, recorded seismic activity would be major finding.

3.4.2 Permittivity Probe

The permittivity probe defines further parameters of the upper surface. Together with the camera and seismic parameters of the seismic network experiment it constrains the composition of the ground. In addition the experiment is closely connected to the penetrating radar as it sets in-situ calibration.

3.4.3 Environmental Monitoring System

The monitoring system measures temperature, pressure, wind speed, and sound during the descent and active operation on the surface. It is required to correct the detected seismometer signal and also referring to the permittivity measurements.

3.4.4 Multispectral Imager and Panorama Camera

Multispectral analysis is used to define rock composition. The Panorama Camera will provide an overview of the surrounding. Such images are highly priced for public outreach.

3.4.5 Radar Reflector

The radar reflector identifies the landing site from the lander. It can be detected by the SAR at high resolution. With this, both lander positions and baseline between both stations can be defined. The baseline is required to derive wave velocities from the seismic signal. Two reflector constructions are suggested: An opening umbrella construction of high radar reflecting material or an iron hair star constellation, connected at the parachute. Both options need deliberative investigation and testing on Earth.

4 Entry, Descent and Landing of the LOVE Lander

The lander module will be released shortly after arrival at Venus when the Earth configuration is such that the selected landing site hemisphere is facing towards the Earth. At the apoapsis of initial orbit, the launcher decelerates into an entry-trajectory that intersects Venus. After the separation of spacecraft and lander, the spacecraft accelerates again and begins aerobraking. The landing module descends through the Venusian atmosphere at a path angle of -25° which minimizes the heat load. The entry probe enters the Venusian atmosphere with an initial velocity of 12 km/s. After 57 s the heat shield is ejected. In this phase of the descent, the stability of the spacecraft is vital for a successful landing. The LOVE lander uses spin vanes to increase the rotational speed. This ensures, that the landers land in an upright position. After 65 s, the two landers separate. The parachute of LOVE 1 opens 5s after separation. From this moment on the environmental parameters including temperature, pressure and altitude are measured by LOVE 1 and additional pictures are taken with the camera during the remaining descent. Opening of the parachute of LOVE 2 is delayed by 10 s from LOVE 1. Due to their different ballistic coefficients and an appropriate design of the parachutes, the intended local separation of the two landers is achieved. The parachutes are jettisoned 30 min after the atmospheric entry. Both landers reach the Venusian surface 60 min after their release from the spacecraft with an velocity of 40 m/s.

5 Orbiter design

The main features of the orbiter are a 3 x 2 m phased array SAR antenna attached to the body, 2 m diameter dish antenna for communication and steerable solar panels. The orbiter's dry mass is 1681 kg and the dimensions of the main cuboid structure are 2m×2m×5m. A 3D-CAD model of the whole spacecraft is illustrated in figure 5. Internal parts of the payload as well as the most voluminous parts of the orbiter bus are arranged in the graphical representation.

5.1 Mass Budget

Table 1 summarises the mass budget VISAGE. The estimated mass is around 4.1 tonnes including a 20% margin.

5.2 Power Subsystem

The electrical power subsystem consists of three parts: solar arrays, batteries and Power Conditioning and Distribution Unit (PCDU). The two symmetric solar arrays, each counting about 5 m^2, are based on Spectrolab 28.3% Ultra Triple Junction (UTJ) $GaInP_2/GaAs/Ge$ (Spectrolab, 2010). The solar arrays have previously been applied in several interplanetary missions to Mars, Jupiter and asteroids. Maximum available power near Earth is 1,371 W/m^2, while at Venus it is 2,800 W/m^2. The peak power usage of the satellite, when all subsystems are active (excluding propulsion/deployment subsystems), amounts to 2240 W. The EPS is to supply the necessary amount of power at all times. However, taking the average duty cycles of the subsystems into account, the mean power consumption per orbit is significantly lower at an average of 473 W per orbit. During eclipse or when the power demand exceeds the capacity of the solar arrays, electrical power is supplied by six 24 Ah ABSL rechargeable lithium-ion batteries that are charged by the solar-generated power. Total capacity of the batteries will be 144 Ah. The control and distribution of power is handled by a medium power Power Conditioning and Distribution Unit (PCDU). The PCDU

