Venus Aerobot Multisonde Mission: Atmospheric Relay for Imaging the Surface of Venus

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Abstract—Robotic exploration of surface of Venus presents many challenges because of the thick atmosphere, high surface pressure and high temperature. The Venus Aerobot Multisonde Mission (VAMuS) concept addresses these challenges by using a robotic balloon or aerobot to deploy a number of short lifetime probes or sondes to acquire images of the surface, perform atmospheric measurements and measure a fine composition of the atmosphere. Deployment of sondes from an aerobot has two compelling advantages – it permits more precise deployment than with direct entry and it makes it possible to acquire high-rate data from the sondes using very low power transmitters because of the short communications ranges of a few tens of kilometers. Sonde data stored on the aerobot can be transmitted to Earth at much lower rates because the aerobot will operate for at least a week in the Venusian atmosphere. This paper describes the Venus Aerobot Multisonde concept, which is a foundation for Venus Exploration of Volcanoes and Atmosphere (VEVA), a proposal to NASA's Discovery program. Besides discussion of aerobot performance, the paper deals with communications, navigation and drop sonde instrumentation issues, which are key factors for mission success.

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1. INTRODUCTION

In spite of a number of successful missions to observe the surface and interior of Venus, a number of fundamental questions about the planet have yet to be resolved. The Venus Geoscience Aerobot (VGA) concept developed in 1995-1997 planned to make multiple excursions from high altitudes in the Venus atmosphere to conduct observations at or near the surface in order to address these questions[1]. The VGA requires a number of new technologies, including high-temperature balloon materials, gondola thermal control systems and a reversible fluid altitude control technique which will require a significant investment and at least five years of development. The VGA also requires an orbital relay system that significantly increases the overall mission cost.

The Venus Aerobot Multisonde (VAMuS) Mission was conceived to provide many of the scientific capabilities of the VGA with existing technology and without requiring an orbital relay which would result in a significant reduction of mission cost. It consists of two or three autonomous floating stations (aerobots), which would deploy 4 to 6 drop sondes equipped to acquire high-resolution science data from near

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the Venus surface. Data would be communicated from the sondes to the floating station and relayed from there to Earth. The total mission cost is believed to be well within the scope of a NASA Discovery mission. In this paper, we describe the VAMuS mission concept [2] with emphasis on communication aspects of the mission.

2. VENUS AEROBOT MULTISONDE MISSION CONCEPT

The environment of Venus presents major challenges for scientific exploration. A thick atmosphere of carbon dioxide, with a surface pressure of 92 bars and clouds and haze in the upper reaches, totally obscures the planet's surface from orbital observation except for radar imagery. The vertical structure of the atmosphere of Venus is shown in Figure 1 (see [3]).

The surface temperature is about 460 °C and therefore long duration surface vehicles for in situ investigation require radioisotope powered refrigerators or high temperature electronics or both and become complex and extremely costly. Short duration observations in the lower atmosphere using small expendable sondes that maintain their contents at the operating temperature of conventional electronics through passive thermal protection for a few hours are a much more attractive solution. However, to be effective as an exploration tool, these sondes must be able to communicate large amounts of data during their limited lifetime. In particular, it is desired to acquire high resolution aerial imaging from near the surface of the planet for a number of targets of high scientific interest.

Although the surface of Venus is hostile, the environment in the upper atmosphere is quite mild. In fact, Venus above 52-53 km altitude resembles the atmosphere of Earth except for the presence of sulfuric acid haze-like clouds. With permanent clockwise 65 to 100 m/s winds, this region provides many advantages for aerobots. However, because of clouds, hazes and Rayleigh scattering the surface of Venus can not be seen from this altitude in the visible band.

The innovative feature of the VAMuS mission is to use aerobots (balloons) flying at 55-60 km altitude as both a *delivery system* and a *high data rate communications relay* for multiple low-cost imaging drop sondes. By using an aerobot delivery and relay system it is possible to deliver more sondes with higher accuracy and with higher data return than when sondes are delivered to Venus by direct entry. The VAMuS mission concept is illustrated in Figure 2.

