Acknowledgments

Abstract

Since the 1970s several spacecraft have landed on Venus and returned valuable scientific data. However, the scientific return of these missions was severely limited by imposed mass and power requirements; in addition, the harsh environment restricted materials selection, subsystem design, and the implementation of communication systems. The elementary analyses allowed by these constraints have left Venus' planetary characteristics relatively unknown despite the breadth of knowledge to be gained from Earth's sister planet.

To increase the scientific return of a mission to Venus, the members of the NASA Academy at Goddard Space Flight Center propose a mission for Venus Sample Targeting, Attainment, and Return (V-STAR). Based on current technologies developed for recent exploration missions, the V-STAR architecture will successfully land a spacecraft on the surface of Venus and return at least three uncontaminated samples of the planet - including atmosphere, surface, and subsurface - to Earth for analysis. Beyond planned scientific tests, returned samples will grant a large degree of adaptability to the study of Venus; tests can be carried out in response to unanticipated findings with flexibility unmatched by Venus-bound instruments. Coupled with *in-situ* measurements for context, these samples will dramatically strengthen human understanding of Venus.

The results of a V-STAR landing will open whole new realms in scientific exploration. Significant amongst the potential returns will be insight, through comparative planetology, into the mechanisms affecting global warming. Knowledge of the climate change for which Venus is notable will supplement current climate models of Earth. Beyond the relationships to planet Earth, Venus's age, volcanic history, and origins can be examined in the hope of answering the fundamental question of whether or not life has ever existed on Earth's sister. These, among others, will be the rewards of V-STAR.

The challenges inherent in landing a spacecraft on Venus and returning an uncontaminated sample to Earth will be great, as such a mission has never been attempted. However, the rewards will far outweigh the cost. By understanding Earth's neighbor, human beings will better understand their own planet.

Table of Contents

List of Figures

List of Tables

<u>List of Acronyms</u>

Basic Environmental Science Instrument Package	BESIP
Cape Canaveral Air Force Station	CCAFS
Change in velocity	ΔV
Command and Data Handling subsystem	CDH
Committee of Space Research	COSPAR
Common Core Booster	CCB
Central Processing Unit	CPU
Expendable Launch Vehicle	ELV
Fabry-Perot Etalon	FPE
Infrared Radiometer	IRR
Joule-Thomson	JT
Lander Laboratory	LL
Low Earth Orbit	LEO
Low Venus Orbit	LVO
Monomethylhydrazine	MMH
Multilayer insulation	MLI
NASA Ground Network	GN Stations
NASA's Deep Space Network	DSN
Orbiter Laboratory	OL
Position Adjustable Workbench	PAW
Radio frequency	RF
Remote Sample Collection Mechanism	RSCM
Solar Wind Plasma in the Vicinity of Venus Experiment	SWP
Surface Radar Mapper	SRM
Telemetry and Command Subsystems	T & C
Ultraviolet Spectrometer	UVS
United Launch Alliance	ULA
Unsymmetrical Dimethylhydrazine	UDMH
UV/Visible Camera	UVVC
Venus Atmosphere Samples Collector	VASC
Venus Bedrock Penetrometer	VBP
Venus Combined Infrared Spectrometer	VCIS
Venus Electric Field Detector	VED
Venus Ground Sampling Drill	VGSD
Venus Magnetospheric Magnetometer	VMM
V-STAR	Venus Sample Targeting, Attainment and Return

1   Mission Overview

The planet Venus retains many unanswered questions, as it is, thus far, one of the solar system's least studied bodies. Venus is often referred to as 'Earth's sister planet', due to its similarity in size, formation, and history, and its proximity to the Earth. Due to Venusian atmospheric effects, it remained inaccessible to scientific observation until the space age began. Venus is no exception to this challenge. Planetary exploration has become a primary challenge in the space program, due to the large science return from such missions, and interest in the future of humans in space. Science from a Venus exploration mission will extend knowledge of planetary formation, history, and metamorphism since the beginning of the solar system on a body that has been isolated from exploration due to its unusually harsh environment.

The 2007 NASA Academy at the Goddard Space Flight Center presents a conceptual design for a Venus Sample Return Mission. This mission consists of sending a spacecraft to Venus to acquire and return to Earth a set of surface, subsurface and atmospheric samples, which will require expert engineering and innovative techniques. The mission concept utilizes an Orbiter that releases a Lander onto the surface of Venus. During the approach, the pre-defined landing site will be identified by the Orbiter. Throughout the ascent and surface operations, the Lander will collect samples of atmosphere, surface and subsurface material. These samples will be loaded into a return capsule and inserted into an ascent vehicle, which will be followed by a launch into a low Venus orbit. The capsule will then rendezvous with the Orbiter and return to Earth orbit, where it can be brought safely to Earth. In order to minimize costs and to facilitate early scientific results, the time spent on the Venusian surface will limit the mission's strategy to both departure and return within one Venus opportunity.

2   Environment and Surface Properties of Venus

Venus' basic orbital statistics are exhibited in Table 1. It is a terrestrial-like planet ("telluric"), often called Earth's sibling since they are similar in size, mass and composition.

Table 1: Venus' Physical Properties			
Property	**Value**	**Property**	**Value**
Mean radius	6051.84 (km)	Inclination of equator to orbit	177.4°
Mass	4.8685×10^{24} (kg)	Inclination of orbit to ecliptic	3.39°
Mean density	5.243 (g cm^{-3})	Temperature at modal radius	740 (K)
Gravity	8.870 (m s^{-2})	Pressure at modal radius	95.6 (bars)
Eccentricity of orbit	0.0068	Mean visible cloud temperature	230 ± 10 (K)

The temperature, pressure and density are all altitude dependant, as shown in Figure 1, but generally Venus is characterized by extreme temperatures, pressures and density values and so contains a 'hot-house' atmosphere. These parameters vary along the thick layers of atmospheric cloud and surface properties as displayed in Table 2.
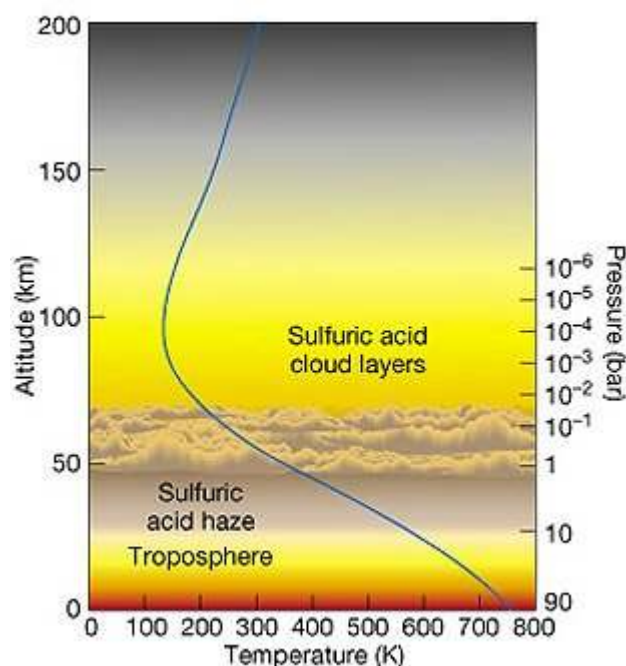
Figure 1: A simplified map of the Venus atmosphere shows altitude dependency of temperature and pressure.

Table 2: Temperature, Pressure, and Density in Venus' Atmosphere

Altitude (km)	Temperature (K)	Pressure (Pa)	Density (kg m^{-3})
0	735.3	9,210,000	64.79
10	658.2	4,739,000	37.72
20	580.7	2,252,000	20.39
30	496.9	958,100	10.15
40	417.6	350,100	4.404
50	350.5	106,600	1.594
60	262.8	23,570	0.469
70	229.8	3,690	8.39×10^{-2}
80	197.1	447.6	1.19×10^{-2}
90	169.4	37.36	1.15×10^{-3}
100	175.4	2.660	7.89×10^{-5}

Venus' topographic environment is composed of mountains, flatlands and valleys, similar to the rugged terrain as found on Earth. Its interior consists of an iron core with a radius of approximately 3000 km, with a rocky molten mantle that makes up most of the planet. The surface has relatively few craters, suggesting that older craters have been erased by volcanic activity (ancient or recent), crustal uplift, or other geologic activity. Much of the surface of Venus is covered by lava flows. Venus has several large shield volcanoes similar to those to Hawaii. Recent findings indicate that Venus is volcanically active in a few spots, but for the most part, it has been geologically inactive for the past few hundred million years. The atmosphere of Venus is mainly made up of carbon dioxide; this heavy atmosphere is due to a runaway greenhouse effect that occurred early in Venus' history. This atmosphere contains sulfuric acid, with compounds of chlorine and fluorine. Venus is generally characterized by extreme temperatures, pressures and densities. These properties are currently unmatched by any other known surface found within the solar system.

2.1   Foreseen Challenges - Venus Environment

In addition to the usual issues, complications and configuration problems encountered by any sample return mission, Venus' local environment presents further difficulties. The 'hot-house' environment is currently unmatched by any other known surface found within the solar system. Therefore the composition of the Venusian atmosphere and surface features must be accounted for, in particular, in the selection of material and subsystem design that will impact on the mission analysis, thermal control and aerodynamics. The energy sources of the spacecraft must also be considered, as the Venus's clouds block out the majority of the incoming radiation and Venus experiences a large ellipse time, which would limit the conventional use of solar power.

The high level of radiation reflection also affects the design and implementation of any remote sensing instruments and the utilization of radio communication. The return to Earth of samples of the surface of Venus presents formidable challenges. Not only does Venus have a large gravitational field, comparable to that of Earth, but it also has a high surface temperature and pressure. The most challenging obstacle to overcome in a Venus surface mission is preparing for the planet's extremely hostile environmental conditions.

3   Past Missions to Venus

The first successful fly-by of Venus was achieved by the American spacecraft Mariner 2. Eventually the Soviet spacecraft Venera 4 entered the atmosphere of Venus transmitting data detailing the planet. This data included temperature, density and pressure measurements. The first successful landing on Venus was made by Venera 7 in 1970. This lander revealed surface temperatures between 457 and 474 degrees centigrade. Following these missions, the USA Orbiter called Pioneer Venus 1 was the first spacecraft to map the planet using radio science. Preceding this preliminary mapping, other missions including the recent ESA Venus Express spacecraft were sent to study Venus in more detail. A complete list of Venus missions is detailed in Appendix A.1.

4   Science Considerations

4.1   Science Justification for a Venus Sample Return Mission

The primary science goals of this mission are to determine the mineralogical, chemical, and isotopic structure of Venus's crust and subsequent atmosphere composition. In particular, characterizing the lower atmosphere will support the analysis of a surface sample. To many scientists, Venus acts as the closest analogue to Earth as it is similar in size and distance, however, its atmosphere it often described as the 'runway greenhouse effect'. Understanding the history and dynamics of Venus' atmosphere will shed considerable insight regarding the processes within and development of the terrestrial atmosphere, and the structural development of Earth. Using comparative planetology and the knowledge of Earth's own greenhouse situation, scientists will achieve a better understanding of the divergent evolution of each environment. The specific details of the Venus' atmosphere are not thoroughly understood. Although the planet itself rotates very slowly with a period of 242 days [1], the high cloud level within the upper atmosphere moves with a period of only four days - this is sixty times faster than the surface. From its early discovery in 1970s, the exact mechanism that supports this super-rotation is still unknown [2]. In addition to the atmospheric questions, a large number of other scientifically important questions remain. These include:

- **The Origins of Life** – What does our current understanding of the origins and early evolution of life tell us about the possibility of life on Venus and the rest of the solar system?

- **Dynamics of the Planet** – What causes the geological restructuring of the crust? Is Venus still geologically active/does it have any volcanic history? What is the origin and age verification of the planet?

- **Environment of the Planet** – Could life have existed on Venus in an earlier, pre-greenhouse phase? What was the environment before the runaway greenhouse effect? What is the post and current environment in Venus' clouds?

Through the analysis of the returned samples by using state-of-the-art techniques, these and other fundamental questions can be answered whereby an array of scientific investigation and evaluation can be performed. Due to the imposing mass, time and cost restrictions, this analysis can not otherwise be addressed through remote sensing or *in-situ* analysis. Therefore to successfully achieve these scientific aims, a Venus Sample Return mission has been designed, whereby the collection and retrieval of surface, subsurface and atmospheric samples has been addressed.

4.2   Science Requirements for the Venus Sample Return Mission

As a planetary exploration mission, the Venus Sample Targeting Attainment and Return (VSTAR) mission will support both *in-situ* and remote sensing measurements of Venus science. Remote sensing capabilities are the responsibility of the Orbiter, *in-situ* experiments will take place within the Lander spacecraft once it has landed on the surface.

The Orbiter Laboratory (OL) spacecraft, as a remote sensing laboratory, will carry several instruments to study the basic science of Venus. There are many objectives within this science mission, and therefore there are a lot of return data requirements. The first of these objectives is to study the ionosphere of Venus. Secondly, although there is little to no Venusian magnetic field, it is important to include magnetic field testing capabilities in the form of a magnetometer on the OL so that this can be studied further. A third requirement of the OL is to monitor the solar wind motion and particle composition as it passes Venus in the absence of a large magnetosphere such as that around the Earth. Similarly, another objective of the OL is to measure the interplanetary magnetic field direction and strength at Venus. In addition to these space science studies, planetary science studies are also within the scope of the OL (although planetary science is mainly covered by the lander). The OL is responsible for surface radar imagery of Venus as it flies over, as well as taking infrared radiometry measurements.

The Landing Laboratory (LL) has two main operational intervals. One is surface operations, the other is atmospheric operations. Upon landing on the surface, the LL begins its role as simple geologic and chemical laboratory. Since the main goal of VSTAR is to collect rock samples, the drill will be used to drill into the bedrock and extract a core. Secondly, a scooper arm will pick up surface rock samples. These samples will be returned to Earth for study. In addition, the LL contains instruments that will be used for *in-situ* studies for the duration of its time on the planet. These experiments include basic science, as in pressure (barometer), temperature (thermometer), and wind speed (anemometer) measurements at the surface. Also, a magnetometer will measure the magnetism of the ground. The LL will also deploy a penetrometer to measure the compressibility of the surface regolith. In addition, infrared and visible imagery will be used to capture the view from the surface of Venus. It is important to obtain images of the landing and sample collection sites for future contextual reasons. In addition, it is important to image the sky of Venus from beneath it, and also to see the storms that exist in the atmosphere.

The primary objective of VSTAR is to collect rock samples from the surface and subsurface of Venus. Venusian rocks have never been returned to Earth, and it is therefore a priority to attain the most geologically interesting and valuable samples as possible. A landing site has been chosen in the Aphrodite Tessera region, or more specifically, in the Ovda Regio area, the largest crustal plateau on Venus. These highlands have not been observed by previous landers (i.e. the Russian Venera

missions of the 1970's), but have been imaged at high resolution by remote sensing spacecraft. These regions are made up of the oldest crust existent on Venus – ancient lava flows that consist of low-lying flat areas and mountain chains that thrust upward by crustal uplift. Since this crust is comparatively ancient, it promises the best chance that the samples returned could hold traces of water-bearing minerals. One of these water-bearing minerals is the mineral tremolite, which only forms in the presence of water and can exist in extreme environments for long periods of time. This metamorphic mineral and others would suggest that at least one point in its history, there was water on the surface of Venus. The best chance to find such minerals would be in these older sections of crust, as they hold more history than do the younger lava fields in the lowlands.

Once the surface samples have been collected and contained and surface *in-situ* science has been completed, the ascent section of the Lander will continue to act as a science module for atmospheric samples. During ascent, temperature, pressure, and compositional data will be taken at twelve specific points in the atmosphere by the Venus Atmosphere Samples Collector (VASC). These twelve points will occur between 0 km and 110 km in altitude. These points are chosen to maximize the science return while the spacecraft is moving slow enough through the atmosphere to collect reasonable data. The points at which atmospheric samples will be collected are shown in Table 3.

Table 3: Showing the eleven proposed atmospheric sampling points, approximate temperature and pressure values, and descriptions of atmospheric changes. These sampling points are located at various points in the atmosphere to achieve a temperature, pressure, and compositional model of the Venusian atmosphere.

Sample	Altitude	Temperature	Pressure	Comments
0	0 km	758 K	93 bar	
1	10 km	675 K	52 bar	Near-surface - light haze/clear visibility
2	20 km	575 K	23.33 bar	
3	32 km	460 K	13.12 bar	
4	40 km	410 K	4.29 bar	Cloud layers - some sulfuric acid content
5	54 km	293 K	.79 bar	
6	58 km	260 K	.43 bar	
7	70 km	230 K	.23 bar	
8	80 km	190 K	.088 bar	
9	90 km	175 K	.058 bar	Upper atmosphere: tenuous/below freezing
10	100 km	140 K	.019 bar	
11	110 km	150 K	.027 bar	

The atmospheric sampling instrument will collect atmospheric material at each point and return it to Earth for study. With compositional information, in addition to temperature and pressure data, a model of the Venusian atmosphere will be possible. These results are of great interest due to previous studies of the atmosphere, which showed a surprising drop by a factor of ten of sulfur dioxide in the atmosphere between 1978 and 1986. A possible reason for this large decrease is the decreasing effects of volcanic activity. Measurements of the atmosphere content by VSTAR may introduce more

interesting atmospheric and/or volcanic behavior since that time. The combination of science collected remotely by the OL and on-site by the LL will contain valuable information in the form of remote sensing, *in-situ* tests, atmospheric science, and sample return.