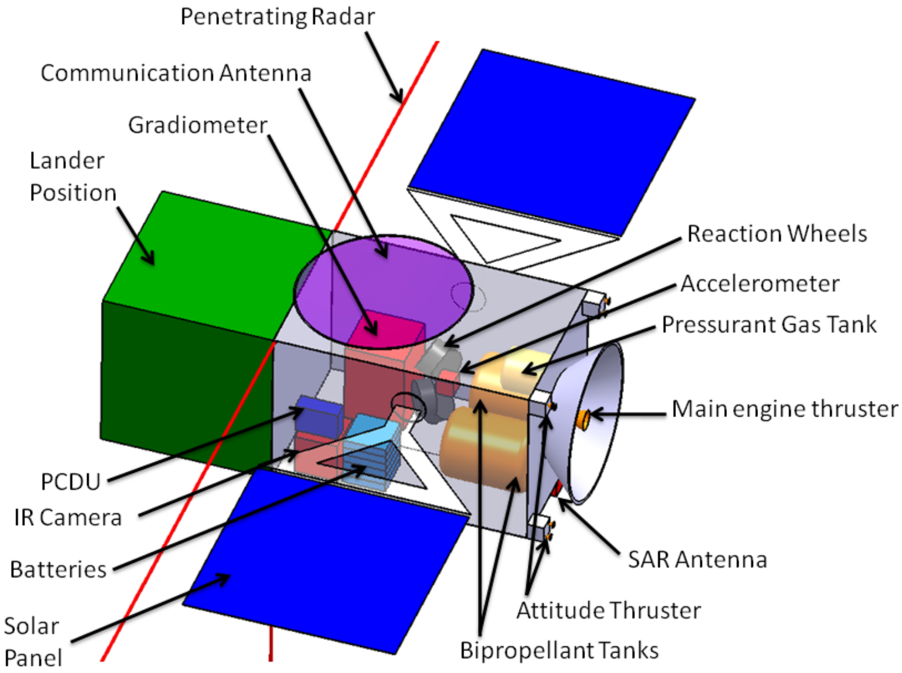

Fig. 5— *3D model of VELOCITÉ orbiter VISAGE.*

Tab. 1— *Mass Budget of the VELOCITÉ spacecraft*

Subsystem	Nominal Mass (kg)	Margin (%)	Mass with Margin (kg)
SAR (Payload)	300	20	360
Gradiometer (Payload)	180	10	198
Ground-penetrating radar (Payload)	20	10	22
IR Camera (Payload)	20	10	22
Structure (20% of dry mass)	228.2	20	273.8
Mechanisms	35	20	42
TT&C	60	20	72
ACS	90	15	103,5
OBDH/PDH	20	10	22
EPS	60	10	66
Thermal	75	20	90
Propulsion	200	10	220
Lander	323	20	387.6
Harness (5%)	70	0	70
Total (dry)	1,681.2		
Margin			1,948.9
Total with extra Margin (15%)			2,241.2
Propellant	1,600	5	1,680
ACS Propellant	100	100	200
Launch Mass			**4,121.2**

manages the batteries and the MPPT of the solar panels. The PCDU provides a regulated bus voltage of 28 V.

5.3 Thermal Design

Careful thermal design is required this mission. The thermal requirements are driven by worst-case cold conditions when in eclipse and the worst-case hot conditions during orbit, whilst also taking into account the fact that the solar flux would increase by 1,335 W/m^2 from Earth to Venus. Due to expected high surface temperatures, together with an intense ultraviolet environment, a thermal design was estimated. For the spacecrafts external coating a Kapton Multi-Layer Insulation (MLI) was chosen. It covers most of the spacecraft, while optical reflectors (OSRs) are used as well as a sulphuric anodisation on the launch-vehicle adapter (LVA) rings external surface (ESA, 2005a). Additional Radiators will ensure dissipation of the heat during hot conditions. Heaters are also required during early cruise and during eclipse phases.