Each aerobot upon emplacement consists of a gondola and multiple drop sondes suspended from a superpressure balloon. The balloon maintains the vehicle at an altitude of constant atmospheric density in the Venus atmosphere except for perturbations caused by downdrafts and probe deployments. Superpressure balloon deployment and inflation was successfully demonstrated in 1985 in the Venera Vega balloon mission. Each of two Venera Vega balloons was tracked for two days in the Venus atmosphere. More recently, in August 1998, JPL demonstrated at Earth an aerial deployment and inflation of the Vega-size balloon but made of material 17 times lighter. This successful demonstration indicates the feasibility of modern, high-payload mass fraction aerobot missions to worlds with the dense atmospheres like Venus and Titan.

Sonde Deployment—Aerobot platforms make it possible to sequence deployments and target sondes based on what has already been learned from earlier missions. A radar map of Venus was obtained by the U.S. Magellan mission in the 1980s and allows important scientific targets to be identified. From a float altitude of about 60 km, the sondes can be dropped with an accuracy of a few tens of km which is much better than could be achieved from a direct entry.

After deployment from the aerobot, each sonde will descend rapidly towards the surface. At an altitude of a few kilometers, the descent is arrested by a parachute or gliding device that permits an extended data acquisition period near the Venus surface. Carried by the fast westward high altitude winds, the aerobot will move rapidly to the west of the dropped probe. Based on initial analysis, the descent speed of the sonde, the thermal survival time, and the period for which the aerobot remains within visibility of the sonde are roughly commensurate permitting about 15-30 minutes of high rate imaging data near the surface..

Communications—The proximity of the aerobot to the sondes provides high data rate communications at rates of the order of 1 Mb/sec. These data must then be stored on the aerobot and communicated to earth with a directional antenna to provide high performance communications with Earth at rates of order 10 kb/sec. There is no requirement for the use of a relay spacecraft or orbiter at Venus which reduces the cost and complexity of the mission.

3. VEVA MISSION OVERVIEW

The proposed NASA Discovery mission, Venus Exploration of Volcanoes and Atmosphere (VEVA), involves the delivery of two identical payloads to Venus. Each entry vehicle consists of a large sonde designed for atmospheric composition measurements and a balloon/gondola system with drop sondes. An aerodynamic heat shield encloses the payload and provides initial g load protection and support for the entry phase. After entry, the heat shield is jettisoned,

