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VENUS SAMPLE RETURN MISSIONS — A RANGE OF SCIENCE, A RANGE OF COSTS

Ted Sweetser, Craig Peterson, Erik Nilsen, and Bob Gershman
Members of the Technical Staff
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

Venus sample return missions have been studied occasionally for the last forty years, but only recently has technology advanced to the point where this kind of mission has been realistic. At the same time, however, cost constraints have become more important. NASA recently has been studying a set of Venus sample return missions which span a range of scientific goals and which have a corresponding range of costs.

The simplest sample return from Venus is to fly through the upper atmosphere and return some of the gas to Earth. This turns out to be possible using a free-return ballistic trajectory. The gas sample would be captured at hypersonic velocities and would be greatly affected by the process, but we could still determine isotopic ratios to very high precision on the ground and may be able to determine elemental ratios. This mission is roughly a moderate Discovery class mission reminiscent of Stardust.

The next level of sample return mission would be another atmosphere sample mission, but would involve much more benign sampling conditions. At Venus arrival the spacecraft would be aerocaptured into orbit at Venus and aerobrake to a circular orbit. A sample-gathering vehicle would enter the atmosphere and slow significantly, allowing capture of a well-mixed atmosphere sample which preserves chemical composition. An on-board rocket would then return the sample to Venus orbit, where the orbiting spacecraft would retrieve it and bring it back to Earth. This mission is somewhat beyond Discovery class, though not outrageously so.

The most difficult level of sample return mission would be a sample from the surface of Venus. The surface of Venus is the hottest surface and has the greatest atmospheric pressure and density of any known surface in the solar system. This presents great challenges to both the sampling lander and to the Venus ascent vehicle (VAV) which must return the sample to orbit. Indeed, it is impossible in any practical sense to use a rocket ascent vehicle directly from the surface; instead; a balloon is used to lift the VAV with the sample to an altitude above the clouds where both temperature and pressure are not unlike Earth's, whence the rocket fires to orbit the sample. This mission is substantially more difficult and costly than the atmosphere sampling missions described above, but would allow direct examination of Venus to answer questions about solar system formation and Venus's evolution since then.

INTRODUCTION

The phrase "low-cost Venus sample return" would seem at first thought to be an oxymoron. Venus has one of the harshest, most extreme environments of any place in the solar system because of the high temperature, density, and pressure at the surface, all of which are unequaled at any other planetary surface. Previous studies[1, 2, 3, 4] of Venus sample return missions have concluded that such missions are well beyond even the Viking class of mission in terms of cost and complexity. So how can we talk of such a mission at a low-cost mission conference?