5.4 AOCS

The attitude and orbit control system (AOCS) of the orbiter is used for orbit correction and determination and for tilting the satellite in order to ensure desired coverage of the ground with the InSAR antenna. It consists of six Sun and six ground sensors that are used for coarse determination of the attitude on the order of 5 to 10° (Sechi et al., 2006). Two star trackers are used for precise attitude determination with an accuracy of 1” (Jorgensen et al., 2003). Active attitude control is realised by four reaction wheels with a maximum rotational speed of 6000 rpm. Each reaction wheel can conserve 12 Nms(Sivac and Schirmann, 2004). RCS engines are used to desaturate the reaction wheels and can serve as extra active attitude control systems.

5.5 Propulsion

A propulsion system with helium-pressurised bi-propellant is used for orbit insertion and attitude and orbit manouvers. It consists of a 400 N main engine for orbit insertion and 8 RCS thrusters with a power of 10 N each. The RCS engines are positioned at the edges of the rear of the spacecraft in pairs for redundancy. The combination of MMH as fuel and MON-3 as an oxidiser results in a specific impulse of 317 s. The fuel is stored in separate tanks at a tank pressure of 20 bar while the helium tank is at a tank pressure of 276 bars at the beginning of the the mission. The same concept has been successfully used on Venus Express (ESA, 2005a). The propellant load is set to 1680 kg due to the high ΔV requirement. Most of it will be used during the aerobraking manouver for Venus orbit insertion. The residual fuel is used for orbit correction and deorbiting at the end of the mission.

5.6 Data Handling

The spacecrafts data-handling architecture is centered on two Control and Data management Units (CDMUs), which constitute the Data Management System (DMS), a Remote Terminal Unit (RTU) and a Solid-State Mass Memory (SSMM) (ESA, 2005a). The main tasks of the CDMUs are:
- Decoding of the telecommands from the ground and ensuring their execution, onboard housekeeping and scientific data telemetry formatting for transmission.
- Execution of DMS software for overall data management.
- Execution of the attitude and orbit control system software.

The RTU is the interface between the DMS system and the payload and platform units. Instructions to these units are passed over one of the two redundant CAN busses. In the return direction, telemetry from the payload or platform unit is gathered by the RTU for return to the DMS. The SSMM is a 1 TB mass memory storage for housekeeping and science data collected by the DMS system. However, the payload generates large volumes of data at high speed and, consequently, has its own dedicated direct link to the SSMM.

5.7 Telemetry, Tracking and Command (TT&C)

The TT&C subsystem is dedicated to the retrieval of telecommands and the transmittance of telemetry. The telemetry data consists of the housekeeping data of the subsystem including information on voltages, currents, pressures, temperature, operational states etc. Next to the housekeeping data, the scientific data acquired by the payload of the spacecraft is downlinked to the ground stations. The data transmission/reception is performed by a parabolic antenna with a LNA. The parabolic antenna with a diameter of 2 m consumes 50 W during data transmission/reception. The frequency band of the data transfer is the Ka-band and, assuming a range of 1.7 AU between Earth and Venus, enables a data transmission rate of 500 MB per day and a nominal data rate of 400 kbps.

6 Lander design

The LOVE lander is a challenging endeavour that will yield vital information on the structure and tectonics of Venus. However, the harsh environment on the surface requires an efficient protection against the high pressures and temperatures. This section is dedicated to the design of the LOVE landers.

6.1 Protection of the lander

Figure 6 shows the set-up of the LOVE landers. Due to significant heating (during the descent in the Venusian atmosphere (up to 60 MW/m^2) the two landers have to be packed in a landing module equiped with a heat shield. The frontal cone of the heat shield is shaped in a way that allows at the same time an aerodynamically stable descent and a sufficiant speed reduction(Colin, 1980), hence, no active control during the descent is required. The heat shield will be made of carbon phenolic which withstands heat loads up to 300 MW/m^2 (Van den Berg and Falkner, 2007).