4.3   Considerations of Planetary Protection Requirements

To fully protect the scientific value and analysis of the returned Venus samples, the integrity of the samples should be considered during all stages of containment, preservation and retrieval. In accordance with the Committee of Space Research (COSPAR), any proposed Venus Sample Return mission has been classified as a Category II [3].This classification includes all mission to a target body where there is significant interest relative to the process of chemical evolution and the origins of life, but where there is only a remote chance that contamination carried by the spacecraft could jeopardize future exploration. With respect to planetary protection, the following conclusions from COSPAR were made [4]:

- • No significant risk to forward contamination exists in landing on/ or returning from the surface of Venus owing to the high temperature of the surface, absence of water and the toxic chemical environment.

- • No significant forward-contamination risk exists regarding the exposure of spacecraft to the clouds in the atmosphere of Venus. The clouds consists of droplets of concentrated sulfuric acid, therefore any terrestrial organism would be immediately destroyed by chemical degradation.

- • No significant back-contamination risk exists concerning the return of atmospheric samples from the clouds in the atmosphere of Venus.

- • No significant risk exists concerning back contamination from Venus surface sample return. Although it is impossible to completely rule out the possibility that life might exist in such a hostile environment, this assumption is considered to be extremely low. It is also believed that any organism that had managed to adapt to such a chemical environment would not be able to survive in the Earth's environment. Therefore the risk to Earth posed by organisms indigenous to Venus is considered to be negligible.

Therefore under this classification, no major protection of the planet is necessary and therefore no requirement, other than documental, is imposed. Hence the only containment issues are generated from the stringent science requirements where no terrestrial organism, their remains or organic matter in general could inadvertently be incorporated into the sample material returned from Venus. Contamination with terrestrial material would compromise the integrity of the sample by adding confusing backwards contamination.

5   Launch from Earth

5.1   Trajectory Introduction

In order to carry out the mission, the spacecraft will be traveling from Earth to Venus and back by performing a number of orbital maneuvers, including two atmospheric entries: one to Venus and the other to Earth. As an overview, the Orbiter, with the Lander attached, will first be launched into a parking orbit around Earth, and then the dual configuration will travel from Earth to Venus. Once in orbit around Venus the Orbiter and Lander will separate where the Lander will descend onto the surface of Venus allowing for sample collection to pursue. During sample return, the Orbiter will rendezvous with the sample return capsule, and the combined spacecraft will return to Earth, landing in a desert region of Utah.

5.2   Launch Date

In order to have a Hohmann transfer from Earth to Venus, the transfer must take place when Venus and Earth are at a certain phase angle, given by the following equation,

$$\theta_{e,v} = \pi \left[1 - \left(\frac{1+R}{2} \right)^{3/2} \right]$$ Eq. 5.2.1

Where *R* = 1.38 as calculated before. R is defined as terminal radius ratio. Using this, the phase angle is found to be -54 degrees. Therefore, the spacecraft must be launched from Earth when Venus is 54 degrees behind Earth. The synodic period of Venus is 584 days, so Earth and Venus are 54 degrees apart every 584 days. The chosen launch date is October 18, 2013. This gives about 5 years for spacecraft design and testing before launch.

5.3   Earth Orbit

From launch, the spacecraft will be placed into a circular parking orbit at an altitude of 1500 km (low Earth orbit). By placing the spacecraft into a parking orbit first, it has a safe haven where the ground operations can communicate to the vehicle, check the status of all the major systems, and deploy necessary components, including solar panels. From this point in the interplanetary trajectory, the method for calculating the impulsive orbital maneuvers necessary to reach an orbit around Venus will be done by solving the two body celestial mechanics problem.

5.4   Earth to Venus Trajectory

In regards to the orbital maneuvers for this mission, the two parameters that can drive the design of the mission are the amount time that it takes for the trajectory to occur, and the amount of fuel consumption that the trajectory takes. Due to mass and cost considerations, it was decided that fuel consumption will be the design driver, and that the amount of time for the vehicle to reach Venus would only come as a secondary concern. Because energy efficiency via low fuel consumption is the primary design driver, the orbital maneuver chosen for the mission is a Hohmann transfer. The Hohmann transfer is known to be the most energy efficient two-impulsive maneuver for transferring between two coplanar circular orbits sharing a focus (Curtis 257). Additionally, a bi-elliptic transfer was explored, but a standard Hohmann transfer was chosen. The terminal radius ratio from Earth to Venus is given by,

$$R = \frac{r_1}{r_2} = \frac{1AU}{0.723AU} = 1.38$$

Eq. 5.4.1

Where r_1 is the radius from Earth to the Sun, and r_2 is the radius from Venus to the Sun. The bi-elliptic transfer is only fuel efficient if $R > 15.58$. (Prussing and Conway 108-111). Since $R = 1.38$ for this mission, it is more efficient to use a Hohmann transfer.

For this trajectory design, the orbits of both Earth and Venus are considered to be coplanar and circular, with the Sun as a common focus. The actual eccentricity, e, for the Earth's orbit around the Sun is 0.0167, and the eccentricity of Venus's orbit around the Sun is even less at 0.0068. This implies that the orbits of Earth and Venus around the Sun are indeed very close to circular, so this assumption is valid for our purposes. With these assumptions, the problem of getting from Earth-orbit to Venus-orbit is reduced to two impulsive changes in velocity (ΔVs.). The values of the required ΔVs can be calculated by using a specific energy balance. For an elliptical orbit the specific energy is a negative value and can be determined using Eq. 3.3.2.

$$\varepsilon = -\frac{\mu}{2a}$$

Eq. 5.4.2

Where μ is the standard gravitational parameter for the body which is as at the primary focus of the elliptical orbit, ε is the specific energy, and a is the semi-major axis of the elliptical orbit. The specific energy of the orbit is also defined using Eq. 3.3.4.

$$\varepsilon = \frac{v^2}{2} - \frac{\mu}{r}$$

Eq. 5.4.3

Where, v is the velocity at a given point of the trajectory, and, r is the radial position from the primary focus at a given point. By setting the specific energy equations equal for a circular orbit (where r = a), the velocity is found to be;

$$v = \sqrt{\frac{\mu}{r}}$$

Eq. 5.4.4

By using the above three equations, the required impulsive changes in velocity in order to carry out and interplanetary trajectory from Earth to Venus were calculated. The total mission timeline and required ΔVs for each stage of the mission is illustrated in Table 4.

Table 4: Mission Timeline and Required ΔVs

Mission Timeline		ΔV		
Earth Launch	October 18, 2013	ΔV_1	3252 m/s	Earth Departure
Venus Arrival	March 13, 2014	ΔV_2	3319 m/s	Venus Capture
Venus Launch	June 21, 2015	ΔV_3	3319 m/s	Venus Departure
Earth Arrival	November 14, 2015	ΔV_4	*3504 m/s*	*Earth Capture*

5.5 Transfer orbit Vehicle Configuration

During cruise to Venus, V-STAR will conduct housekeeping and checkup procedures to ensure that all systems are functioning properly. Upon reaching the separation point, the adapter will split in half, releasing the Lander on its transfer path to the surface of Venus, while the Orbiter attains a trajectory for orbiting Venus.
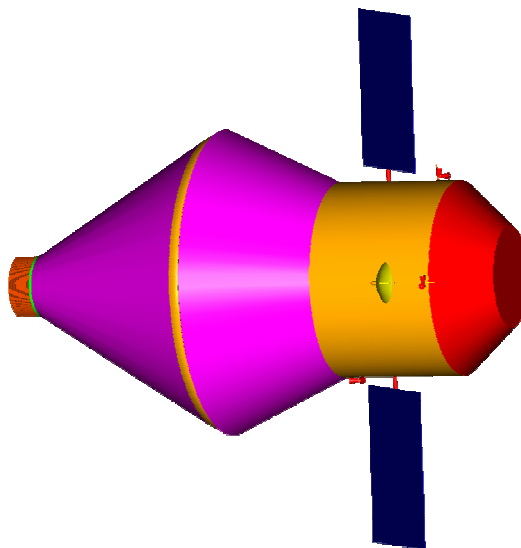
Figure 2 : Earth to Venus Vehicle Configuration

5.6 Launch Vehicle

The Atlas V Expendable Launch Vehicle (ELV) should be used to launch the entire mission assembly to Venus. The payload weighs approximately 7850 kg and consists of the Venusian Orbiter, surface Lander, sample return system, and all associated propellants. The Atlas V family of launch vehicles can launch over 20,000 kg to Low Earth Orbit (LEO), which is within the range of our combined calculated mass of 7800 kg. The ELV will place its collective payload into LEO at approximately 1500

km. The Atlas V Launch Vehicle is manufactured by the United Launch Alliance (ULA) and will be launched from Cape Canaveral Air Force Station (CCAFS) in Florida. There are two fairing designs that can be used in conjunction with Atlas V Launch Vehicle, which allow for greater flexibility and more freedom in order to meet science objectives of the mission and limits the constraints on the vehicle design. The nominal fairing option is 4-meters in diameter and comes in either a normal or stretched length, while the other is a 5-meter diameter composite fairing. This flexibility in fairing design makes the Atlas a useful and adaptable vehicle capable of withstanding many changes that come with such a large project. The Atlas V Launch Vehicle Common Core Boosters (CCB) which each contain a Rocketdyne RD-180 which produce 4,152 kN of thrust a piece. The Atlas V can launch within anywhere between one and five CCB depending on the weight of the payload and orbit desired. The Atlas V has two stages. There have been ten launches of this vehicle, with nine being successful [5]. Due to the high launch success rate, flexibility in fairing design, and thrust capabilities, the Atlas V Launch Vehicle has proven to be the best launch vehicle for the V-STAR mission.

5.7   Launch Configuration

At launch, the Orbiter sits atop an adapter which connects it to the Lander assembly. The Lander fits inside of the launch vehicle fairing that contains the transfer stage rocket engine. The transfer stage puts V-STAR on its course toward Venus. Once the transfer stage is spent, the upper fairing splits in half, exposing the Orbiter. The bottom of the fairing and engine are ejected, the solar arrays are deployed, and the V-STAR spacecraft is now in its cruise configuration.
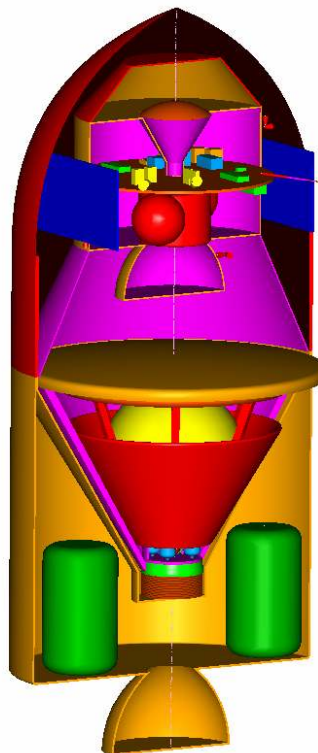
Figure 3: Launch Vehicle Configuration

6   Vehicle Design

The purpose of the vehicle design team is to integrate and support the science requirements onto the Orbiter as well as deciding the optimal launch configuration of the Orbiter, Lander, and Venus Launch System. In addition, vehicle design team oversees the material selection for the different modules involved at the various stages of the mission.

The vehicle design process was started was by satisfying the needs of the science requirements, specification and constraints; a number of instruments were selected to perform the required experiments and data was gathered to accomplish the mission objectives. Mass and power needs were taken into consideration when designing an efficient orbiter design that meets all requirements in terms of duration of flight, guidance and navigation, thermal protection, and propulsion.

6.1   Orbiter

6.1.1   Introduction to the Science Instruments

The orbiting spacecraft will carry remote sensing instruments to study the surface and atmosphere of Venus, as well as *in-situ* space weather instruments to study the environment surrounding Venus. It will carry a total of six instruments.

6.1.2   Venus Orbiting Laboratory Remote Sensing Instrument Package

The remote sensing instruments (based on instruments flow on past planetary missions [6]) of the Venus surface and atmosphere include:

- Surface Radar Mapper (SRM): The radar mapper will image the surface of Venus to measure elevations of landforms on the Venus surface. Using advanced radar imagery, the OL will return high resolution data that will enable further study of the surface.

- Infrared Radiometer (IRR): The infrared radiometer will measure the IR radiation emitted by Venus' atmosphere. The IRR will operate on eight bands of the IR spectrum, and so will consist of eight detectors.

- UV Spectrometer (UVS): The UVS will measure the ultraviolet light that is either scattered or emitted by the gas and clouds of Venus' atmosphere. These measurements will reveal the size and chemical composition of cloud condensation nuclei (CCNs), or aerosols, in the atmosphere. This study also allows for the modeling of the distribution of clouds, hazes, and gases in the atmosphere.

6.1.3   Venus Orbiting Laboratory *In-situ* Instrument Package

The *in-situ* analysis of the space environment in the vicinity of Venus, also based on past planetary and heliospheric missions, include the following instruments:

- Venus Magnetospheric Magnetometer (VMM): The magnetometer, designed to operate at sensitive signals due to the very weak structure of a Venusian magnetic field, is a flux-gate magnetometer. It will analyze the surface for surface-correlated magnetic features. These features could come in the form of abnormally-magnetized crust (most likely in the older parts of the surface), which would have been magnetized in the ancient solar system when Venus had a magnetic field like that of the Earth. This instrument will assist scientists in studying the possibility of Venus interacting with the solar wind.

- Venus Electric Field Detector (VEFD): The electric field detector will provide data about how the solar wind is deflected around Venus, how much the ionosphere is heated by passing solar wind, and ionization rates of the exosphere due to solar wind interaction.

- Solar Wind Plasma in the Vicinity of Venus (SWPVV): This instrument, based on the Plasma and Suprathermal Ion Composition Investigation (PLASTIC) instrument[i] on the latest Solar-Terrestrial Probes mission (STEREO), will be used to measure the solar wind activity and turbulence around Venus. It will take data about solar wind speeds, densities, direction, temperature, and thermal speeds in the area. In addition, it will calculate mass-per-charge ratios and measure the energy distribution of the ambient solar wind and solar storm events. These data will improve understanding of the affect of a small magnetic field on the passing solar wind.

The science instruments will be powered on, tested and calibrated during cruise. Imagers will be tested by either observing nearby objects such as the Moon or Earth several days after launch or by activating the instruments well before arrival and imaging Mars.

6.1.4   Guidance and Navigation / Attitude Control

The guidance and navigation of the Orbiter is accomplished by a system of image navigation obtained through star trackers and gyros. These instruments are mounted on a rigid structure that is highly resistant to thermal distortion. This structure provides a stable alignment between the attitude control sensors and the payload instruments.

Data from the star trackers is compared to an onboard star catalog to update the onboard attitude estimate. Data from the three-axis gyro is also used to propagate the attitude corrections needed, and this information is sent to the onboard computer, which in turn sends it to corrective OMS bipropellant thrusters to keep the spacecraft on track. Once in Venus orbit the information will be fed to several Reaction Wheels Actuators that will manage the proper three-axis stabilized orientation. This will

provide precise pointing of the Imagers (Visible, UV, IR, Radio) to get the best possible science of Venus' atmosphere and terrain, as well as good communications back to Earth. During cruise the spacecraft will fly with its communication antenna pointed towards Earth at all times, while keeping the solar panels pointed toward the Sun in a three-axis stabilized mode.

The Attitude Control Electronics consists of circuitry and software to control the spacecraft attitude, supporting battery and thermal requirement. The following systems are proposed;

- Sensors used: (Attitude determination)
    o Inertial Guidance system [gyroscopes]
    o Star Trackers [3 small 1-inch telescopes, and starfield database]
    o Sun Sensor [Solar Panel Alignment]

- Maintained By: (Attitude Control)
    o Bipropellant Thrusters
    o Momentum wheels (Reaction wheels)
    o Control gyros

6.1.5   Data and Communication Systems

The spacecraft communications subsystem provides transmission, reception, and routing of mission data signals and telemetry. This is crucial for the science returns and also for housekeeping operations, making sure everything is working properly throughout the mission. The system consists of a set of antennas on the spacecraft and Earth Ground Stations. Such a system will include the following components:

- Low-gain Antenna
- Medium-gain Antenna
- High-gain Antenna
    - Wide-transmitters
    - Receivers

Figure 4: Mojave Desert Space Network

The Orbiter will transmit to Earth using its medium-gain antenna and will receive commands on its low-gain antenna during the early portion on its flight. After a month or so, operations to send and receive will be transferred to its high-gain antenna. Very little cruise commands will be needed to be uplinked as the orbit transfer is a simple Hohmann maneuver. Periodic communication will be kept through the quiet cruise phase but will increase to continuous coverage for ΔV maneuvers approaching arrival to Venus through NASA's Deep Space Network (DSN) which has stations located in the Mojave Desert - California, Madrid – Spain, and Canberra – Australia. NASA Ground Network (GN Stations) will keep track of launch and orbit rising.