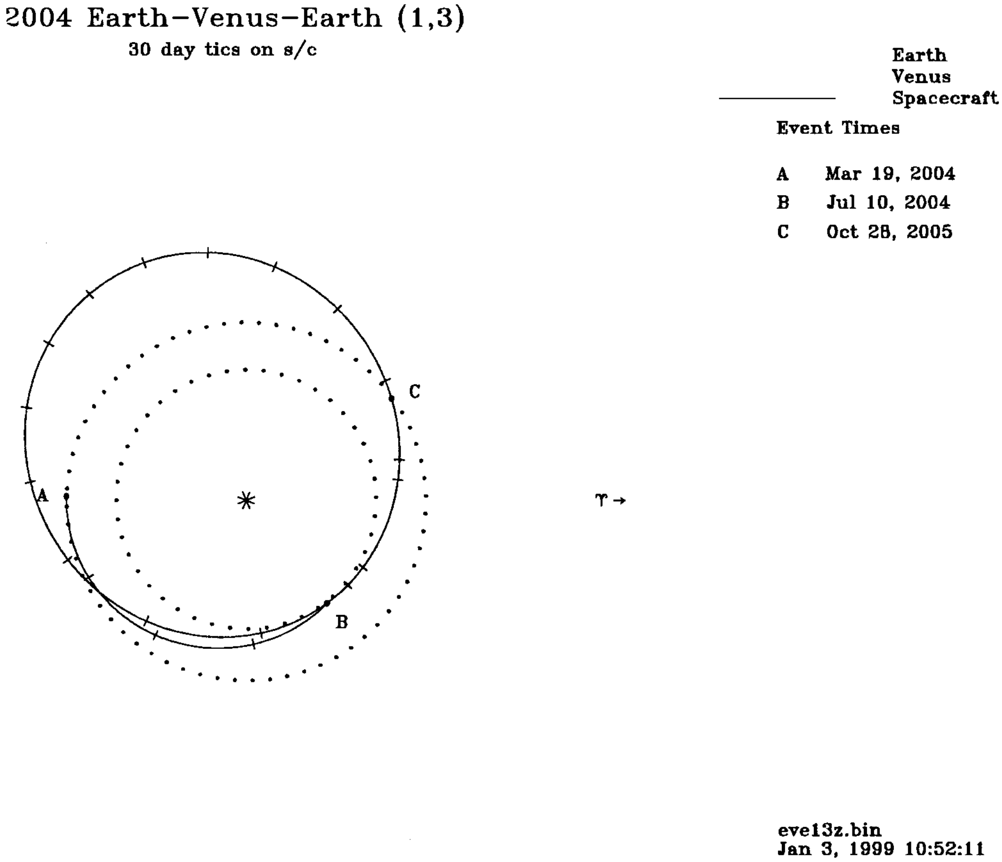

Figure 1. A free return trajectory to Venus and back without maneuvers (solid line). The orbits of Venus and Earth are shown as dotted lines. The dates of launch from Earth (A), Venus flyby (B), and return to Earth (C) are given.

In the studies reported here, the application of a number of principles has reduced the cost of such a mission, both in relative and in absolute terms. These principles are:

- Reduce the scope of the science objectives
- Simplify the mission as much as possible
- Use available technology when it suffices to meet requirements
- Reuse technology developed for other missions when available
- Use new technology if it offers significant reductions in mass or power use

By applying these principles to varying extent we have developed a series of Venus sample return missions, ranging from a minimal mission which could actually be called low-cost without blushing (too much) to a surface sample mission which admittedly is low-cost only in a relative sense. For the purposes of these studies we specified a launch in 2004 for the trajectory designs, taking this to be a typical opportunity for Venus missions. For programmatic reasons an actual flight of any of these missions would not occur for some years after that so we specified a technology cut off date of 2005.

VENUS ATMOSPHERE SKIMMER

We start by asking what the maximum reduction in scope could be for a sample return mission from Venus. The simplest mission we could conceive of wouldn't even stop at Venus—just grab something as a spacecraft flies by for return to Earth. Carl Sauer at the Jet Propulsion Laboratory (JPL) has generated the ballistic trajectory shown in Figure 1 that leaves

Earth, flies by Venus at a low altitude, and returns to Earth, all without any maneuvers after launch except to correct for trajectory errors. This trajectory begins with a launch on 2004–03–19 with a C_3 of 11.8 km^2/s^2, flies by Venus on 2004–07–10 with a velocity of 11.8 km/s at a periapse altitude of 110 km, and returns to Earth on 2005–10–28 with a hyperbolic approach velocity of 10.6 km/s. This *free return* trajectory is the basis for the Venus atmosphere skimmer mission.

Because Venus has a gravity well equivalent to Earth's, the velocity at any low-altitude fly by is quite high—more than 10 km/s for any free return trajectory. At this velocity it is impossible to get to the surface and still keep going; we can't even get very deep into the atmosphere. Furthermore, any sample gathered at this speed is going to be a plasma sample. Thus the sample return goal for this mission is to return an ionized sample from high in the atmosphere for elemental and isotopic composition analysis at Earth. There is some concern that sampling at this velocity could involve chemical and physical reactions which would lead to fractionation which would affect the elemental composition of the sample. Isotopic fractionation, however, is less likely. These issues need further study to establish the scientific utility of such an atmosphere sample.