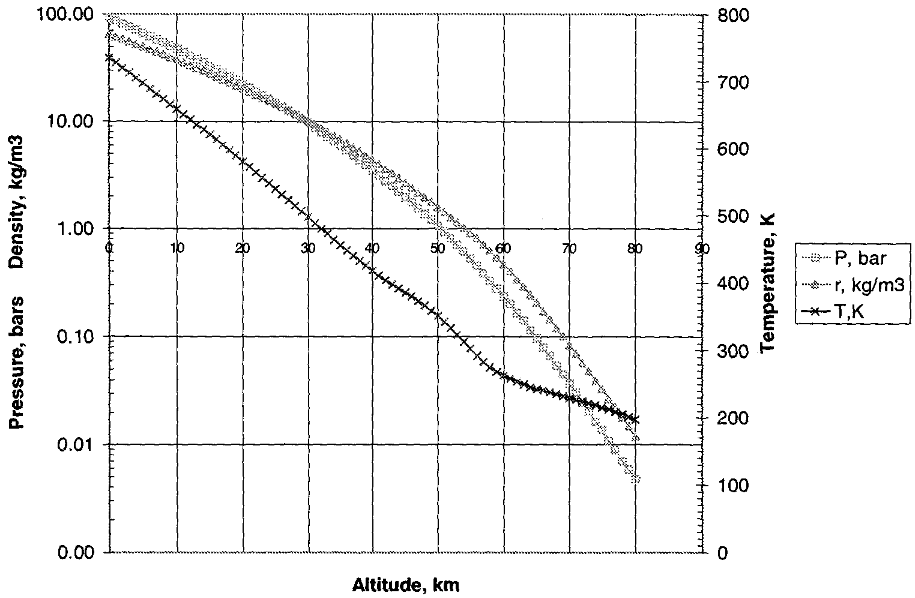

Figure 1. Vertical structure of the Venus atmosphere

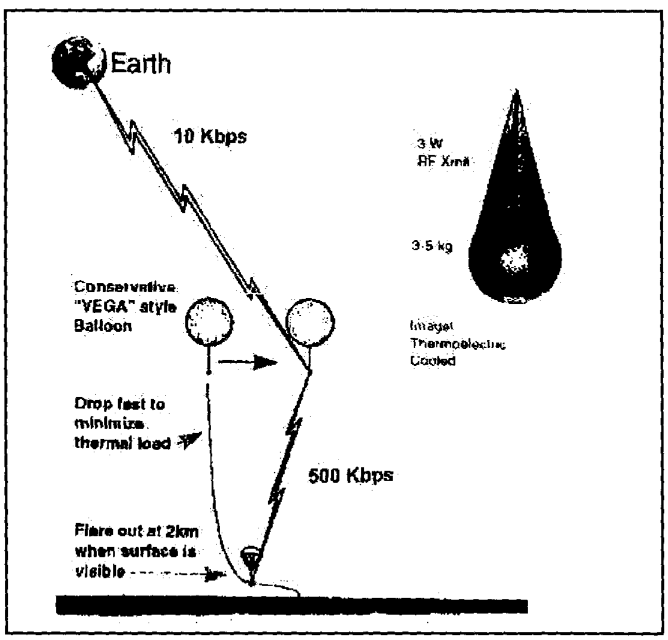

Figure 2. Venus Aerobot Multisonde (VAMuS) mission concept

the atmospheric sonde begins its fall to the surface and the balloon inflates, which arrests its descent and provides lift to maintain a 60-km float height. The balloon carries an instrumented gondola with battery power for 7 days as it circles Venus. Each gondola carries four small (imaging) sondes for release at different times during the mission. Several kinds of science measurement are made:

- The two large sondes are released from their respective gondolas on entry and fall to the surface in about 37 minutes. They measure composition below 20-km altitude to the surface and an integrated suite of instruments provides a detailed characterization of the atmosphere.
- The eight smaller sondes free fall to 5 km above the surface where a small gliding parachute opens to slow the descent and provide horizontal offsets between successive images. These imaging sondes also carry an integrated atmospheric physics sensor suite to measure ambient conditions. Each sonde will be equipped at a minimum with an imaging system. The feasibility of an integrated imager, laser altimeter and spot spectrometer is being explored. Initial indications are that once below 5 km the contrast attenuation produced by the Venus atmosphere for albedo features is less than a factor of five. Consequently, features in the Magellan imagery will be readily recognizable for putting the probe data in a global context. The highest quality, best spatial resolution images will be acquired beneath 2km altitude Measurements of the chemistry in the low atmosphere is another key objective and micro-miniaturized mass spectrometers are being examined for this application
- The gondola also carries an atmospheric physics suite to measure ambient conditions at the 60 km altitude for a period of up to seven days an will use a magnetometer to search for solar wind produced and intrinsic magnetic fields. Radio tracking with the Deep Space Network will be used for precise measurements of horizontal winds

The primary communications mode for both large and small sondes is through the balloon. A low data-rate S-band system can be used to derive positional and wind information from the ground-based VLBI and Doppler measurements.

Parameters of the sonde descent and of the relative motion of the aerobot and the sonde are shown in Figure 3. When the sonde approaches the surface the distance to the aerobot is about 90 km. In the next 20 min it grows to 200 km. At this time an elevation angle of the aerobot is ~ 19 deg. Atmospheric absorption practically does not influence a performance of the UHF link between sonde and balloon.