6.1.6   Telemetry and Command Subsystems (T&C)

This subsystem provides the functional interface between the spacecraft, ground command and control; it is composed of both radio frequency (RF) and digital (baseband) segments. Telemetry parameters describe the status, configuration, and health of the spacecraft payloads and subsystems, and are dowlinked to the V-STAR control center.

Information from the spacecraft provided via telemetry includes:

- Configuration status and housekeeping data from operational instruments
- Health status for each receiver
- Health status for each transmitter.
- Power system parameters and voltages for critical electronics
- On/off status of all commandable equipment and heaters
- Temperatures of all major subsystems
- Spacecraft determination and control parameters

All of V-STAR's computing functions will be performed by the RAD6000, a radiation hardened Central Processing Unit (CPU) that is used in most models of Macintosh computers. Developed by IBM this single board computer is mainly known as the onboard computer for many NASA spacecraft including the Spirit and Opportunity Rovers, STEREO, Spitzer Infrared Telescope and many others. The processor will run V-STAR's flight software and controls.

Redundancy is important in most space missions and so another identical computer and peripherals will be used in case of a major failure. Another interface card will be placed in order to handle communications of important housekeeping and scientific telemetry, and finally a large memory card will be used to store imaging data.

6.1.7   Electrical Power

The power system of the Orbiter will mainly consist of solar and battery power. The primary bus voltage will be redirected to the higher power consuming instruments, such as the communications subsystem, attitude control (momentum wheel), and thermal subsystems. A secondary bus, fed by the primary, but operates at a lower voltage will control the remaining spacecraft systems and science instruments. Another secondary bus will charge the Venus Lander batteries to full capacity in preparation for its landing. The electrical power subsystem's primary function is to generate, store, condition, control, and distribute the required power.

The vicinity to the Sun of the Venus Sample Return mission is ideal for solar array use. Always Sun-pointing, the Orbiter will use two 10-meter-square panels to fulfill all of the spacecraft's energy requirements. The arrays will be composed of high-efficiency dual-junction gallium arsenide (GaAs), which has proven itself time and time again on several missions including STEREO, all the Mars rovers, Stardust, and many others. The arrays will track the Sun throughout the orbit transfer, Venus orbit and return. During launch all the way to Earth parking orbit the solar array will remain stowed and attached to the spacecraft until the desired orbit is reached. Pyrotechnic devices will release the arrays once the spacecraft is in operational conditions. During eclipse power will be supplied by the batteries

The batteries are the secondary power source for the V-STAR Orbiter instruments. It is composed of nickel-hydrogen cells and will provide power whenever the solar arrays produce less than the required power to support the spacecraft. The batteries provide power during launch, transit (when the arrays have not been deployed) and through the Earth / Venus eclipse. The batteries need to be kept above -10 ºC and away from any of the temperature sensitive instruments, such as the infrared radiometer. It will be kept warm by way of heaters through the thermal control system.

6.1.8   Structure

The Orbiter spacecraft structure will be very similar to previous planetary exploration missions. A central bus structure will ideally be fabricated from aluminum honeycomb panels. These consists of an interior layer of thin aluminum arranged in a honeycomb pattern sandwiched between carbon fiber reinforced composite sheets. This exceptional construction material provides high structural strength and minimal weight. It is also a very good thermal isolation method to ensure that the interior of the orbiter remains at a controlled temperature. On top of this, a thin aluminum 6061 T6 skin is wrapped around the bus. An aluminum honeycomb deck mid-craft provides a surface to mount necessary electronic and scientific equipment, as well as a physical barrier between the return rocket engine and sensitive equipment.
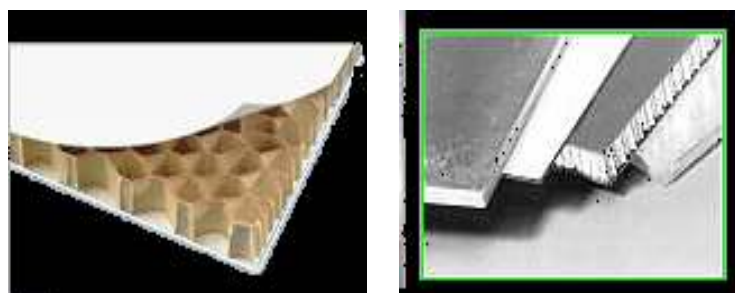
Figure 5: Structural Composition of the Orbiter

6.1.9   Thermal Protection

Thermal Protection is critical when placing a spacecraft in the extreme environment of deep space. The thermal control subsystem helps maintain the components of the spacecraft within their

respective temperature limits enabling them to function properly. See Table 5 for a list of typical temperature ranges of various spacecraft components. There are several types of thermal energy acting on a spacecraft; solar radiation, albedo (the solar heat reflected by a planet's surface and its atmosphere), earth emitted infrared, and heat generated by onboard equipment [8].

Table 5 Thermal Design Temperature Limits of Various Spacecraft Components

Thermal Design Temperature Limit (°C) Min/Max

Subsystem/Equipment	Nonoperating/Turn-on	Operating
Communications		
Receiver	-30/+55	+10/+45
Input multiplex	-30/+55	-10/+30
Output multiplex	-30/+55	-10/+40
TWTA	-30/+55	-10/+55
Antenna	-170/+90	-170/+90
Electric power		
Solar array wing	160/+80	-160/+80
Battery	-10/+25	0/+25
Shunt assembly	-45/+65	-45/+65
Attitude control		
Earth/sun, sensor	-30/+55	-30/+50
Angular rate assembly	-30/+55	+1/+55
Momentum wheel	-15/+55	+1/+45
Propulsion		
Solid apogee, motor	+5/+35	---
Propellant tank	+10/+50	+10/+50
Thruster catalyst bed	+10/+120	+10/+120
Structure		
Pyrotechnic mechanism	-170/+55	-115/+55
Separation clamp	-40/+40	-15/+40

In general, there are passive and active thermal control systems; a passive system relies on conductive and radiative heat paths and has no moving parts or electrical power input. An active system is used in addition to the passive system, for example, on manned missions. Active systems rely on pumps, thermostats, and heaters, use moving parts, and require electrical power. The Orbiter for this Venus sample return mission will use a passive system.

Venus' atmosphere is approximately 260° C, thus the Orbiter must dispose of the heat it acquires into deep space. A space radiator located on the outside of the Orbiter can be used to dissipate heat into deep space. One example of a space radiator is a second surface mirror; "a second surface mirror is a mirror that reflects incident energy and can radiate out internal energy" [7]. Multilayer Insulation blankets can be wrapped around components on the Orbiter, such as the sensors and payloads, to thermally isolate them. Multilayer insulation (MLI) is composed of closely spaced layers of aluminized Mylar or Kapton, alternated with a course net material. MLI reduces the rate of heat flow per unit area

between two boundary surfaces and prevents a large heat influx [8]. A solar shield can be used to protect the Orbiter from solar radiation. Thermal barrier coatings can be applied to the Orbiter's surface to reduce heat transfer and wall temperature by increasing the surface emissivitiy and decreasing its absorptivity. Coating efforts with rhenium are ongoing. A list of thermal paints and materials are in Table 6.

Table 6: A list of materials and there solar absorption and emittance

Typical Surface	Application	Solar Absorptance, α_S		Emittance, e	
		BOL	EOL	BOL	EOL
paint	Interior structure	0.9	0.9	0.9	0.9
White paint	Antenna reflector	0.2	0.6	0.9	0.9
Optical solar reflector	North and south panel radiators	0.08	0.21	0.8	0.8
Graphite/ epoxy	Solar panel and antenna structure	0.84	0.84	0.85	0.85
Aluminized kapton	Thermal insulation	0.35	0.50	0.6	0.6
Tiodized titanium	Apogee motor thermal shield	0.6	0.6	0.6	0.6
Aluminum, aluminum tape insulation deposited aluminum	Propellant	0.12	0.18	0.06	0.06
Anodized aluminum	Interior structure	0.2	0.6	0.8	0.8
Solar cells	Solar panels	0.65-0.75	0.65-0.75	0.82	0.82
Gold		0.2-0.3		0.03-0.06	

George Sutton, a consultant for the aerospace industry, states that heat is transferred to all internal hardware exposed to hot gases such as the injector face, the thrust chamber, and nozzle walls [9]. Sutton notes that the amount of heat transferred by conduction from the chamber gas to the walls in a rocket thrust chamber is negligible. He further states that the largest part of the heat transferred is by convection and usually 5-35% of the transferred heat is due to radiation [9].

Cooling helps reduce the rate of oxidation and corrosion of the thrust chamber walls. There are two methods for cooling thrust chambers, cooling with steady-state heat transfer and cooling with transient heat transfer [10]. In the steady-state method the heat transfer rate and chamber

temperatures reach thermal equilibrium. Steady-state heat transfer includes regenerative and radiation cooling. The duration is only limited by the amount of available propellant. [9] Sutton explains that in regenerative cooling a cooling jacket is built around the thrust chamber to circulate one of the liquid propellants (usually fuel) through it before it is fed to the injector [9]. In radiation cooling the chamber/nozzle has a single wall made of high temperature material and when the wall reaches thermal equilibrium it radiates heat away to its surroundings. Sutton notes that insulation or heat shields have been successfully applied on the exterior of radiation-cooled thrust chambers to reduce the heat transfer to adjacent sensitive equipment [9]. This technology is suited for bipropellant chambers of medium to large thrust [8]. Steady-state heat transfer is a suitable way to dissipate heat on the Venus sample return orbiter. Ablative or heat sink cooling is used for transient heat transfer and the heat absorbing capacity of the hardware determines its max duration. This method is typically applied when there are low chamber pressures and low heat transfer rates for solid propellant rockets [11].

6.1.10 Propulsion

There are several rocket propulsion system types in common usage. Liquid propulsion is the best option for the Venus sample return mission. Liquid propellant rocket engines use liquid propellants that are fed from their tanks into a thrust chamber. These chemical rockets use chemical combustion to supply energy to the propellants which are ejected out of the back of the rocket providing thrust [12]. One way to classify chemical rockets is by the number of chemicals involved in the reaction: monopropellant, bipropellant, or multipropellant [12]. The best option for this mission is to use a bipropellant rocket. According to Sutton a bipropellant rocket unit has two separate liquid propellants, an oxidizer and fuel that are stored separately and are not mixed outside the combustion chamber [13]

The Orbiter's propulsion subsystem features eight small thrusters and a main engine. The thrusters are used to perform attitude control and trajectory correction maneuvers and the main engine is used to place the spacecraft into orbit around Venus. The recommended propellant configuration is Nitrogen Tetroxide as the oxidizer and monomethylhydrazine (MMH) as the fuel. These propellants are favorable because they are hypergolic meaning that they combust upon contact with each other at a low temperature. Some propellant will be utilized by the thrusters.

Propellants may be fed into the combustion chamber by pressure or by a turbopump system. The propellant mass of the mission's propulsion system is about 2,200 kg and calculations have shown that tubopump fed systems provide a greater payload than pressure fed systems for missions requiring more than 450 kg propellant [12]. Hence, a turbopump system should be used.

7   Venus Landing

7.1   Venus Capture

Near the end of the Hohmann transfer, as the spacecraft approaches Venus, separation of the Orbiter and Lander will occur right before the second ΔV.   Also after separation, the Orbiter will do its second ΔV which will allow it to be captured into a circular parking orbit of Venus, with the final altitude of the orbit being 300 km.   The atmosphere of Venus ends at an altitude of approximately 250 km ("Atmosphere of Venus.").   The spacecraft needs to be as low as possible in order to allow the launch vehicle from Venus to have a minimum ΔV with the sample launched from the surface.   Choosing an altitude of 300 km allows this, while still being out of the atmosphere in order to avoid atmospheric drag.

7.2   Venus Atmospheric Entry

The atmospheric entry must provide controlled dissipation of the combined kinetic and potential energy associated with the vehicle's speed and altitude at the entry point. The landing site selected for the Venus lander is the Ovda Regio region. This is close to the Venusian equator, on a plateau that is 4 km above average elevation on Venus (Leitner, et al).

7.3   Landing Site

The Ovda Regio highland region on the surface of Venus has been selected as primary landing site for this mission. The site is located near the equator, and extends from 68°E to 109 °E and 13°S to 4°N. It is the largest crustal plateau on the surface of Venus with an altitude of 4 km above the surrounding lowland plains. It covers an area of 6300 km x 2200 km. Figure 6 illustrates a radar image of the Ovda Regio region.

Figure 6: Ovda Regio Landing Site
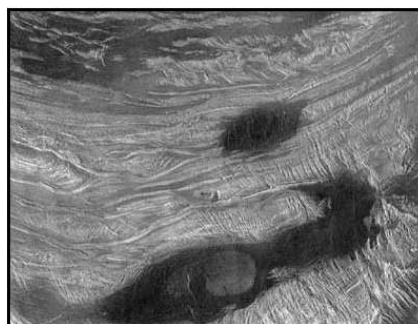
In radar imagery, dark colors are flat and smooth while light colors are rough and fractured. In Figure 6, the black regions represent flat, lava filled basins. The Lander will be exploring these basins due to the wealth of information regarding surface formation on Venus within them, as well as the ease of landing provided by this flat surface. The Ovda Regio area is one of the oldest pieces of crust left on the planet, surrounded by lowland plains created out of the most recent global resurfacing event.

This makes this region very interesting to scientists due to the amount of history held there. There are three major structures in the Ovda Regio region. Folds can be found everywhere in this territory. Grabens appear at folds' crust. These are lens shaped depressions bounded by faults. Ribbons are 1-3 km wide, steep-sided, flat floored valleys that can be found every 1-5 km. Ovda Regio is in fact a mountain chain formed most likely by crustal uplift, as there are not plate tectonics on Venus. The quickly alternating peaks and valleys of the region suggest difficulty for landing spacecrafts. However, the lava filled basins, which formed after the mountain building event, provide flat landing sites. The Ovda Regio landing site was chosen because it is an unexplored territory, holds the most history in terms of geological age, and also because scientists already have relatively good topographic data from this region. In addition, it is located at a high altitude where atmosphere and land interactions can be studied. The region is relatively large allowing for a large margin of error upon landing. These dark, flat regions occur often enough to land in one of them, which is preferred for the autonomous spacecraft landing. An equatorial landing site also helps with the mission ascent trajectory by reducing the ΔV required to launch due to the planetary rotation.

7.4   Entry and Descent to the Venusian Surface

The VSTAR Lander will reach the Venusian surface via a combination of aeroshell, parachutes and a deployable, disk-shaped aerodynamic brake. These mechanisms will be controlled by a combination of a timer and altimeter The main structure of the Lander consists of concentric shells, the center of which houses the Venus Ascent Vehicle.

First, the blunt-body aeroshell containing the Lander will meet the atmosphere traveling approximately 8 km/s, at an altitude of 125 km [rsw.com, Jason]. An ablative heat shield will dissipate the bulk of entry velocity, slowing the spacecraft to approximately 250 m/s (Figure 7, #1). Pyrotechnics then jettison the aeroshell in sections.

At this point a primary braking parachute will deploy, operating long enough to slow the craft to 50 m/s (Figure 7, #2). This parachute will then jettison, to be followed by three main parachutes (Figure 7, #3). Parachute descent will be faster than previous Venus landing missions in order to achieve the maximum time available on the surface, while primary atmospheric measurements will be left to the Venus Ascent Vehicle as it returns to the Orbiter.