The Skimmer requires precise navigation on Venus arrival. If the entry angle is too small, it will skip out. If the entry angle is too large, it will bury itself in the atmosphere. Approach navigation errors are often specified in terms of error in the B-plane aiming point. Per Bobbie Williams and others at JPL, typical B-plane control accuracy using Earth-based radio navigation is about ±10 km, which corresponds to entry angle control of about ±0.7 deg. Angus McRonald at JPL has looked at the allowable entry corridor for entry vehicles of various design (i.e. different L/D ratios and different ballistic coefficients). He concluded that an entry vehicle with L/D ratio near zero is too sensitive to the above entry angle errors. He recommends a vehicle with L/D near 1 and with a fast-response control system to maintain the desired flight path. Such entry vehicles are currently being designed, but are not yet flight tested. Another advantage of using a vehicle with active control is that it can compensate for uncertainties in the Venus atmosphere. Of course, improvements in Earth-based radio navigation and in optical approach navigation might remove the need for the lifting vehicle with active control.

Using the above assumptions concerning the mission, the Advanced Projects Design Team (Team X) at JPL developed a preliminary mission and flight system design to the point where an initial cost estimate could be made. In that study the assumption was made that the velocity lost due to drag at periapsis is made up by a propulsive maneuver shortly after periapsis. Angus McRonald estimated the drag loss at about 700 m/s for a vehicle with lift/drag ratio, L/D=1. Allowing margin for delay in maneuver execution and 100 m/s for cruise trajectory corrections, the propulsion system for the flight system was sized for 1100 m/s.

The hyperbolic velocity approaching Earth on the return leg is about 10.5 km/s. This results in atmospheric entry velocities of about 15.2 km/s. This is a large entry velocity, but comparable to other Earth return missions such as Champollion at 15.0 km/s and Stardust at 12.9 km/s. The same L/D=1 vehicle would be used again at Earth entry, and the sample container would be released on a parachute after entry at about Mach 2.

The use of a single aeroshell at both Venus and Earth, and an X-band patch antenna, makes the flight system as simple as possible. The only deployable element is a retractable solar array which would tuck inside the aeroshell for the Venus flyby. Assuming relatively modest improvements in technology which are already in development, such as X2000 avionics and the Space Transponding Modem, mass for this flight system is only on the order of 300 kg dry mass inside the aeroshell. The one significant, but necessary, technology development is the biconic aeroshell itself, along with a fast-response control system, which was assumed to mass on the order of 16.5% of the wet mass of the spacecraft at Venus. A total wet system mass on the order of 600 kg allows launch with a Delta II 7425 class launch vehicle.

Subsequent to the Team X session, a more optimal trajectory for this mission was developed by Paul Penzo at JPL. He found that by adjusting the flyby and return dates he could get a flyby which naturally had a difference in approach and departure velocities at Venus matching the ΔV created by the drag during the atmosphere passage. This improved trajectory launches on 2004–03–19 with a C_3 of 13.8 km^2/s^2, flies by Venus on 2004–07–10 at a periapse altitude of

110 km with a velocity of 12.8 km/s at periapse on the incoming leg and a velocity of 11.8 km/s at periapse on the outgoing leg, and returns to Earth on 2005–10–23 with a hyperbolic approach velocity of 10.5 km/s. With the reduction in mass entailed by reducing the propulsion requirements down to a hydrazine system only for doing trajectory correction maneuvers, the total system mass would be less than 400 kg and could be launched on a Delta II 7325 class launch vehicle even to the higher launch energy needed for this revised trajectory.

Team X estimated that the cost of this mission would be well within the Discovery guidelines even before the improvements in the trajectory. To the extent that Discovery missions are low-cost, this would be a true low-cost mission.