The outer structure of the two landers will be a combination of titanium alloy and a material with low thermal conductivity such as aerogels. Additional thermal protection of the electonics inside the landers will be achieved by using a phase changing material such as lithium nitrate trihydrate. After the separation, the landers will be descellerated by the opening of parachutes. A promising candidate for the parachute material is Zylon which has high tensile stress and survives temperatures up to 600 °C (Cressier and Mantooth, 2012).

At the moment of landing the probes will still have a speed of 40 m/s. The shock will be absorbed by a honeycomb structure, the circular structure at the bottom of the main lander is hollow and will fill up with venusian atmosphere, this will provide extra shock absorbtion.

6.2 Mass budget

The mass budget of the LOVE landers is 387.6 kg. The most massive components are the thermal shielding and the structure. The landers hold a payload mass of 12 kg in total.

6.3 Separation subsystem

The separation subsystem design has been derived from the Cassini-Huygens mission (Herlach et al., 1995). The separation mechanism is electrically induced. When activated, pyroactuators release springs that drive the lander away from the spacecraft. A

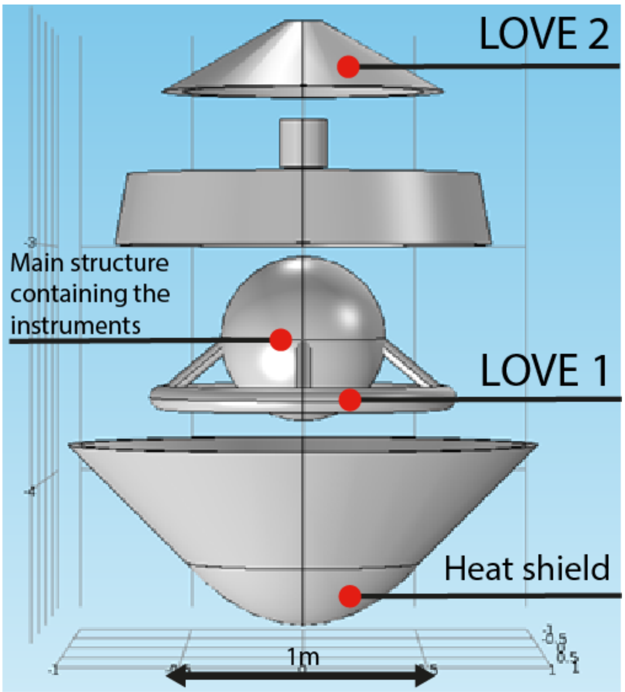

Fig. 6— *Main structure of the landing module showing the heat shield and the two landers*

guiding trail determines the path of the ejection and induces a spin on the lander. The guiding trail ensures a well defined and stable trajectory of the lander with a relative velocity of 0.27 to 0.375 m/s and a spin rate of 5-10 rpm. It should be noted, that the rotation of the lander induces a spin on the spacecraft that has to be accounted for. The total weight of the separation subsystem ranges between 30 to 40 kg.

7 Launcher

The VELOCITÉ spacecraft can be launched with an Arianespace Ariane 5 ECA launcher. This version of the Ariane 5 has a liftoff mass of 780 tonnes and is able to carry up to 9.6 tonnes of payload into GTO, which is approximately 4.5 tons for deep space. The VELOCITÉ mission has a total payload mass of 4.3 tonnes, which leaves a margin of 200 kg. The launch is expected to take place in December 2032 from the Guiana Space Centre, Kourou, French Guiana. In case of an increasing spacecraft mass, the Ariane 5 ME is a possible alternative. This type of the Ariane 5 is actually under development and will be able to carry up to 11.5 tonnes of payload into GTO. First qualification flight is estimated for 2018.