The higher parachute descent speed will be offset by a flexible, disk-shaped aerodynamic brake which will be deployed at an altitude 50 km (Figure 7, #4). . The aerobrake disc is used to increase drag, slowing the Lander down. The high density of the Venusian atmosphere allows a very gentle descent speed of 7-8 m/s to be achieved by this method [Sweetser, Cameron, Chen, p. 4]. The landing spacecraft will free-fall to its landing site (Figure 7, #5) from this point, guided by

manipulations of the flexible disk to avoid large hazards at landing. Despite this ability for manipulation, the Lander will have limited steering capability and must be targeted for a relatively flat region.
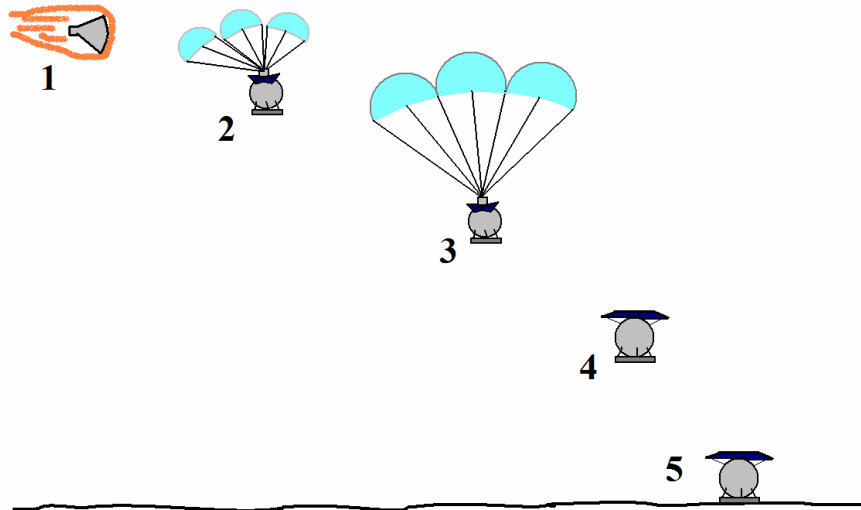
Figure 7: Profile of the VSTAR descent and landing through the Venusian atmosphere.

7.5   Lander Systems

Design of the VSTAR planetary Lander is loosely based on the many successful Venera spacecraft which landed on Venus in the 1980s. The Lander will initially consist of a spherical pressure shell, crushable landing pad, and cylindrical core - all surrounded by a protective aeroshell. Each of these sections exists for a specific purpose outlined in this section.
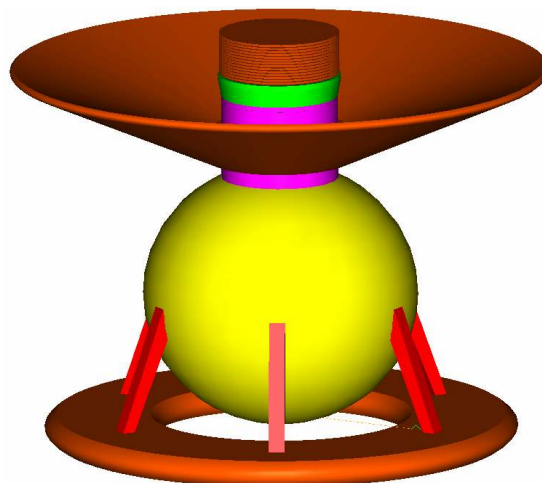
Figure 8: CAD Generation of the Lander

The robotic arm is mounted to the side of the spherical pressure shell, and the drill is mounted underneath. Onboard batteries supply power to the Lander. *In-situ* measurement probes protrude from the Lander to gather measurements during surface operations.

7.5.1   Aeroshell

The aeroshell will protect the Lander during entry into the Venusian atmosphere, as seen in Figure 9. A blunt-body design, it will keep the spacecraft oriented properly during the descent. The bottom (-z) of the aeroshell will consist of an ablative phenolic heat shield to dissipate the majority of the energy during entry. The two carbon composite halves enshrouding the sides of the pressure vessel will create an aerodynamic surface and protect the landing system from direct exposure to the heat of entry. Once the Lander has been slowed sufficiently and the correct altitude has been reached for parachute deployment, the aeroshell will be jettisoned by pyrotechnic bolts.
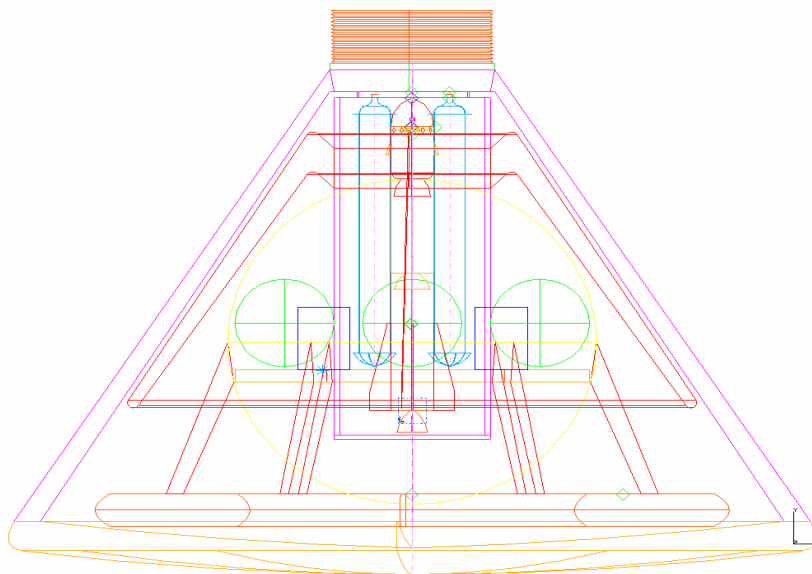
Figure 9: Drawing of VSTAR lander, encompassed in aeroshell

7.5.2   Spherical Pressure Shell

The pressure shell will encompass all hardware which is essential to the operation of the spacecraft as well as the *in-situ* scientific analysis hardware. The sphere, with a cylinder down the longitudinal axis allocated for ascent vehicle hardware, will contain the necessary volume to accommodate the systems necessary for surface operations. It will protect sensitive instruments from the extreme environment on Venus's surface by providing controlled pressure, temperature, and atmospheric composition.

The Lander's batteries, cooling system, and cryogen tanks will be arranged in the bottom half of the spherical volume in order to keep the center of mass as low to the surface as possible. This is to offset the high center of mass of the ascent rocket, which will stand upright in the cylinder at the center of the pressure vessel.

The science instrument electrical systems will be organized in the top half of the pressure vessel, along with the Lander's communication and navigational hardware. These systems will require approximately 0.5 m^3. To conserve internal volume and preserve the integrity of the pressure vessel,

the science sampling arm and containment system will be entirely exterior to the pressure vessel, encased at the base of the sphere near the attachment points of the impact absorber. Power and coolant will be conducted to the drill and associated systems through the pressure vessel with minimized structural risk.

In order to accommodate all of the volume required by the science hardware, as well as the volume of the spacecraft systems and the central core which will be subtracted from the available space, the sphere will be 1.75-2 meters in diameter. The optimization of this parameter constitutes future work for the program, as small changes in diameter exert large (3rd order) changes on the volume of the vessel. Furthermore, structural considerations come into play because the vessel and attached impact-absorbing pad must be able to support the ascent vehicle segment extending above the sphere.
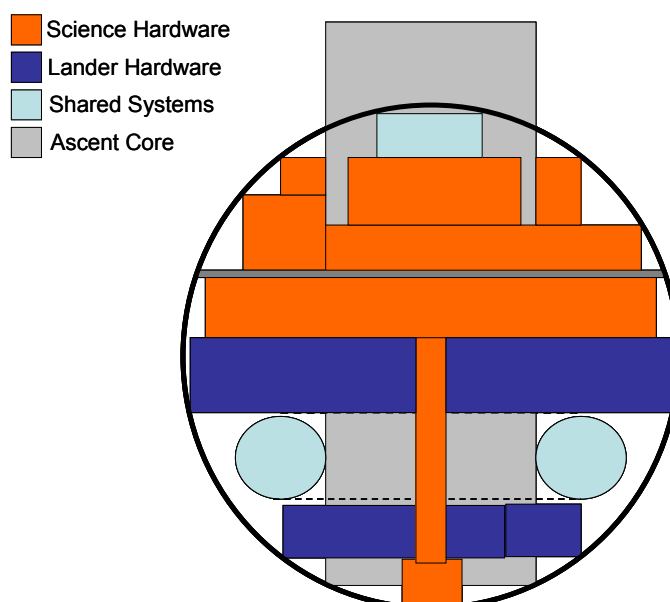
Figure 10: Layout of the Lander's spherical pressure vessel, with respect to instrument volume allocation.

7.5.3 Central Core

The central, cylindrical core through the pressure shell will contain the Venus Ascent Vehicle, as outlined later in this report. Approximately 1 meter in diameter, this core will extend above the pressure shell in order to accommodate the size of the Venus ascent system. The ascent systems will be independent of those in the pressure vessel.

The Lander must be much more robust than the Orbiter so that it can survive the harsh environment entry and operation on Venus presents. For this requirement the construction material is chosen to be titanium 6AL-4V, which exhibits superior strength and resilience at temperatures up to 600 degrees Celsius. The titanium is milled into panels employing the isogrid structural pattern, which maximizes the strength to weight ratio of the Lander.

The Lander is also insulated using Aerogel panels inserted into the isogrid hollows. A central deck provides a mounting interface for the onboard science instruments, electronics, and sample gathering devices. A spherical pressure vessel that employs isogrid reinforcement surrounds the majority of the Lander's core, protecting all of the components from the extreme pressure at the surface.

7.5.4   Air Brake

The air brake will slow the Lander during the final moments of descent. Anchored to the cylindrical core just above its intersection with the pressure vessel, the air brake will be constructed of parachute-type fabric which is folded and stowed prior to use. It will deploy once the probe has reached a safe speed under the main chutes.

The brake will allow avoidance of large terminal hazards as it is manipulated by a wire-motor system controlling the exact shape of the disk, similar to the manipulation of a parafoil by a skydiver.

7.6   Landing Mechanism

The energy and impact of landing will be absorbed by a crushable pad on the base of the Lander that is composed of Duocel Foam [14]. This recently developed material absorbs a large amount of energy at impact while also having a high strength-to-weight ratio as displayed in Figure 11. Furthermore, the foam is capable of compressing non-uniformly to create a level landing surface despite small obstacles which may be encountered in the landing area.
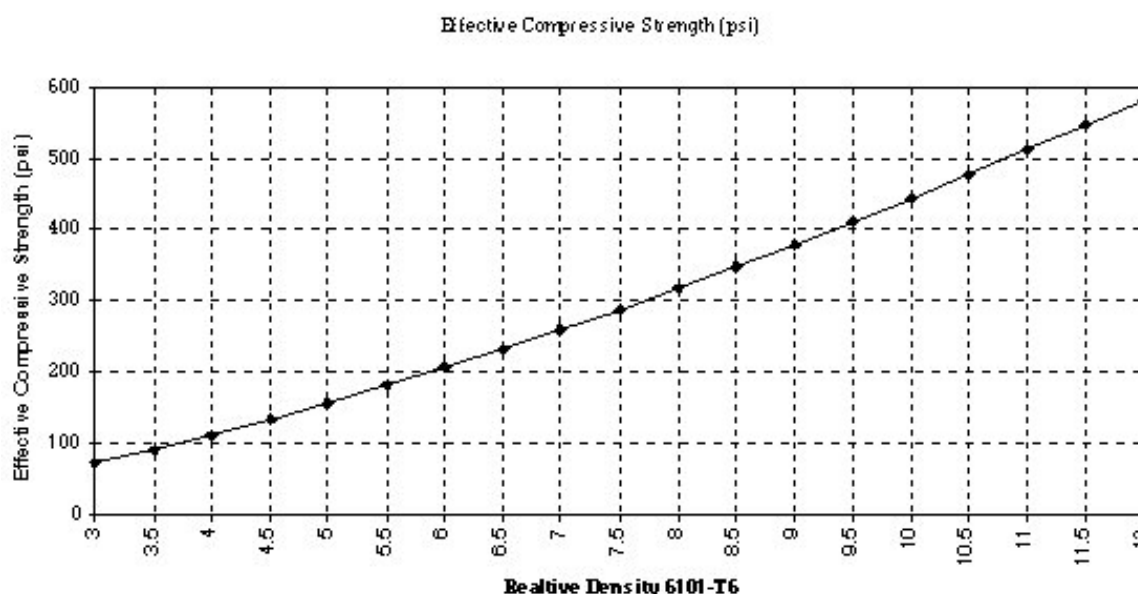
Figure 11: Effective compressive strength versus relative density for Duocel foam, courtesy ERG Materials and Aerospace Corporation.

Duocel foam has been developed by ERG Materials and Aerospace Corporation in Oakland, California. Manufactured from a choice of aluminum, ceramic (Silicon Carbide), or reticulated vitreous carbon, the foam has many desirable properties for a space flight impact absorber, including:

- High (and variable) surface area to unit volume;
- High strength-to-weight ratio;
- Almost completely isotropic load response;
- Variable stress-strain characteristics.[14]

The exact mass of this crushable landing mechanism constitutes future work.
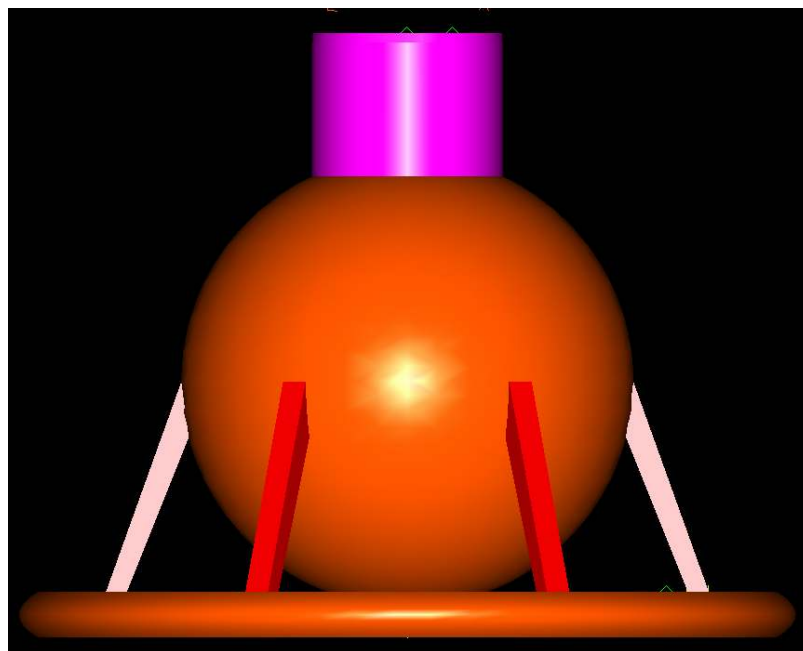
Figure 12: External view of landing system, with crushable Duocel impact absorber visible at the bottom

7.6.1 Command Timeline

During the descent of the Lander, the command to execute the first of the stages of deceleration will be based on a velocimeter and an onboard clock. When the speed of the Lander reaches approximately 50 m/s, a command will be sent to a braking parachute system. A redundant system of a timer command will be programmed into the system in case of failure of the first method. The onboard clock will be used for the second stage of deceleration, sending a command to release the drogue parachute, which will also pull out the main parachute. The final stage of deceleration is the flexible, disc brake. This is a deformable disc that will be used also for hazard avoidance. The release of this mechanism will be activated by Radar altimetry, which will send the command to release at 50 km altitude. Once landed on the surface, all commands to the Lander subsystems and science instruments will be initiated by the timer.

7.6.2   Guidance, Navigation, and Control

The guidance, navigation and control subsystem of the Lander will be responsible for providing a safe landing in the desired landing zone. Due to the long delay of communication between the Earth and Venus, the landing of the spacecraft on the surface of Venus must be completely autonomous. Optimally, the Lander will remain on a safe trajectory and not have to use the control system. The navigation system will consist of a camera and image processing algorithms to analyze the features of the terrain. If the system recognizes landing hazards, the sectioned disk brake will have the capability to be controlled. This controllable brake will cause differential lift on the spacecraft to alter the path, in order to avoid hazardous terrain. Movement of the brake will be controlled by a small cable and motor system which can deflect specific sections of the disc.

7.6.3   Lander Power Requirements

Electrical power will be supplied to the Lander's on board systems and science instruments by a set of lithium ion batteries. Some of the considerations reviewed for the design are that lithium ion technology has been well proven to work efficiently with past missions, as well as the short period of planned operations in the Venus surface. Nuclear power was also considered, but it increases the spacecraft complexity, which results in higher mission costs.

Figure 13. Design selected for the Mars 2001 lander (25 A-hr, 28-V).

7.6.4   Power System Design

It is important to ensure that the all instruments remain at a constant predefined amperage and voltage in order to avoid any type of electrical failure. Hence, a set of four batteries will be used to provide back-up systems; these redundancies increase the spacecraft weight, but also improve the reliability and safety of the overall system design.
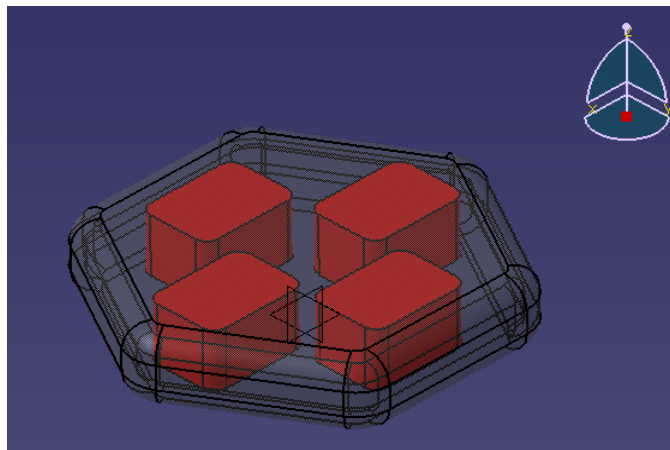
Figure 14: Conceptual design for the battery pack surrounded by an insulation shield

Some of the most important operations that will depend on the battery power are keeping continuous communications with the Orbiter during landing, as well as supplying power to the drilling mechanism for the surface sample attainment. The Lander should be able to operate with two-running batteries, the remaining two will be actuated in case there is any type of considerable alterations on the operating power levels.