VENUS ATMOSPHERE SAMPLE RETURN

By definition, the atmosphere skimmer mission accomplishes minimal science. In order to collect an atmospheric sample which has not been compromised by the sampling process, the spacecraft has to be moving considerably slower for the sampling than the skimmer spacecraft above does. But it does not need to go very deep into the atmosphere to collect a scientifically important sample. A sample from an altitude of 110 km would be from the well-mixed part of the atmosphere and would allow achievement of one of the most important measurement objectives of an atmosphere sample, the analysis of noble gas abundances. In addition, some measurement of ambient reactive species could be done.

A sampling velocity of 700 m/s was chosen for this mission, well within the speed limit for the required science and yet still providing some boost for departure from the atmosphere. Because it requires a ΔV of 7250 m/s to return to orbit around Venus from this state, a four-stage solid-motor rocket based on an early Mars Sample Return concept puts a 6 kg payload with a 2 kg, 1 liter sample container into a 300 km altitude circular orbit. This is done in several steps: (1) vertical ascent from 110 to 120 km by the first stage, (2) horizontal injection into a 120 x 300–km orbit by the second and third stages, and (3) circularization into the 300 x 300–km orbit by the fourth stage. Even for such a small payload the rocket masses 1150 kg, a mass ratio which makes it necessary to leave the Earth-return spacecraft in orbit around Venus while the sampling is done. Thus the science requirements lead us to an architecture with two major elements—a rocket with a sampling system for getting an atmosphere sample to Venus orbit and a spacecraft for delivering the rocket to Venus and returning the sample to Earth.

Each of the elements needs to be captured at Venus. The rocket in particular needs to enter the atmosphere so must have an aerocapture/entry system. By choosing to use a new technology for this system, a hypersonic drag device called a ballute[5], Team X was able to use the same aerocapture system for both elements and save the orbiter from having a separate aerocapture or propulsive capture system. In this scenario, the combined elements are targeted for an entry to the desired sampling altitude and the ballute is deployed to provide drag at low density where the heating on the elements is small. The orbiter is released from the ballute at a speed somewhat above its circular orbit velocity and exits the atmosphere with little additional drag, while the sample collection and retrieval package stays on the ballute and continues to decelerate until it reaches an altitude of 110 km with a vertical component of velocity of about –100 m/s and a horizontal component of 600 m/s. Then the ballute is released, the sample is taken, and the launch is initiated to the 300–km altitude circular orbit, while the orbiter uses its own propulsion system to raise its periapse and achieve the same orbit. This mission may not be so sensitive to entry-angle errors as the atmosphere skimmer mission above because it can enter at a steeper angle and the elements can separate from the ballute when the desired ΔV is achieved. Once both the orbiter and the sample container are in orbit, the orbiter uses the same technology as planned for the Mars Sample Return mission[6] to rendezvous with and capture the sample. When the geometry is correct after a stay of 440 days at Venus, the vehicle is injected into the Earth return trajectory requiring 3411 m/s of injection capability from the orbiter propulsion system (which will vary somewhat depending on the actual year of the mission).