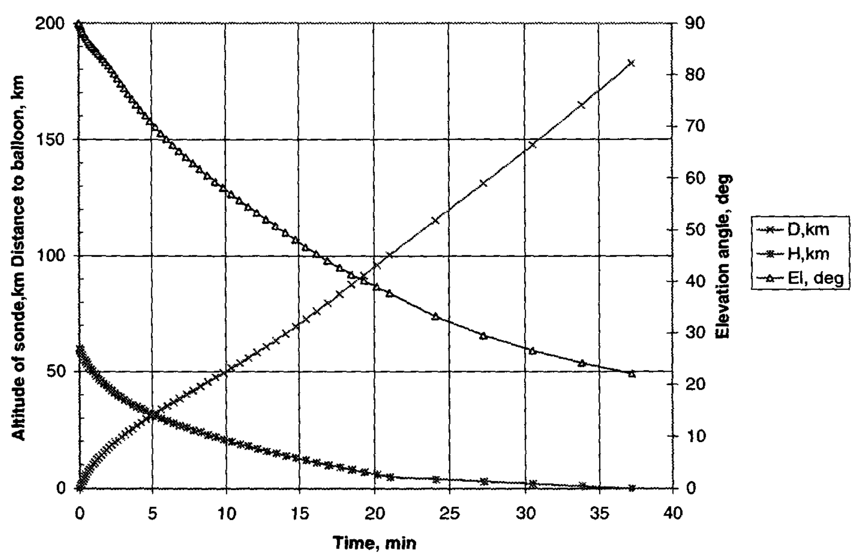

Figure 3. Parameters of the sonde descend and of the relative motion of the aerobot and sonde

4. COMMUNICATIONS

The relatively short distance between drop sonde and aerobot enables very high data rate transmissions with a simple low-power UHF link as compared to 150 million km direct transmission link to Earth.

The link budget at the maximum distance between the drop sonde and aerobot is shown in Table 1.

Table 1. Drop sonde—relay balloon link budget

Parameter	Units	Value
Transmitted power	W	1.0
Drop sonde antenna gain (monopole at 20° elevation)	dB	1
Frequency	MHz	400
Range	km	200
Receiving antenna gain (monopole at 70° nadir angle)	dB	1
Data rate (Convolutional code 7,1/2)	kbit/s	512
Bit error rate		10^{-6}
Data margin	dB	3.5

This link would allow transmission of one 1024 x 1024 pixel frame in approximately 20 s. Given 45 to 60 high resolution pictures for each of four drop sondes, the total volume of data from all sondes will be approximately 2.5 Gbit. A mild 3:1 data compression on the aerobot will reduce this volume to 830 Mbit. The baseline concept is to transmit this data to Earth using an articulated high-gain X-band antenna on the aerobot. The Mars Pathfinder flat array antenna was used as the baseline concept for analysis. The link budget for direct-to-Earth link is given in Table 2.

Table 2. Relay balloon direct-to-Earth link budget

Parameter	Units	Value
Transmitted power	W	13
Aerobot antenna gain	dB	24
Frequency	MHz	8430
Range	Mln km	150
Receiving antenna gain	dB	74.1
Data rate (turbo code)	kbit/s	10
Bit error rate		10^{-6}
Data margin	dB	6

Approximately 24 hrs is required to transmit all data stored on the aerobot to Earth.

The aerobot antenna beamwidth is roughly 10° so the antenna needs to be pointed in the Earth direction with an accuracy of 2° or better. The signal transmitted by the DSN stations will be used as a beacon to find the Earth direction. During free flight, the aerobot moving with the wind remains exceptionally stable in the vertical direction, although it can slowly rotate along the vertical axis with the typical rotation period exceeding 20-40 min. After initial acquisition of the Earth, a simple one-dimensional tracking will be sufficient to maintain communications.

A stable nature of Venus circulation (during Vega balloons flight in 1985 [4] wind variations were within 2 m/s) makes possible Doppler, range and VLBI measurements will be used to determine position and drift of the aerobot and to target the drop sondes.

5. TECHNOLOGIES FOR VENUS MICROSONDEMISSION

Here we review the status of some of the key technologies needed for such mission.

Balloon Deployment and Inflation—After separation from the aeroshell, the descent velocity of the VEVA payload elements is reduced by a 7-m diameter parachute. The thick Venus atmosphere provides ample time to deploy and inflate the robustly designed balloon. After the first sonde (with the gas chromatograph/mass-spectrometer) is released, the balloon container opens and the balloon extends with the gondola and inflation system suspended below. A ripstitch mechanism helps to absorb the impact loads of the deployment. A low friction swivel and a long riser between the parachute and the balloon prevent twisting motion of the balloon. Gas is injected through the bottom of the balloon using a diffuser and windsock developed in a recent JPL technology development program. This bottom inflation system dramatically improves the aerodynamic stability of the system, it eliminates problems with the parachute separation, and it provides a substantial gain in payload fraction over the top inflation system used on the first planetary VEGA balloon mission in 1985 [5].