The lander power has been estimated to be at 120 watts peak, which will be provided by two batteries working in parallel. The approximation has been done by researching on past lander missions to Mars and Venus. About 70 to 90 watts are required for science instrumentation, as well as for computer operations, and the remainder is to keep communications with the orbiter.

The batteries overall efficiency and integrity relies on the environment temperature. Since the Venus surface temperature is very high, around 750 K, the entire power system will have sufficient insulation, as well as a cooling system to maintain the power systems at operational temperatures.

7.6.5   Communications Subsystem

Communications will take place by the use of an Ultra High Frequency (UFH) antenna that will provide a link to the Orbiting spacecraft. Due to size constraints of the Lander, there will not be a high gain antenna to communicate with the Earth. All data transmission will be transmitted first to the Orbiter, then to Earth by use of the Orbiter's high gain antenna.

A UHF antenna communicates by line-of-sight, therefore communication between the Lander and the Orbiter will only be possible during a specific period of the orbiter's 4 hour and 23 minute travel around Venus. During the portion of time that the Orbiter is behind Venus, it will be out of range and unable to communicate with the Lander.

7.6.6   Command and Data Handling

The Command and Data Handling subsystem (CDH) of the Lander will perform the functions of data transmission and storage, time keeping, and the processing and executing of commands.   This system is a key component in the scientific instrument operation and data collection. All scientific instrument deployments will occur with commands from the CDH subsystem based on the clock. During the science activities, all data collected will be packaged and stored on the onboard solid state recorder until transmission to the Orbiter via the communication system is possible. Information about ambient conditions, including temperature and pressure, and instrument state of health readings will also be stored and transmitted to the Orbiter and then to Earth.   The onboard data storage is redundant, but if the communication link was lost, the data would still be available once the craft returned to Earth.

7.6.7   Cooling System

Maintaining low temperatures for the Lander's operation systems is considered one the biggest challenges for the mission. Electronics can easily fail when the temperature is not adequate. It is thought that past VENERA missions lost communication due to the overheating of onboard electronic systems. Several cooling processes were studied, such as: radiators, stored liquid or solid cryogens, and high pressure gas.
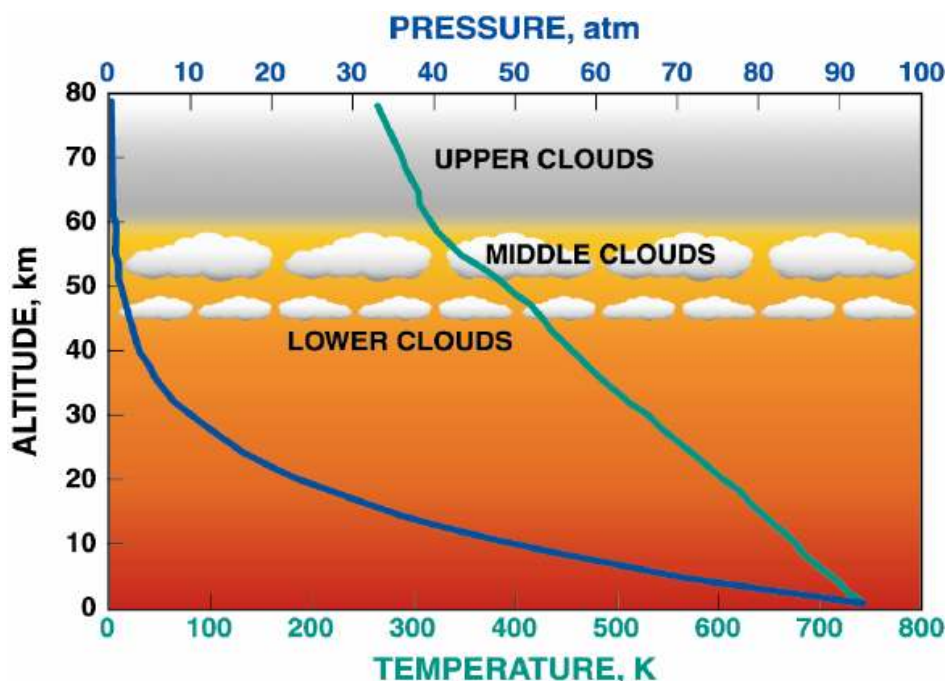

Figure 15 Venus Environment: temperature and pressure behavior with respect to the point of elevation.

7.6.8   Cooling System Design

To achieve the correct temperature, the system will incorporate high-pressure Helium gas storage with a Joule-Thomson (JT) expansion valve system. JT systems are most often used for short time missions due to leakage problems of the gas.

Figure 16. Joule-Thomson expansion valves

The system works by taking advantage of the changes in the internal energy that the gas undergoes as it passes through the JT expansion valve. These changes cause the gas to cool down to very low temperatures, as the operational range of temperatures of the cooling system is from near zero absolute to 300 K. Such cooling could not be possible without high pressure or low temperature conditions. Once the gas has gone through the expansion process, it can be channeled to cool down the incoming gas as a form of recuperative cooling, which increases the efficiency of the system.

7.7   Lander Laboratory Scientific Instruments

The surface Lander contains the largest amount of instruments, as it is the most relevant to the primary science goal of the mission: sample return and surface study.

7.7.1   Venus Lander Laboratory *In-situ* Instruments Package

Four instruments are responsible for sample collection, while another four instruments are responsible for *in-situ* analysis during surface operations. These static instruments include:

- UV/Visible Camera (UVVC): A camera that detects in the ultraviolet and visible wavelengths will be used to image the surface and sample collection sites. Not only will the camera serve to return images of Venus in general, but will be useful once the samples are returned to the Earth in terms of context clues for science teams studying the rock samples.

- Venus Bedrock Penetrometer (VBP): Upon landing on the surface, a penetrometer will hit the surface below the Lander. With the force of this impact known beforehand, it will be possible after measuring the depth of the impact "crater" to calculate the compressibility of the Venusian bedrock.

- Basic Environmental Science Instrument Package (BESIP): This environmental instrument package will carry Venus weather experiments. It is proposed that these experiments

include an anemometer to measure wind speed, a barometer to measure atmospheric pressure, and a thermometer to study temperatures.

- Venus Combined Infrared Spectrometer (VCIS): An infrared spectrometer searches for heat and can determine an object's composition by these temperature differences. This instrument will be used to find preliminary composition data on the surface and measures from mid-infrared to far-infrared.

7.7.2   Venus Lander Laboratory Sample Collection Instruments Package

The Venus Geologic Sample Collection System (VenusGeo) consists of instrumentation to collect surface, subsurface, and atmospheric samples. These instruments have been designed by the VSTAR team and are detailed in the design section of this report. The total amount of materials returned should not surpass two kilograms.

- Venus Ground Sampling Drill (VGSD): The first type of sample to be collected by the Lander will be the ground core sample. The VGSD, much like those used to make ice cores on the Earth in Antarctica, will be used to excavate a circular rod of bedrock so that a sample of subsurface material is also returned. This core sample should not surpass one kilogram.

- Robotic Arm: A surface sample will be extracted by a robotic arm capable of lifting small surface pebbles and placing them the containment facilities. This surface sample should not surpass one kilogram.

- Integrated Mole Instrument: A mole will be used to burrow into the subsurface to collect subsurface material that differs from the rock core excavated by the drill. This mole is connected to the robotic arm for increased mobility. This sample should not exceed one kilogram.

- Venus Atmosphere Samples Collector (VASC): During the ascent phase from the Venus surface, the VASC will collect twelve samples at specific altitudes in the atmosphere. All samples will be taken prior to the point at which the spacecraft reaches 120 km above the surface. The goal of this instrument is to create a compositional map of the lower Venusian atmosphere.

7.7.3   Scientific Mission Timeline

After the successful spacecraft landing and Landing Laboratory deployment, the drill and robotic arm will begin sample collection. The sample collection process requires 45 minutes. The retrieved samples will be transferred to the Orbiting Laboratory via balloons in 4 hours. In the meantime, the instruments on the Lander will conduct *in-situ* analysis. From past mission experience, the remainder

of the Lander's spacecraft is left on the surface after ascent and will be destroyed in approximately 2.5 hours. The *in-situ* analysis will continue until the Lander has shut down.

7.7.4 In-depth Studies of Venus Sample Collection Instruments

There are three separate stages of science experiments present on the VSTAR spacecraft. The first is on the Orbiting Laboratory, the second is on the Landing Laboratory, and the third is the atmospheric collection on the ascent section of the Landing Laboratory upon its escape from the surface.

7.7.4.1 Robotic Arm

To increase the reliability, redundancy and verification of the returned sample, a fully integrated robotic arm will be integrated into the Lander's main structural base. Robotic arms have been used on a range of diverse space exploration missions since the 1970s, when an arm was used on the Viking 2 mission to Mars, show in Figure 17.

Figure 17: Viking Lander extendable boom with scoop [15]

As depicted in Figure 17, the arm was a simple design with retraction capabilities and a scoop for obtaining a sample. The 3 m reach of the arm enables trenches to be dug that were otherwise out of reach of the Lander itself, therefore adding flexibility into the mission. However, the shallow penetration depth of 10 cm limits the amount of sample that can be collected and is far more applicable for dusty surfaces [15].

More recent missions have included robotic arms with a higher degree of sophistication. The Mars Exploration Rovers used an actuated arm that allowed more freedom of movement when compared to Viking 2. A complete analysis summarizing the advantages and disadvantages from the trade study of the exclusion or inclusion of an arm on the Lander is displayed in Appendix A.2. Whilst a robotic arm requires a higher degree of automation and an allocation of internal space, the ability to collect multiple samples from sites around the Lander gives it a strong advantage over a Lander with instruments fixed underneath. There is also the possibility of using the arm in conjunction with sample instruments onboard the Lander to add redundancy to the total mission design.

Developments in instrumentation also meant that small, light-weight instruments could be attached to the arm to perform both *in-situ* analysis and sample collection. Such instruments include an alpha/x-

ray spectrometer this can be integrated with a robotic arm to serve as an analytical tool to characterize and collected samples. This allowed more data to be gathered as instruments could be moved to different sites rather than being statically fixed to the underside of a Lander. However, sophisticated arms have strict operating conditions in order for the joints to withstand temperatures and loading. The most sophisticated arm examined is the robotic arm and accompanying Position Adjustable Workbench (PAW) included on 2003's Beagle 2 Mars mission, detailed in Figure 18.
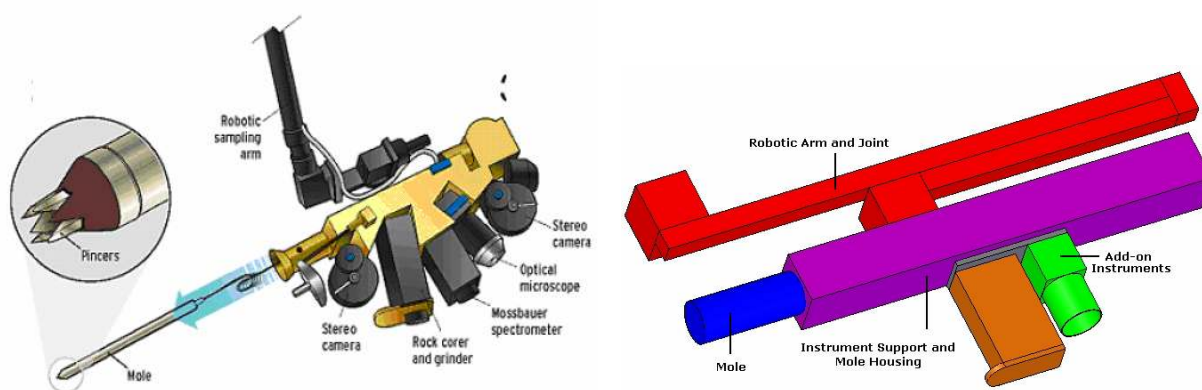

Figure 18: Sophisticated Robotic Arm and PAW [16]   **Robotic Arm- Folded Position**

The PAW is effectively a workbench with a range of small instruments, capable of moving in a 0.75 m radius [16]. PAW was able to incorporate several analysis instruments, including a rock grinder and corer that could expose surfaces for a spectrometer to analyse. A major development with PAW was the inclusion of a 'mole' in a separate housing that was capable of being released in any direction to dig and retrieve samples from a 3m depth [16]. The proposed operations of Beagle 2 was designed to be extremely versatile as the PAW was capable of sending samples to an analysis package or dropping samples onto the flat lid for *in-situ* analysis. This can be easily expanded to develop return capabilities. Therefore a robotic arm was selected for the Lander in order to maximize the potential science return.

The arm is composed of three sections: a shoulder joint joins the sample retrieval cylinder and the first arm section, an elbow joint connects the two arm pieces, and a wrist joint attaches the scoop to the arm. The rim of the scoop contains a top layer of tungsten steel to give the scoop added toughness for trenching. Three narrow pieces of tungsten steel, known as ripper tines, protrude from the back of the scoop. A door connecting the sample container and the arm opens as the dirt begins to descend down the arm. The pressure in the sample container is less than that on the surface, so when the door opens a suction force helps collect the dirt falling down the arm. The mechanical arm continues to dig and drop the samples through the hollow arm until a device in the sample container informs the arm that the sample has been obtained. At this time the door to the sample container seals shut. Through the procedure of using the suction force of the sample container, an atmospheric sample at surface level is obtained in addition to the rock sample.

7.7.4.2   Integrated Mole Instrument

To provide flexibility in the sample site selection a small automated burrow device entitled a 'mole' is to be incorporated into the Lander's robotic arm instrument array. A mole is a subsurface penetrometer that is connected to the Lander by a tether rather than a rigid structure. The mole is composed from a slender cylinder approximately 0.02 m wide and 0.0028 m long [17]. At its free end is a small pointed sample device that collects the subsurface sample and subsequently brings it back to the surface for onboard analysis. The advantage of a mole based system is that, if required, can be repeatedly deployed and retrieved. This is because the number of attempted penetrations is only limited to the wear of the hammering and mole mechanism. It also has the flexibility of being deployed in either a horizontal; to obtain sample from beneath a local rock, or vertical direction as illustrated in Figure 19.
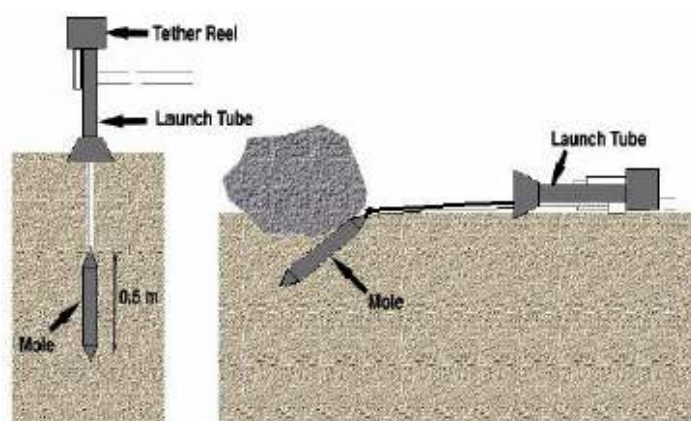
Figure 19 - Dual Configuration of the mole either vertically or horizontally [17]

When compared against conventional drilling technology, the mole produces minimal thermal disturbances, allowing for the collection and measurements of undisturbed volatile samples. A complete breakdown specification is displayed in Table 7.

Table 7: Mole Specification [17]

Mole Parameter	Value
Mole mass (with reserves) [kg]	1
Total mass (including tether, reels and launch tube [kg]	2.5
Length [m]	0.5
Diameter [m]	0.04
Peak Power [W]	10
Baseline Penetration Depth [m]	5
Performance Floor Penetration Depth [m]	2
Duration to Performance Floor Depth [h]	1.3
Reaction Mechanism Force Capability [N]	300
Target Sample Volume [cm^3]	5
Number of Holes (at 1 m depth)	10

Integrated into the mole is a complete instrument package that includes dual spectral sensors, a small microscopic camera and a short wave infrared spectrometer that is combined with a raman spectrometer. In the event of a malfunction, these instruments are able to analyze the collected soil samples without retrieving them to the surface. Such measures include the determination of particle size and shape (viewing the subsurface material through an optical port) and detecting the present of any elemental substances.