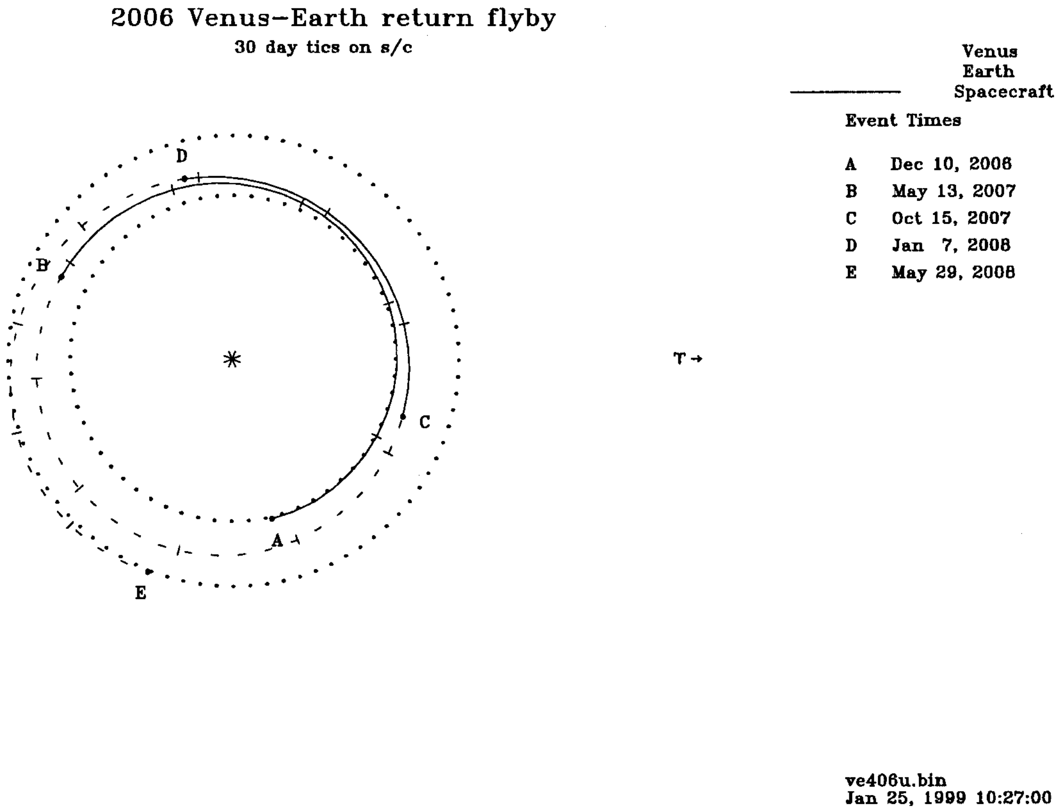

Figure 2. A low-thrust trajectory from Venus to Earth; thrust arcs are solid lines, coast arcs are dashed lines. The orbits of Venus and Earth are shown as dotted lines. The dates of departure from Venus (A), thrust/coast changes (B,C,D), and return to Earth (E) are given.

This atmosphere sample mission is more complicated than the skimmer mission, but has the advantage that the atmosphere sample is collected at relatively low velocity. Also the Earth return entry velocity is lower at 11.7 km/s at 200 km altitude because the Venus–Earth transfer is done on a minimum energy return orbit. The sample enters in a sample return capsule and descends on a parachute from about Mach 2, releasing its heatshield, in a manner similar to Stardust.

The main differences with the skimmer mission are the addition of the large rocket for getting the sample into Venus orbit, the rendezvous and capture system on the orbiter, and a significantly larger propulsion system on the orbiter for the return to Earth. With these additional elements the launch mass from Earth has increased by almost an order of magnitude to about 3400 kg, which makes a Delta IV/Atlas V class launch vehicle necessary. The cost of these changes, even assuming high inheritance from the Mars Sample Return mission, is enough to push the mission somewhat beyond the Discovery guidelines. Total mission time increases by about eight months because of the stay at Venus; this is another addition to the cost but a relatively small one. Another change is the replacement of the fast-control biconic aeroshell by a ballute entry system, but these are roughly equivalent in development effort, cost, and risk.

VENUS SURFACE SAMPLE RETURN

For the next mission study we raised our sights significantly to attain new depths for sampling—all the way the surface, in fact, to obtain a piece of rock in a regolith sample. As in the atmosphere sampler above, a rocket is used to return the sample to Venus orbit and a separate orbiter captures it and brings it back to Earth. But now additional elements are needed to actually get the sample from the surface and return it to an altitude where use of the rocket is feasible. Adding these elements to the mission above increased the mass of the total system so much that

Table 1. Engineering trades considered and made for the Venus surface sample mission.