A prototype deployment and inflation system has been tested in a relevant environment in a helicopter drop test conducted in cooperation between JPL and Dryden Flight Research Center in California's El Mirage Dry Lake in August 1998. Atmospheric pressure and gravity field were very similar to those that would be encountered at Venus. The series of frames in Figure 4 below shows the descent of the payload beneath a parachute, deployment of the balloon envelope with ripstitch shock absorber, and inflation of the balloon. The balloon envelope stabilized rapidly after deployment and inflation was initiated successfully 16 sec later without rotation of the balloon envelope occurring.

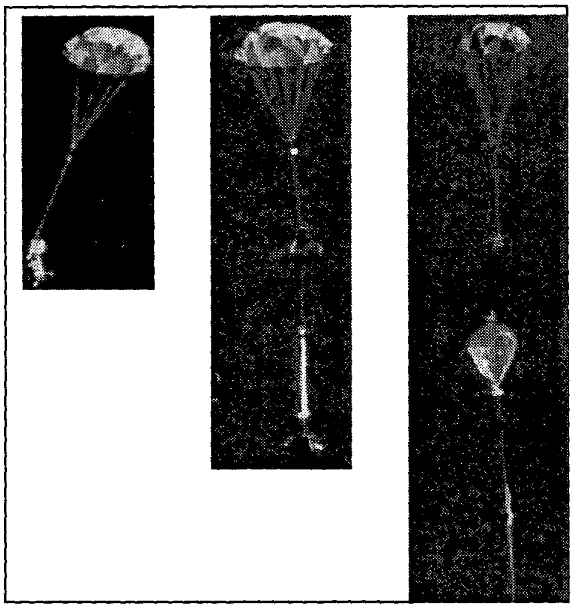

Figure 4. Low-altitude deployment and inflation test of 3-m diameter Mylar balloon

Balloon Envelope Technology—Compared to other candidate Venus Aerobot missions, the Venus Geoscience Aerobot (VGA) and the Venus Sample Return (VESAR), the balloon requirements for Venus Multisonde missions are less demanding, because the balloon only operates at high altitudes where the temperature ranges from –20 to 0 °C. However, the materials must still survive exposure to sulfuric acid haze clouds. In one sense this is a proven technology because the Venus VEGA balloons operated successfully for the 2-day duration required for VEVA mission for example. However, the VEGA balloons used a heavy teflon cloth which greatly exceeds the mass budget for the VEVA mission. Therefore, alternate, lightweight materials are required. Two concepts for such materials have been devised. Both seem feasible and the choice will be an engineering decision. One of them is a bilaminated mylar (23 um x 23 um) balloon with a kevlar scrim reinforcement and a external teflon sheath. It has been tested and shown to tolerate the sulfuric acid effects. The other concept is a polyethylene and mylar laminate. Recent tests have confirmed that polyethylene is resistant to sulfuric acid.

Sonde Technology—Development of technology for short duration trips to the near surface of Venus was originally motivated by the high pressure, high temperature protection needs of the Venus Geoscience Aerobot (VGA) mission. The VAMuS mission drop sondes will use capabilities developed for the VGA and other technology programs including the ongoing ground based planetary aerobot validation program and the New Millennium program DS 2 microprobes. At this time there are no new enabling technologies that are required for VAMuS. Some new enhancing technologies may be utilized but not where risk in their use compromises overall mission goals. New instrumental techniques will be important in broadening the scope of the scientific questions that can be addressed.

For drop sonde thermal and pressure protection, the results of the VGA sonde experiments are relevant [6]. A concentric sphere design was selected for VGA with the 38cm outer sphere taking the external pressure load and a 15.6-kg dummy payload housed inside a 30 cm diameter inner sphere. The concentric sphere design was selected to permit vacuum insulation between the two spheres. However, it was later determined that fiberglass insulation filled with a low conductivity gas like nitrogen or xenon is almost as effective as vacuum insulation given the number of insulation penetrations and other parasitic losses. The prototype was built (Fig. 2) and tested for both structural and insulation performance. Measured heat leaks through the insulation were 111 W for xenon and 256 W for nitrogen filled fiberglass insulation. Computed insulation performance based on these values has been incorporated into the designs for VAMuS drop sondes. Pressure tests of the VGA prototype were successfully performed at Venus surface conditions of 460 °C and 9.2 MPa. The final VGA prototype test was a 250-g centrifuge test, which was completely successful with no damage or plastic deformation of gondola components.

On the basis of these tests designs for both the large sonde and the small sonde have been developed.

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