When deployed, the mole progresses into the Venus surface through an internal slider hammer system which is driven by a small electric motor. The hammer is a spring loaded system and when released, a proportion of the converted energy is transferred to the mole casing and to the surrounding soil. This results in the surrounding soil becoming compressed and displaced and so enables the initial penetration of the mole into the surrounding material. To suppress the backwards directed impulse reaction, the forward shock is transferred to a second weaker spring. No reactive forces are provided by the Lander. All supportive surface elements, which include the launch tube, tether and reels, and the winch mechanism, are incorporated into the Lander's structure. It is also the role of the Lander's power control system to power the mole. To minimize the diameter of the mole, the detector and instrument electronics are built into the Lander and remain on the surface. Light is transferred to the mole through optical ports and fiber optics cables that are inbuilt along the length of the tether and are located within the mole itself. Upon collection of the subsurface material, the mole is retrieved to the surface by a surface winch mechanism which reverses the direction of the hammer.

7.7.4.3   Venus Ground Sampling Drill (VGSD):

The Venus Ground Sampling Drill (VGSD) instrument will serve the purpose of sampling the basaltic ground on the Venus surface once the Lander has successfully touched down. The drilling equipment consists of a drilling device, modified for the specific conditions of Venus's core acquisition under a high pressure and temperature environment. The Venus Ground Sampling Drill itself consists of a storage unit, a rotary table with independent axial and rotary articulation, a sample canister and the drill itself. Once the sample is successfully collected, the sample canister will be put in the third stage of the rocket, this is achieved through the Remote Sample Collection Mechanism (RSCM).

The storage unit is a cylindrical tube of 20 cm which is in charge of containing and protecting the drill and the sample canister during the launch and the travel to the Venusian surface. The rotary table contains four mandrils whose goal is to form the subsurface drill. These mandrils are activated by four little brushless motors. It was decided to use this kind of motor in order to adhere to the low cost design in term of size, weight and power. Moreover, these motors offer several advantages over brushed motors, including higher efficiency and reliability, reduced noise, and longer lifetime (no brush erosion). Drilling is performed with a rotation rate between 10 and 100 rpm depending on the resistance of the soil materials. The drill will be a cylindrical tube of 20 cm with a diameter of 4 cm as

well as the sample canister. At the bottom of the sample canister, a core cutting and closure device is attached in order to cut the sample and to close the canister before bringing it back to the rocket. It is based on a concept patented by *Diamant Boart* and comprises a cutting diaphragm system and a spring plate basket for retention of the sample particles in the container tube.
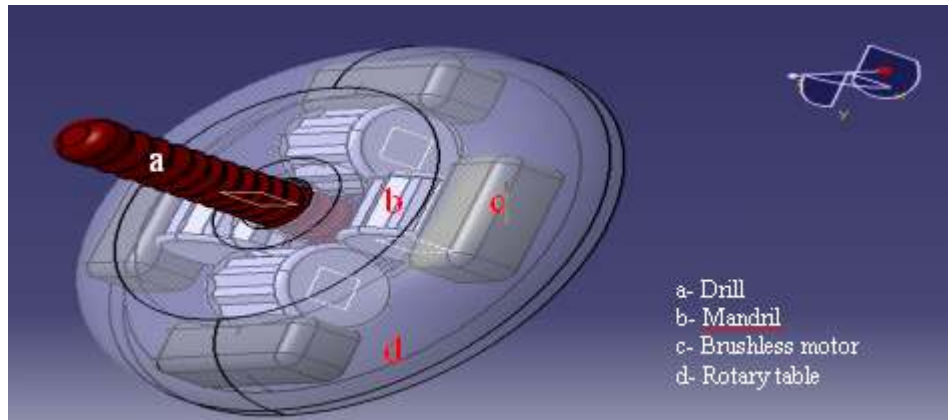
Figure 20: View of the Drilling System
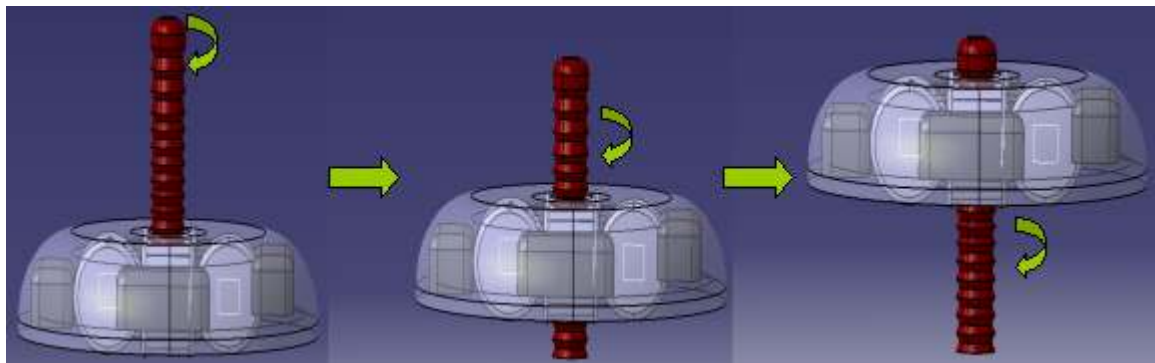
Figure 21: Front View of the Drill Under Operational Conditions

Table 8: Venus Ground Sampling Drill Characteristics

Parameter	Value
Mass (Kg)	10
Power (W)	45
Size of the sample canister (cm)	4x20
Mass of the sample (Kg)	0.7
Drilling speed (mm/min)	6
Drilling time (min)	34
Drilling depth (cm)	20
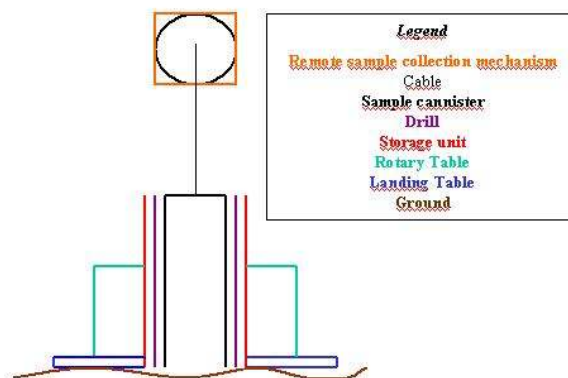
Figure 22: Ground Operations

Drilling Operations Activated

End of the drilling, core cutting and closure device activation

Sample canister extraction
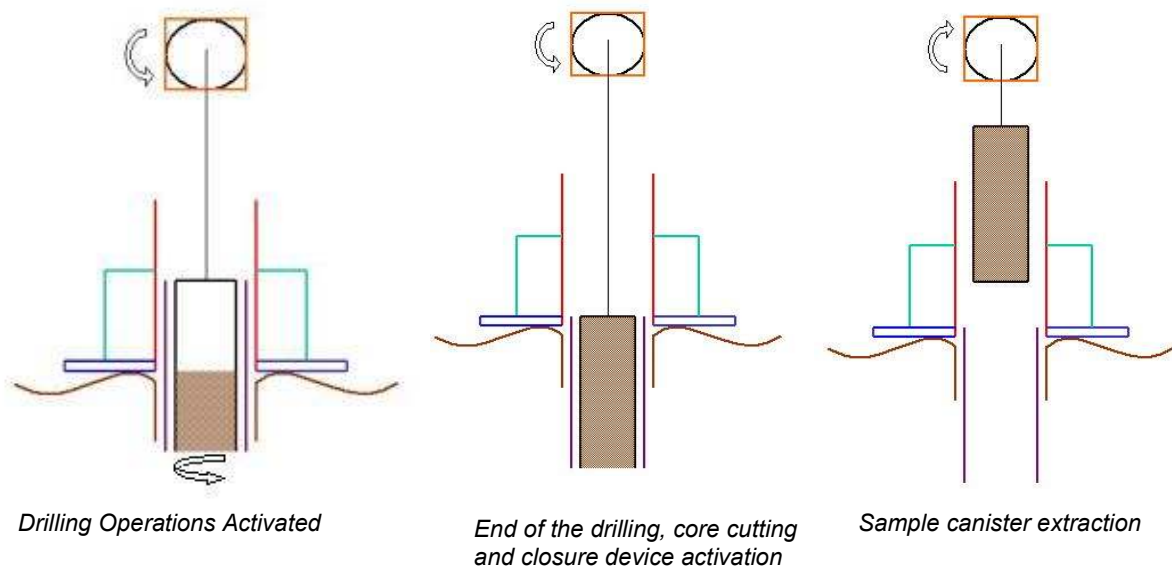
Figure 23: Operational Sequence

The Remote Sample Collection Mechanism system is an innovative approach to the extraction of the drilled samples. By a cable deployed by a wheel, the system rapidly retrieves a sample while the spacecraft is momentarily drifting approximately 5 meters above the surface. More precisely, the sample collector is retrieved by a Storable Tubular Extendable Member manufactured by TRW Astro Aerospace.

For our mission, by using this system, both sample canisters (mole's and VGSD's) will be brought back in the rocket through the two holes made on the sides of the rocket while the rocket will be flying attached to the balloon.

7.7.4.4   Science Deployment Mechanism

Due to time constraints the operations to obtain a surface sample will run in parallel with other processes; the drilling mechanism will be activated once the Lander has been stabilized on the ground. To start the sample extraction from the surface, the drilling probe will commence first.

7.7.5   Sample Protection and Containment

In order to conduct scientific studies on the returned samples, the integrity of the samples must be maintained. The core sample will be excavated by the drill (VGSD) and will have a specific length and diameter. This sample rod will then be placed in a fitting cylindrical canister. Surface samples will be placed in sealed containers, as will additional subsurface samples obtained by the mole. Atmospheric samples will be captured in pods described in a later section.

The conditions that the sample is exposed to should be recorded until its return to Earth. Measurements made should include temperature, pressure, radiation exposure, magnetic field, shock and acceleration experienced by the sample. Such knowledge will allow for a better understanding of its integrity level.

8   Venus Surface Launch and Orbiter Rendezvous

8.1   Venus Surface Launch Overview

After descending to the surface, landing successfully, and conducting all relevant science objectives, the collected samples must be returned to orbit.

Due to the vastly different conditions present on the surface and in the atmosphere of Venus, many considerations had to be taken into account. Since the pressure close to the surface of the planet is almost ninety times that on Earth and the sulfuric acid content is astronomical throughout the atmosphere, a joint metal bellows, weather balloon, two stage rocket approach was taken to safely return the sample to LVO [18]. The metal bellows will be filled with Helium from cryogenic cooling tanks being used to cool the Lander. The bellows will expand to a predetermined size and corresponding height. At which point, using pressure valves, the helium will be transferred to an attached weather balloon. The weather balloon will act in a manner similar to the bellows, expanding to a given diameter. At this point, the enclosed payload will be launched on a two stage rocket, in order to reach LVO. The first stage will be used to climb the last few kilometers to orbit, and the second stage will be used for orbital insertion. At this point, soft docking techniques will be used to safely capture and stow the Venetian samples aboard the orbiter for return to Earth (see Figure 24).
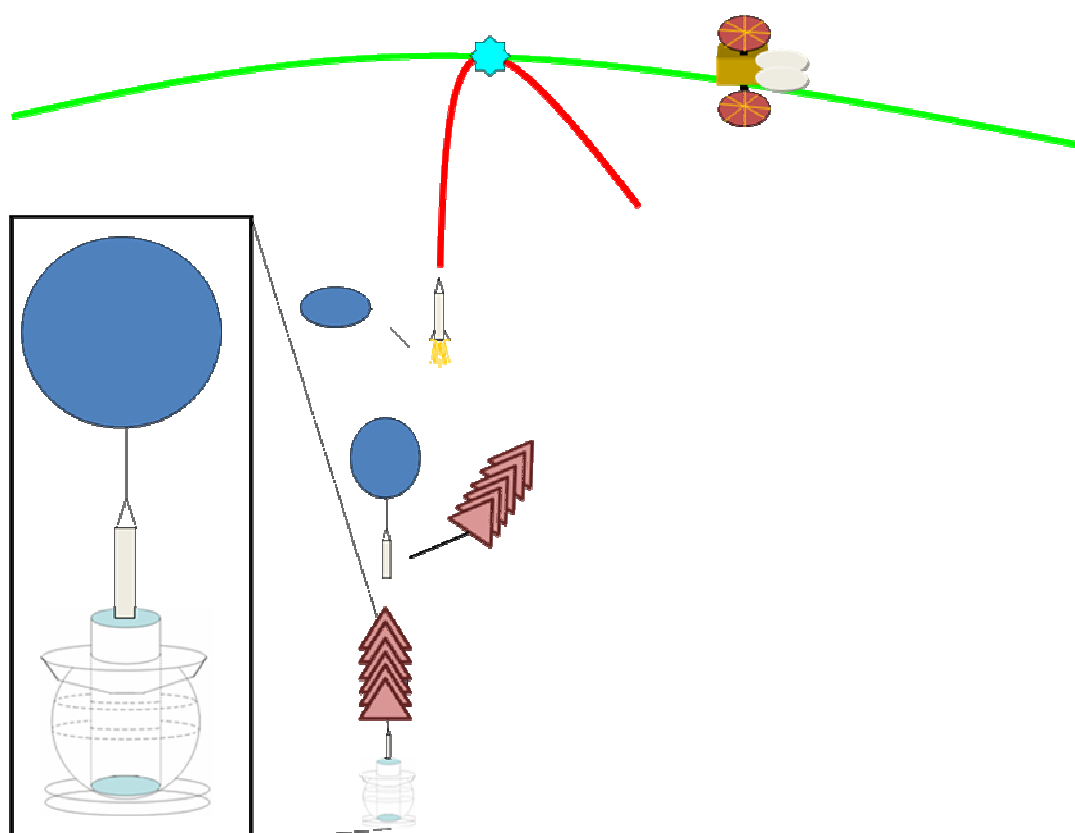
Figure 24: Proposed method of ascent from the surface of Venus

8.2   Launch from Surface of Venus

To begin the ascent from Venus, liquid helium will vaporize from the temperatures on the Venetian surface. The helium gas will escape through a pressure relief valve into a metal bellows capable of the first ascent stage. Part of the helium will already be vaporized due to the need for thermal control of the solid rocket booster at the core of the Lander. Without this thermal protection, cracks and premature ignition of the booster would be certain.

8.2.1   Bellows Design

The first stage ascent technology will use a metal bellows capable of lifting the sample/high altitude balloon and booster to ~60 km. This is necessary because of the high temperatures and pressures at the surface which no balloon laminate to date can withstand. The material of choice for this system is to be determined, due to the complexities of the thermodynamic gradient of Venus' atmosphere.

8.2.2   Balloon Design

At the equilibrium altitude for the bellows/payload system, the helium gas will be transferred to a high altitude balloon on the order of 160,000 m^3. Based on first order approximations, this amount of helium will enable the system to reach an altitude of ~120 km, reducing the delta-v required to orbit and allowing for stable atmospheric conditions for the booster ascent. The high altitude balloon to be used will be a standard high altitude balloon often used by the Columbia Balloon Launch Facility / Wallops Space Flight Center. With the helium transfer complete, the bellows will be jettisoned, reducing overall weight and allowing for the continued ascent of the system.

8.2.3   Rocket Specifications

At balloon equilibrium altitude, the booster assembly will ignite, puncturing the high altitude balloon as is begins its ascent, forcibly jettisoning it. The booster will be of multi staged design, allowing for an efficient insertion into orbit at 300 km altitude. The delta-v required is ~8 km/s. The rocket (overall – estimated as a single stage) will have a mass of 1500 kg solid propellant at an Isp of 290s. Since the orbiter will have all attitude and capture control, the booster's main task is to launch the sample to orbit. All docking and maneuvering will be controlled by the orbiter.