8 Ground Segment

The ground segment of VELOCITÉ consists of a ground station (GS), Mission Operations Centre (MOC) and a Science Operations Centre (SOC). It provides capabilities for monitoring and controlling the spacecraft and payload during all phases of the mission, as well as for the reception, archiving and distribution of the data gathered by the payload instruments. The telemetry, telecommand and tracking operations are established with ESTRACK's 35m ground stations at New Norcia (Deep Space Antenna – DSA 1), Cebreros (DSA 2) and Malargüe (DSA 3), which form the European Deep Space Network (ESA and ESOC, 2012). The 35m stations provide the improved range, radio technology and data rates required by current and next-generation exploratory missions such as Mars Express, Venus Express, Rosetta and BepiColombo. All three stations are able to receive X-Band signals. DSA 2 and DSA 3 are also capable of communicating in Ka-Band, which will be used for the VELOCITÉ mission. The Mission Operations Centre will be located at ESOC in Darmstadt (Germany). The Science Operations Centre (SOC) supports the scientific mission planning and experiment command request preparation for consolidated onward submittal to the Missions Operations Centre. The SOC will process data and build the data archive for the scientific community. The exisiting ESA/ESOC ground segment elements and facilities available through other space missions like Rosetta or Venus Express (ESA, 2005b) can be reused for VELOCITÉ, as well.

9 Development and Cost

The TRL have been estimated for the subsystems and components of both orbiter and lander together with a risk assessment with factors of probability and severity.

9.1 Risk

The TLR is low for the components, which are different from those that were previously used on other space missions. The InSAR, ground penetrating radar and gradiometer on the orbiter, all with TRL 6, need more development effort in terms of man-hours and higher cost. The current design of the these prototypes has not been flight-qualified for Venus enviromnent. For the lander, the components that need critical attention are the measurement instruments, especially the separation mechanism for the second lander.

The orbiter components such as InSAR and Lander Release Mechanism need more development effort. This implies also high costs. Importantly, subsystems have low risk, because are a heritage of successful interplanetary missions. A special care must be taken in development of the parachute as it may jeopardize the lander operations. New design of the parachute and also heat shield for the prospective lander shall be well-tested and qualified (increasing the TRL) before implementation.

9.2 Total Cost

The estimated development costs are based on research and development (R&D), production, insurance, testing and facilities with the envisaged budget for mass and power. Furthermore, the cost estimates include launch costs and direct operating costs (DOC) (Craig Peterson and Tibor Balint, 2008). The total mission cost is estimated to be on the order of €1,6 Billion.

9.3 Descoping Options

VELOCITÉ is a complex mission that holds several trade-offs. Reducing this complexity would involve impacts on scientific measurements and a loss of some functions. The main emphasis on descoping the project would rely on relief on cost and mission realizations. Table 6.4.1 shows selected actions and their impacts. Removing the lander would imply a significant loss in scientific measurements, but would relieve some risk and development efforts and, therefore, save approximately €350 million. The removal of gradiometer and/or IR-Camera would potentially reduce costs of approximatey €100,000 and €10,000, respectively. In terms of science, descoping the lander would lead to a loss of scientific data that are important for the studies of the Venus' inner structure (core, mantle).

10 Conclusion

VELOCITE is designed to enhance our understanding of geological processes on Venus' surface and interior. The main selected technology InSAR in combination with pricise gravity field determination and the complementary lander system LOVE 1 and LOVE 2 provides progressive observations enhancing constrains of the upper and interior structure of Venus. Some subsystems (e.g., lander heat shield, lander parts separation) still require development to raise the technology readiness to an adequate level. However, supporting design analyses give confidence that the mission can be conducted within the identified cost and schedule constraints. A European Venus mission would greatly increase the public awareness on space research and give a unique opportunity for outreach and education.

Acknowledgement

TEAM BLUE wish to thank our tutors Jaan Praks and Ruth Ziethe for the accistence throughout the development process of the VELOCITE-Project. Special thanks to Peter Falkner, Markus Hallmann, Richard Ghail and all the other roving tutures, lectures and reviewers for their valuable comments and passion driven help.

References

Aleksandrov Y. N. et al. A planet rediscovered: results of Venus radar imaging from the Venera 15 and Venera 16 spacecraft. *Astrophysics and Space Physics Reviews*, 6:61–101, **1988**.

Colin L. The Pioneer Venus Program. *Journal of Geophysical Research*, 85(A13):7575, **1980**.

Craig Peterson J. C. and Tibor Balint J. B. H. Rapid Cost Assessment of Space Mission Concepts through Application of Complexity-Based Cost Indices. In *IEEE Aerospace Conference*, pages 1–18, California Institue of Technologie, **2008**.

Cressier J. D. and Mantooth H. A. *Extreme Environment Electronics*. CRC Press, **2012**.

ESA . Venus Express: The Spacecraft. *esa bulletin*, 124(11):16–22, **2005a**.

ESA . Venus Express Ground Segment and Mission Operations. *esa bulletin*, 124(11):34–37, **2005b**.

ESA and ESOC . ESA's Deep-Space Tracking Network. In *Estrack*, Darmstadt, **2012**.

Ghail R. C. et al. EnVision: taking the pulse of our twin planet. *ExpAstron*, pages 337–363, **2012**.

Greeley R. et al. Aeolian features on Venus: Preliminary Magellan results. *Journal of Geophysical Research*, 97(E8):13319, **1992**.

Hansen V. Ribbon Terrain Formation, Southwestern Fortuna Tessera, Venus: Implications for Lithosphere Evolution. *Icarus*, 132(2):321–343, **April 1998**.

Helbert J., Muller N., Maturilli A., Piccioni G. and Drossart P. The Long and Hot Way from Brightness Anomalies to Compositional Information – High Temperature Laboratory Spectroscopy for VIRTIS on Venus Express. *40th Lunar and Planetary Science Conference*, **2009**.

Herlach U. R., Tatalis P., Schmid B. and Mussett D. Huygens Separation Mechanisms. *Sixth European Space Mechanisms and Tribology Symposium*, **1995**.

Jorgensen J. L., Denver T., Betto M. and Jorgensen P. S. MicroASC a Miniature Star Tracker, Small Satellites for Earth Observations. In *Fourth International Symposium of the IAA, Berlin*, **2003**.

Lognonne P. and Mosser B. Planetary seismology. *Surveys in Geophysics*, 14(3):239–302, **May 1993**.

Lorenz R. D. Planetary seismology—Expectations for lander and wind noise with application to Venus. *Planetary and Space Science*, 62(1):86–96, **March 2012**.

Meyer F. J. and Sandwell D. T. SAR interferometry at Venus for topography and change detection. *Planetary and Space Science*, 73(1):130–144, **December 2012**.

Sechi G., André , Andreis D. and Saponara M. Magnetic Attitude Control of the Goce Satellite. *Guidance, Navigation and Control Systems*, 606:37, **January 2006**.

Seu R. et al. SHARAD: The MRO 2005 shallow radar. *Planetary and Space Science*, 52(1-3):157–166, **2004**.

Showstack R. Exploring Venus as a Terrestrial Planet. *Eos, Transactions American Geophysical Union*, 89(43):423–424, **October 2008**.

Sivac P. and Schirmann T. The venus express spacecraft system design. *Venus Express*, **2004**.

Solomon S. C. The Geophysics of Venus. *Physics Today*, 46(7):48, **January 1993**.

Spectrolab . 28.3% Ultra Triple Junction (UTJ) Solar Cells. *AS9100 Registered*, **2010**.

Turcotte D. L. An episodic hypothesis for Venusian tectonics. *Journal of Geophysical Research*, 98(E9):17061, **1993**.

Van den Berg M. and Falkner P. Venus Entry Probe Study Overview. *Technology Reference Study*, 3:1–64, **2007**.

Woo R., Armstrong J. W. and Ishimaru A. Radio occultation measurements of turbulence in the Venus atmosphere by Pioneer Venus. *Journal of Geophysical Research*, 85(A13):8031, **1980**.

Yung Y. L. et al. Evidence for carbonyl sulfide (OCS) conversion to CO in the lower atmosphere of Venus. *Journal of Geophysical Research*, 114:E00B34, **March 2009**.