8.3   Rocket and Orbiter Rendezvous and Capture

Once the rocket reaches an altitude of 300 km, it will be place in a parking orbit by the maneuvering of attitude control mechanisms where it is to autonomously rendezvous and be captured by the Orbiter. According to research being conducted under Dr. William Heaps at NASA Goddard Space Flight Center, the procedure for rendezvous will include a laser system that will allow the Orbiter to capture

the rocket safely. The system will consist of three subsystems, each containing a tunable laser, a Fabry-Perot Etalon, a retro-reflector and detector (see Figure 25).
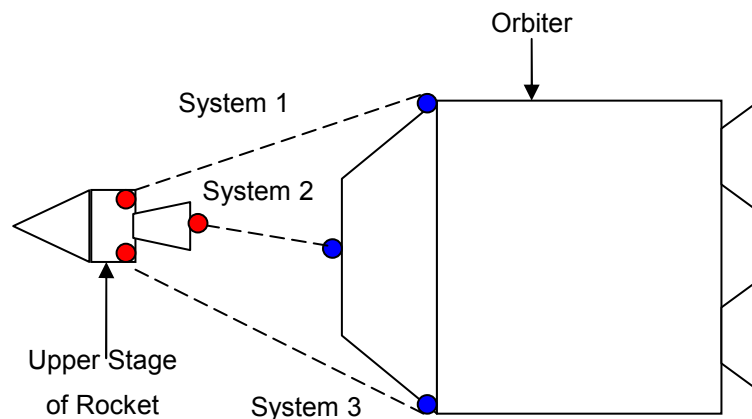
The following represents one system:
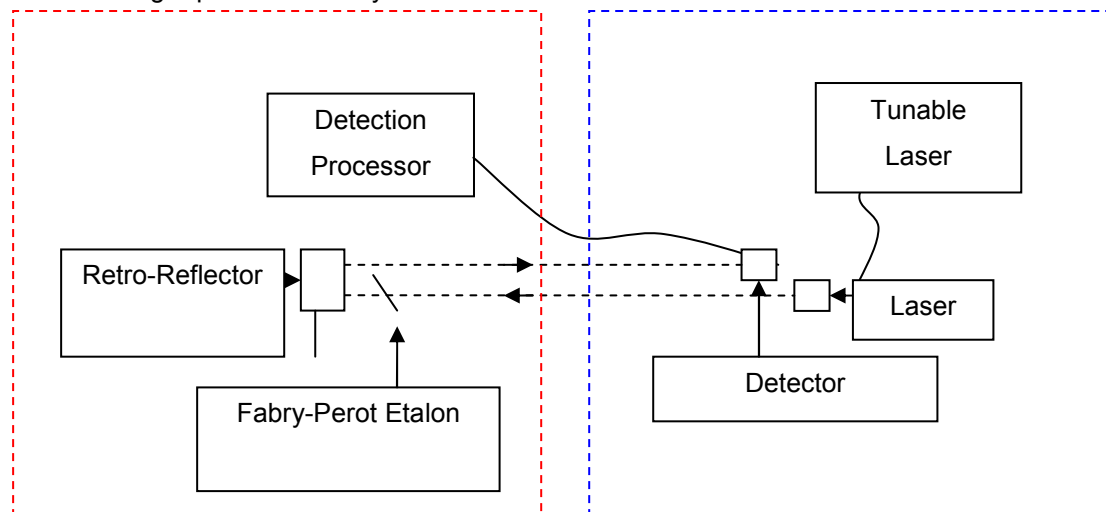
Figure 25: Schematic of the autonomous rendezvous and capture system

The tunable laser will send a range of low infrared wavelength laser beams towards the Fabry-Perot Etalon (FPE) and the retro-reflector. The FPE, due to the multiple reflections of light between the two reflecting surfaces allows for constructive interference for in phase beams which corresponds to high-transmission peaks etalon, will only allow certain wavelengths to pass through it and hit the retro-reflector. The retro-reflector reflects light 180 degrees on a parallel beam back in the direction it came. The sequence of transmitted light through the FPE will appear as a series of flashes of light. From these flashes, the detector can tell the angle and distance the rocket is away from the Orbiter. One reason for three identical subsystems is to ensure the overall system will still work if one subsystem fails. Another reason for three identical subsystems is to provide a three-dimensional coordinate of the rocket.

Opened hatch   Orbiter

Upper Stage
of Rocket

Rocket's
Capsule   Capsule
Cushion   Open slot
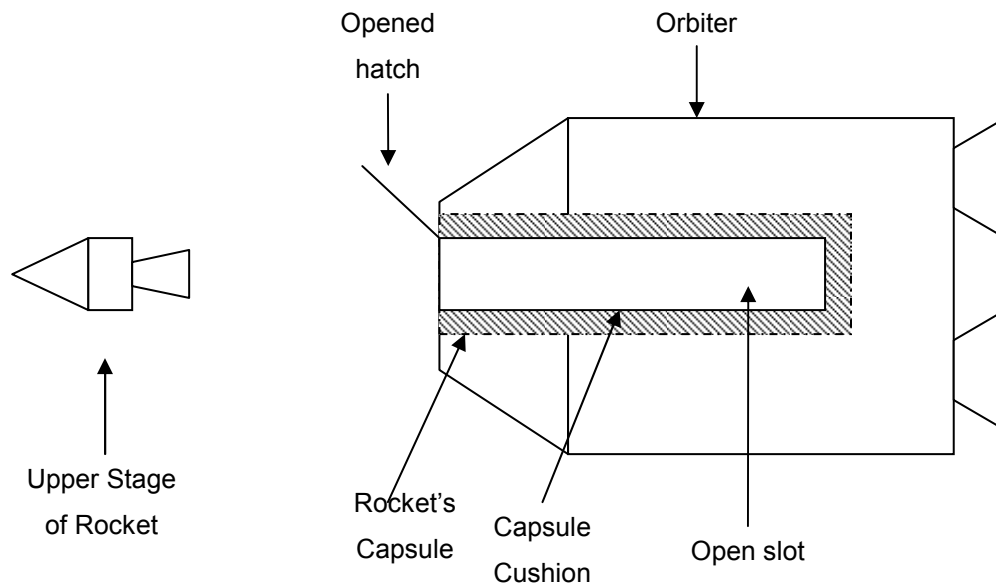
Figure 26: Schematic of the rocket being captured by the Orbiter.

Once the Orbiter is aligned with the rocket, the rocket can guide smoothly into the Orbiter (Figure 26). The Orbiter will contain a cushioned capsule, the same dimension and size as the rocket's capsule aboard the Lander. This capsule will protect the rocket during the Earth's re-entry phase of the mission to its safe return home.

8.4   Venus Atmosphere Samples Collector (VASC):

This instrument is in charge of sampling twelve different layers of the Venus atmosphere. To achieve this goal, the design uses twelve pressurized gas sampling containers. These gas sampling containers are capable of obtaining, isolating and transporting samples of gas under pressure. The containers employ valves which allow introduction, flow through and exit of the gas sample. These containers are especially suited for use in automated sampling apparatus under high pressure environments and are able to be opened and closed automatically. A number of holes will be made all around the exterior wall along the third stage of the rocket coming back from Venus to horizontally access the containers and to allow gas to enter it.

In order to thermally isolate the containers, a layer of aerogel will be used around the containers plane. Aerogel is not like conventional foams, but is a special porous material with extreme microporosity. It is composed of individual features only a few nanometers in size. These are linked in a highly porous dendritic-like structure. This exotic substance has many unusual properties, such as a low thermal conductivity (8 mW/m/K at 1 Torr) that we will use to keep the containers at a temperature as constant as possible.

In addition, there will be two sensors to measure the temperature and the pressure of the atmosphere at the exact moment when the atmospheric samples are taken. For this purpose there are two other holes in the top of the third stage of the rocket.
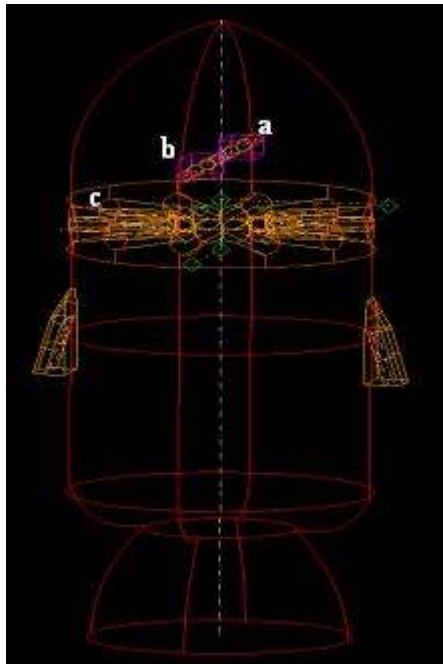
Figure 27: Front view of the Third Stage of the Rocket Coming Back from Venus

a- temperature sensor

b- pressure sensor

c- sample containers

(V_tube = $\pi*0.75^2*6$ = 10.60 cm3 for each sample)
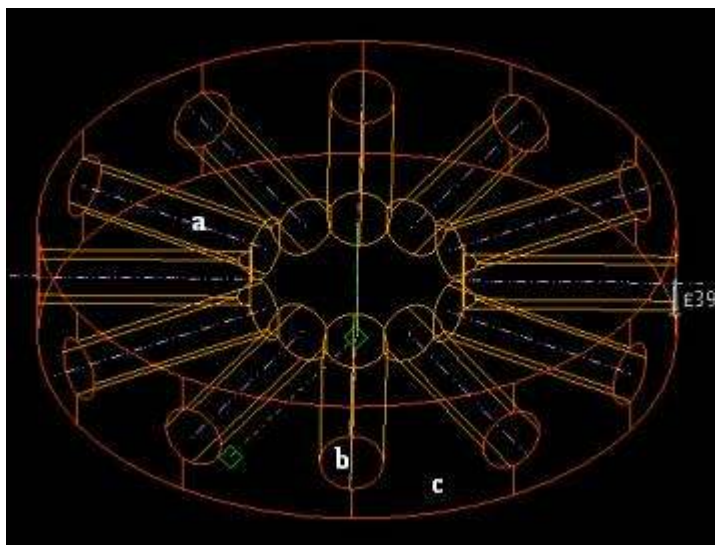
Figure 28: Symmetric View of the Containers and the Aerogel Layer

a- *sample containers*

b- *opening to the atmosphere*

c- *aerogel layer*

   (h aerogel layer = 3 cm)
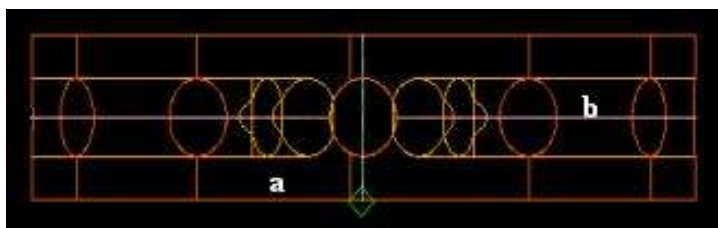
Figure 29: Font View of the Aerogel Layer

a- aerogel

b- sample containers

Within the design, the decision was made to incorporate the sample containers on the third stage of the rocket, on its ascent from the Venusian surface towards the Orbiter. Otherwise the speed and the

temperature would have been far too intense during the descent into the atmosphere to collect the samples let alone collect any *in-situ* measurements. All the measurements will be taken "under the balloon", before lighting of the rocket engine begins.

Given the approximately altitude layers of the atmosphere, it was decided to open each tube for three seconds, completing the sample collection method.

9   Venus to Earth Trajectory

After rendezvous with the sample, the spacecraft does its third ΔV in order to leave the circular parking orbit around Venus and achieves a Hohmann transfer to Earth. Since this is a sample return mission, planetary protection rules, as defined by the Committee on Space Research (COSPAR) must be taken into consideration. For some missions, trajectory biasing might be required, if so, then the spacecraft's return trajectory is designed to take it on a fly-by of Earth. When onboard, if the sensors validate that the sample is still contained, then a final ΔV occurs to insert it into Earth orbit before it passes by.   After consulting the Planetary Protection Officer, Perry Stabekis, it was determined that trajectory biasing is not needed on a Venus Sample Return Mission because of the very low probability of encountering any biological contamination on Venus that might harm Earth (Stabekis). Therefore, the return trajectory from Venus to Earth can be a standard Hohmann transfer. Near the end of the Hohmann transfer, separation of the Orbiter and sample return capsule will occur. The Orbiter will continue on a flyby trajectory of Earth. This will save the fuel that would be necessary to do a ΔV to capture the Orbiter into an Earth rotating orbit. The landing site chosen is the desert region of Utah, which is ideal because it is an isolated area near the equator.

10   Earth Landing

An Earth entry capsule has been designed with the goal of protecting the samples of the Venus atmosphere and surface from harm.   A direct entry approach will be used with a series of parachutes and specific ground operations to transfer the capsule undamaged from the Orbiter spacecraft to the surface of the Earth.

10.1   Sample Canister Release

Before release of the sample return canister, a decision for go-no go will be made by ground operators. If the decision to go is made, a command will be given from Earth for the Orbiter to perform an attitude adjustment maneuver to reorient into the correct position. Also previous to the release of the canister, the batteries and the avionics in the vehicle will be turned on. Both the initialization of the instruments and the release of the canister will be controlled by a timer. A spin mechanism will be used to spin up the canister in order to provide stability in its path to the Earth. At the moment of release, an onboard timer will be activated. Immediately after the release of the

sample canister, the Orbiter will perform a maneuver to prevent the spacecraft from entering the atmosphere of the Earth. The Figure 30 shows the canister being release from the Orbiter.
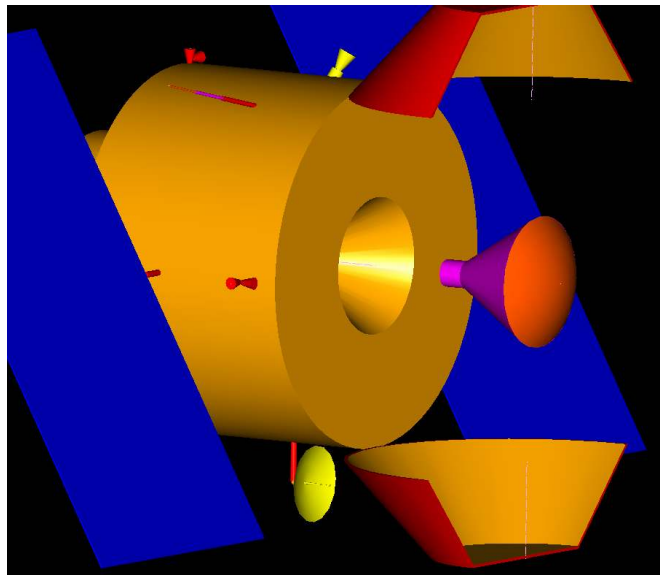
Figure 30: Sample Return Canister Release from the Orbiter

10.2   Re-entry Vehicle Design

The reentry sample canister is a blunt body spacecraft that contains structural and thermal capabilities to protect the samples from the Earth's environment. The first hours after release will be the period of maximum thermal and structural intensity. In order to protect the samples from the heat, the canister will have a heat shield constructed of an ablative material. Extensive thermal analysis and testing of the entry vehicle will be required prior to launch, as the primary goal of this mission is to return unharmed samples back to Earth. For structural protection, the sample canister inner structure will be constructed with a carbon-carbon material. Carbon-carbon is a lightweight, yet structurally sound material that can protect the samples upon impact without adding too much mass.

The earth entry system will rely on an accelerometer, altimeter, and timer for commands to the spacecraft.   Upon entering the atmosphere, the capsule will experience deceleration from aerodynamic friction.   This friction will cause extremely high g-forces which will decrease as the canister descends. The release of the drogue parachute will take place when the accelerometer reaches a value of 3 g's. Above this acceleration, the parachute attachment would not be able to safely withstand the forces.   The command to release the drogue parachute will blow three pyrotechnic bolts which held on the top cover of the canister. There will also be a backup system for the release of the drogue parachute in the case of failure of the accelerometer system. A timer will release the drogue parachute at an instant approximately three seconds after the parachute should have deployed. The drogue parachute will help to stabilize and slow the vehicle until the release of

the main parachute. The main parachutes will be deployed by a command from the altimeter when the reading reaches 3 km.

11   Re-entry Landing Site and Post Landing Operations

The landing site for the Sample Return Mission will be the Outback of the Utah Desert. The dry and consistent weather conditions of this region along with the minimal human population will reduce the risk of tampering. This could otherwise potentially harm the scientific integrity of the samples through cross-contamination. To facilitate the location of the return canister, there will be a UHF beacon antenna for tracking. For visual assistance, the descent parachute will be manufactured from fabrics of bright colors.

11.1   Sample Retrieval

Once the Earth re-entry vehicle has successfully touched down, a dedicated Recovery Team will be sent out to collect the vehicle along with the enclosed sample canister. To reduce the probability of Earth contamination the re-entry vehicle must be retrieved within a reasonable amount of time. Once collected, the Earth re-entry vehicle will be transported to a dedicated clean-room, whereby the re-entry vehicle is then separated from the heat-shield and back-shell and examination of the returned samples can finally begin. Before committing to a Venus Sample Return mission a dedicated Receiving Facility is to be built/adapted and commissioned.

The primary concern for the study of the returned samples will be the issue of possible contamination by non-Venus material. During Earth transportation, modes of manipulation and return capabilities it is critical that no false positive detection will occur. These issues are addressed by a two procedures – minimizing exposure and monitoring potential contaminates [19]. Minimizing exposure can be obtained by double bagging the re-entry vehicle during transport, and establishing a positive pressure N2 purge on the sample canister once it is returned to the clean-room, this methodology was utilized on the NASA Stardust Mission. Once the Earth Receiving Facilities are operational, both primary and secondary barriers are employed. Such primary barriers include; gloves, gowns, mask, bio-safe cabinets, projection suits and the use of good laboratory techniques [19]. In comparisons the second barriers are addressed through facility design with airtight rooms, air handling and filtering.

11.2   Returned Sample Science – Earth Laboratory

Upon their arrival on Earth onboard the VSTAR return spacecraft, the samples will be taken to a laboratory equipped for petrologic study of the specimen. Within this laboratory, the returned samples would be able to be analyzed using accurate, reliable and precision rated instruments that are able to

conduct a greater variety of tests than the *in-situ* science instruments. Proposed analyses of the geologic samples once they have been received at the laboratory include:

- Mass spectrometry: Mass spectrometry measures the mass-to-charge ratio of ions. This can assist in determining the isotopic composition of elements in a compound. It can also observe fractionation and thus determine the structure of a compound.

- Mössbauer spectroscopy: The Mössbauer spectrometer uses gamma radiation to determine the chemical environment of the sample and can be used to characterize it. It is most useful in the study of iron-bearing materials, a group to which basalt belongs.

- Radiation studies: To investigate the penetration of cosmic rays into the Venusian atmosphere, it is important to study the surface rock to find what, if any, amount of the solar radiation that hits Venus travels all the way to its surface. To accomplish this task, scientists would study the amount of rock affected by exposure to cosmic rays.

- Mineral optics: Thin sections of the surface rocks and rock core should be cut for use under the petrographic microscope. With the microscope, the optical properties of the bedrock material can be analyzed.

- Scanning Electron Microscope (SEM): Thin sections of rock can be observed using the SEM to find elemental compositions and abundances. The SEM can also be used to image the sample at close range with high resolution.

- Stable isotope geochemistry: After grinding a part of the sample to powder, it is possible to complete analyses that result in the revelation of the stable isotopes within the sample and their abundances.

- Radiometric age dating: Using RAD scientists can find the age of the Venusian highlands. Since these are the oldest parts of the crust, it is possible that this age will show the time since the most recent global crust replacement.

- X-ray diffraction powder studies: Once a small portion of the sample has been ground into dust, melted at high temperature, and allowed to cool into a glass, XRD analysis shows elemental and mineral composition.

- X-ray fluorescence (major, minor, and trace element geochemistry): XRF analyses are used to determine bulk composition of the sample.

Within an Earth-based laboratory, it would also be possible to perform a number of unplanned tests, when unanticipated questions and/or findings arise. This can not otherwise be achieved through remote sensing or *in-situ* analysis.

12 Conclusion

The Venus Sample Return Mission as discussed in this paper is the result of work completed by the 2007 NASA Academy at the Goddard Space Flight Center. This preliminary concept study involves areas such as, science requirement and justification; launch vehicle analysis and selection; trajectory to and from Venus; spacecraft and subsystem design; landing vehicle architecture and landing site selection. Throughout the investigation and report, the scientific requirements and justifications were considered to be the driving force that influenced all major system and subsystem design.

Following the launch and transfer from Earth via a Hohmann maneuver, the Orbiter is placed in a circular parking orbit around Venus. The Lander is released prior to orbital insertion and follows a ballistic trajectory to the surface. During the descent several key mechanisms are employed to control the Lander maneuvers - these include a heat shield, dual parachute systems and a novel disk break. Once on the surface, the science surface operations commence whereby, through utilization of a drill, robotic arm and *in-situ* instruments, a 2 kg sample of surface and subsurface material will be collected. These samples are then inserted into the Venus Ascent Vehicle for ascent from the surface. The ascent vehicle is comprised of metallic bellows, a balloon and a multi-stage rocket. During ascent twelve atmospheric samples at varying heights are obtained. From Venus orbit, the passive sample canister will be released and picked up by the awaiting Orbiter. After rendezvous the Orbiter will perform a return Hohmann transfer back to Earth. At Earth the entry vehicle descends, entering the atmosphere. Following touchdown the samples are carefully contained, concealed and transported to an Earth Returning Faculty for detailed scientific analysis. Through this analysis the detailed mineralogical, chemical and isotropic composition of Venus is investigated, enabling scientists to gain a deeper insight and understanding into this dynamic planet and its scientific implications for planetary evolution.

To date, a Venus Sample Return mission remains a technology driver for space exploration. Initial studies showed that the immediate use of conventional rocket launching techniques was impractical in direct ascent from the Venusian surface and therefore the avenue of balloon technology was explored. However, within this initial exploration, more detailed analysis is required. This is in specific relation to how Venus's atmospheric environment (wind shear) may potentially impact any near future balloon material selection. While in comparison, a number of other more obvious technology developments are needed. These include: drilling and sample handling systems and a rendezvous and capture mechanism/system. Most importantly, a terrestrial development plan would be required to fully verify the current design of the Lander; although the design is loosely based on past missions the utilization of Duocel impact absorption material must be investigated in aerospace applications.

At this stage in the design and development process it would be premature and inherently difficult to report even a rough estimate of the total mission cost. Many manufacturers are hesitant to provide

cost predictions for the materials and fabrication of a design project such as this. Fabrication and material costs for experimental components such as the Venus Ascent Vehicle, including the ascent balloons, will not be known until the specific material has been selected. However the required technology development, complexity, ground support and multitude of diverse elements required will undoubtedly classify the VSTAR mission as a future flagship mission, with corresponding budgetary implications.

13   References

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14   Appendix A. Science

14.1   Appendix A.1: Past Venus Missions

Spacecraft Missions to Venus				
Mission	**Nation**	**Type**	**Launch Date**	**Remarks**
Sputnik 7	USSR	Flyby	Feb 4, 1961	Failed to depart low Earth orbit
Venera 1	USSR	Flyby	Feb 12, 1961	Communications failure; Now in solar orbit
Mariner 1	USA	Flyby	July 22, 1962	Launch failure
Sputnik 19	USSR	Flyby	Aug 25, 1962	Failed to depart low Earth orbit
Mariner 2	USA	Flyby	Aug 27, 1962	Flyby (36,000 km); Confirmed high surface temperature, First USA success
Sputnik 20	USSR	Flyby	Sept 1, 1962	Failed to depart low Earth orbit
Sputnik 21	USSR	Flyby	Sept 12, 1962	Failed to depart low Earth orbit
Venera 1964 A	USSR	Flyby	Feb 19, 1964	Launch Failure
Venera 1964 B	USSR	Flyby	March 1, 1964	Launch Failure
Cosmos 27	USSR	Flyby	March 27, 1964	Communications failure
Zond 1	USSR	Flyby	April 2, 1964	Communications failure
Venera 2	USSR	Flyby	Nov 12, 1965	Communications failure before arrival
Venera 3	USSR	Atmospheric Probe	Nov 16, 1965	Communications failure before atmospheric entry, Probe crashed on Venus
Cosmos 96	USSR	Probe	Nov 23, 1965	Failed to depart low Earth orbit
Venera 1965 A	USSR	Flyby	Nov 23, 1965	Launch failure
Venera 4	USSR	Atmospheric Probe	June 12, 1967	Measured %CO_2, pressure & temperature, atmospheric composition experiments.; Crash Landed
Mariner 5	USA	Flyby	June 14, 1967	Flyby (3,900 km), atmospheric structure & composition experiments
Cosmos 167	USSR	Probe	June 17, 1967	Failed to depart low Earth orbit
Venera 5	USSR	Probe	Jan 5, 1969	Atmospheric composition experiments; Failed at 26 km
Venera 6	USSR	Probe	Jan 10, 1969	Atmospheric composition experiments; Failed at 11 km
Venera 7	USSR	Lander	Aug 17, 1970	First soft landing on Venus, atmospheric composition & structure
Cosmos 359	USSR	Lander	Aug 22, 1970	Failed to depart low Earth orbit
Venera 8	USSR	Lander	March 27, 1972	Atmospheric composition & structure, photometry, K, U, Th γ-ray analysis on surface, survived for 50 min.
Cosmos 482	USSR	Lander	March 31, 1972	Failed to depart low Earth orbit
Mariner 10	USA	Flyby	Nov 3, 1973	5700 km flyby en route to Mercury, IR, UV spectra, imaging of clouds, particles & fields experiments
Venera 9	USSR	Orbiters &	June 9, 1975	Atmospheric composition &

Venera 10	USSR	Lander	June 14, 1975	structure, photometry, TV images of surface, γ-ray analysis of K, U, Th on surface
Pioneer Venus 1	USA	Orbiter	May 20, 1978	First radar mapping of another planetary
Pioneer Venus 2	USA	Bus & Probes	Aug 8, 1978	Surface, atmospheric science from bus & 4 probes
Venera 11	USSR	Flybys & Probes	Sept 9, 1978	Atmospheric science from 2 probe, no TV or surface analyses
Venera 12	USSR		Sept 14, 1978	
Venera 13	USSR	Flybys & Landers	Oct 30, 1981	Atmospheric science & XRF analyses & color images of surface
Venera 14	USSR		Nov 4, 1981	
Venera 15	USSR	Two Orbiters	June 2, 1983	Radar imaging from north pole to 30° north & atmospheric spectroscopy experiments
Venera 16	USSR		June 7, 1983	
Vega 1	USSR	Landers & Balloons	Dec 15, 1984	Atmospheric science; Balloon floated for 48 hrs at ~ 54 km , XRF & γ-ray analyses of the surface
Vega 2	USSR		Dec 21, 1984	
Magellan	USA	Orbiter	May 4, 1989	Radar mapping, altimetry, emissivity data for surface, radio occultation experiments, atmospheric science
Galileo	USA	Flyby	Oct 18, 1989	Imaging & spectroscopy of atmosphere
Venus Express	ESA	Orbiter	Nov 9, 2005	Atmospheric science, observations of Venus's cloud neck, plasma environment, atmosphere & its oxygen airglow & surface
Messenger	USA	Flyby	Aug 3, 2004	

14.2 Appendix A.2. Robotic Arm versus Self-Contained Instruments Trade Study

Robotic Arm		Self-contained Instruments	
Advantages	Disadvantages	Advantages	Disadvantages
Allows different sites to be explored	Strict operating conditions: Withstanding loads, temperature range, must fold into Lander	Instruments do not have to be deployed from Lander	Can only analyse site where Lander is brought to rest
Makes multiple sampling easier	Joints of arm must be kept lubricated	Drill system can be integrated into Lander legs	Instruments such as x-ray spectrometer must be deployed so that they can view the landing site
Samples can be transported to internal spacecraft instruments or placed on spacecraft for analysis by robotic arm instruments	Must be carefully controlled to collect samples	Samples do not have to be transported to analysis packages	Multiple sampling/analysis may be difficult due to integration
X-ray/Gamma ray spectrometer can be included on the end of the arm to analyze numerous sites	Extra space must be allocated within the Lander	Drill system can have rotating components with multiple drills	
A rock grinder can be included to remove surface dust for samples			
Redundancy is built in as a rock corer/grinder can be combined with a drill system or mole			
Low mass			

15   Appendix B. Trajectory

15.1   Appendix B.1. Lead Angle and Motion Calculations

Lead Angle Calculations

Earth to Venus (outer to inner)		Venus to Earth	
Radians	Degrees	Radians	Degrees
-0.9366242	**-53.6646**	0.625934	**35.86339**

$$\theta_{e,v} = \pi\left[1 - \left(\frac{1+R}{2}\right)^{3/2}\right] \qquad \theta_{v,e} = \pi\left[1 - \left(\frac{1+R}{2R}\right)^{3/2}\right]$$

from outer-to-inner (Earth to Venus   from inner-to-outer, (Venus to Earth)

(Conway and Prussing 114-117)

Motion Calculations

Period of Transfer Orbit				MEAN MOTION VENUS			MEAN MOTION EARTH	
a	1.2888E+11			N (rad/s)	3.2384E-07		N (rad/s)	1.99085E-07
mu_s	1.33E+20			RAD	4.09E+00		RAD	2.51E+00
T	1.26E+07	seconds		DEGREE	234.1251032		DEGREE	143.93
	2.10E+05	minutes			234 DEGREES			144 DEGREES
	3.51E+03	hours						
	1.46E+02	days						
146 DAYS								

Conclusions:
It takes 146 days for the spacecraft to complete the Hohmann transfer, travelling from Earth to Venus.
During the transfer, Venus travels 234 degrees, and Earth travels 144 degrees.

Launch Date Calculations

June 8, 2004 was the last time the lead angle was zero degrees.
Counting backwards from this date, determine when the were -53 degrees apart.

7414710	seconds
85.8184	days

Therefore, 85.8 days before June 8, 2004, Earth had the desired lead angle of 53 degrees.
This same lead angle occurs every synodic period, 584 days.
So to calculate the launch date:

15-Mar-04	85 days before conjunction
8-Jun-04	conjunction (zero degrees lead angle)
20-Oct-05	at desired lead angle
5/27/2007 0:00	at desired lead angle
12/31/2008 0:00	at desired lead angle
8/7/2010 0:00	at desired lead angle
3/13/2012 0:00	**LAUNCH DATE**
10/18/2013 0:00	

15.2 Appendix B.2. MATLAB Code Used to Help Calculate Launch Date

```
%NASA Academy 2007
%8/4/07
%Description: This file uses the mean motion of earth and venus to
%calculate the time when they are 53 deg apart (earth leads venus). This calculation was
%necessary to select a launch date/time.
clear all
clc
close all

nv=3.2384*10^-7;            %mean motion of venus, rad/s
ne=1.99085*10^-7;           %mean motion of earth, rad/s

diff=53*pi/180;             %required angular difference between the two planets
counter=1;
for i=10000:10000:10000000  %iteration to find when the angular difference is 53 deg.
    diffI(counter)=nv*i-ne*i;
    time(counter)=i;
    counter=counter+1;
end
index=max(find(diffI<=diff));    %find index of time at which they are 53 deg. apart
timeLaunch=time(index);          %find time
timeLaunchday=timeLaunch/(60*60*24) %output time in days
```

15.3 Appendix B.3. MATLAB Code Used to Calculate Changes in Velocity

```matlab
clc
clear
% Known Parameters
mu_s=1.327*10^20; %m^3/s^2
mu_v=3.249*10^14; %m^3/s^2
mu_e= 3.986*10^14; %m^3/s^2
AU= 1.496*10^11; %m
r_e_sun= 1*AU; %m
r_v_sun=0.723*AU; %m

r_e= 6378*10^3; % radius of the Earth
r_v=6051.9*10^3; % radius of the Venus
r_v=3389*10^3;
% Velocity of spacecraft wrt to Earth
EO= input(' Altitude of Earth Initial Orbit (km): ');
ro= EO*10^3 + r_e; % initial orbit around the Earth
v_sc_e=sqrt(mu_e/ro);

% Velocity of Earth wrt to Sun
v_e_s= sqrt(mu_s/r_e_sun);

% Velocity of Spacecraft WRT to Sun
v_sc_s=v_e_s+v_sc_e;

%Velocity of spacecraft in hohman transfer at Earth wrt to the Sun
v_he_s= sqrt(((-mu_s/(r_e_sun+r_v_sun))+mu_s/r_e_sun)*2);

% Infinity Velocity at Earth
vinf1=abs(v_he_s-v_e_s);
%Earth Departure
vpe=sqrt(vinf1^2+(2*mu_e)/ro);
DV1=vpe-v_sc_e

%Velocity of spacecraft in hohman transfer at Venus wrt to the Sun
v_hv_s= sqrt((((-mu_s/(r_e_sun+r_v_sun))+mu_s/r_v_sun)*2));

% Velocity of spacecraft in circular orbit around
VO= input(' Altitude of Venus Orbit for Science (km): ');
rf=VO*10^3 + r_v; % initial orbit around the Earth
v_sc_v=sqrt(mu_v/rf);

%Velocity of Venus WRT to Sun
v_v_s= sqrt(mu_s/r_v_sun);
```

```
%Earth Departure
vpe=sqrt(vinf1^2+(2*mu_e)/ro);
DV1=vpe-v_sc_e

%Velocity of spacecraft in hohman transfer at Venus wrt to the Sun
v_hv_s= sqrt((((-mu_s/(r_e_sun+r_v_sun))+mu_s/r_v_sun)*2));

% Velocity of spacecraft in circular orbit around
VO= input(' Altitude of Venus Orbit for Science (km): ');
rf=VO*10^3 + r_v; % initial orbit around the Earth
v_sc_v=sqrt(mu_v/rf);

%Velocity of Venus WRT to Sun
v_v_s= sqrt(mu_s/r_v_sun);

%Infinity Velocity at Venus
vinf2=abs(v_hv_s-v_v_s);
%Venus Arrival
vpv=sqrt(vinf2^2+(2*mu_v)/rf);
DV2=vpv-v_sc_v

%Velocity of Spacecraft WRT Venus (hyperbolic V infinity)
v_inf_v= v_hv_s-v_v_s;

v_hyp= sqrt(((((v_inf_v)^2))/2+(mu_v/rf))*2);

%Velocity of Spacecraft WRT to Sun
v_sc_s = v_sc_v+v_v_s;

%Venus Departure
vpv2=sqrt(vinf2^2+(2*mu_v)/rf);
DV3=vpv2-v_sc_v

% Final Velocity of spacecraft WRT to Earth
EF= input(' Altitude of Earth Final Orbit (km): ');
v_sc_EF = sqrt(mu_e/(EF+r_e));
vpe2=sqrt(vinf1^2+(2*mu_e)/(EF+r_e));
DV4=vpe2-v_sc_EF
```