Mission Trade	Baseline	Alternatives	Reason
Launch	single	multiple	cost
Transfer to Venus	chemical ballistic	SEP, solar sail	cost, simplicity
Capture at Venus	ballute	conic aeroshell, biconic aeroshell, propulsive	mass
Initial Venus orbit	ellipse	circular	ΔV, mass
Lander entry orbit	circular equatorial	ellipse, direct entry	site selection
Entry technology	ballute	conic aeroshell, biconic aeroshell	mass
Sampler element	full lander	tether from floating platform, freeflyer from platform	risk, simplicity
VAV handling	take to surface	hold at floating platform	risk, simplicity
Sample selection	random	selected, rover	cost, simplicity
VAV configuration	"thin" cylinder	toroidal	cost
VAV avionics	IMU on second stage	radio beacon, horizon sensors, sun sensor, star tracker, gyros	mass, simplicity
VAV control	3-axis 1st & 2nd stages, spin 3rd stage	multiple possible combinations	cost, simplicity
Rendezvous tech.	radio beacon+visual	visual only	risk
Rendezvous prop.	chemical	SEP	risk, simplicity
Transfer to Earth	SEP	chemical ballistic, solar sail	mass
Earth entry	capsule aeroshell	ballute	risk, cost

multiple launches would be required (as had been the case in all previous studies of Venus surface sample return missions). We were able to reduce the mass back to allow a single launch with a Delta IV/Atlas V class launch vehicle by replacing the very large orbiter propulsion system by a solar electric propulsion (SEP) system for the return to Earth on the trajectory shown in Figure 2.

This mission was the most thoroughly studied of the three Venus sample return missions. A special study team as well as Team X considered a large number of trades in the process of settling on a final architecture for the mission. A summary of the trades considered and the reasons for making the choices indicated is given in Table 1. Many of these trades were decided directly on the basis of cost but even when cost was not a direct factor many of the other reasons given were indirectly driven by the goal of reducing the cost as much as possible.

Since the details of this mission have been presented elsewhere[7, 8, 9] only a summary of the mission is given here. A single launch places the spacecraft on a ballistic transfer to Venus, where it will spend a year before beginning the return journey to Earth. After aerocapture at Venus, a propulsive plane change and aerobraking put the spacecraft into a circular equatorial orbit. A lander separates from the orbiter and descends to the surface to collect a sample, which is placed in a sample carrier at the tip of a three-stage Venus ascent vehicle (VAV) which has a simpler architecture than the one in the atmosphere sample mission above. (The Mars Sample Return

Table 2. Preliminary mass estimates (kg) for Venus sample return missions.

	Atmosphere Skimmer	Atmosphere Sample Return	Surface Sample Return
Orbiter / Return spacecraft	275	400	600
Orbiter propulsion systems and propellants	50	1300	600
Orbiter entry systems (aeroshell or ballute)	75	500	500
Venus ascent vehicle	—	1150	500
Lander and balloon systems	—	—	700
Lander entry systems (deorbit and ballute)	—	—	200
Total systems mass	400	3400	3100

project has also adopted this simpler architecture.) A variety of passive thermal and pressure protection techniques are used to protect the landed hardware and the VAV during a rapid descent and 90-minute stay on the surface. The lander inflates a balloon which carries the VAV with the sample to a high altitude (60 km – 70 km) in a few hours, from whence the VAV puts the sample carrier into orbit around Venus. Then the orbiter which brought the lander to Venus uses a beacon on the sample carrier and its own telescopes to rendezvous with the sample carrier. After transferring the sample into an Earth entry vehicle (EEV) on board, the orbiter deploys solar arrays to power a solar electric propulsion (SEP) system which is used to spiral out from Venus and travel back to Earth, taking two and a half years in total for the return.

The major new elements for this mission are the lander with its instrumentation and sampling system, additional deorbit propulsion and entry systems for the lander, the balloon system which brings the VAV back up to firing altitude, and the SEP system for the orbiter. Their addition to the atmosphere sample return mission above places this mission about midway between Discovery and Viking class missions. While this is not low cost in any absolute sense it is a significant reduction relative to all previously proposed Venus surface sample missions.

CONCLUSIONS

The dominant principle affecting the range of costs of these missions is the reduction in scope, reinforcing the truth of the cliche, "you get what you pay for." Perhaps the best illustration of this is Table 2, which compares the masses of the various elements and the system total for the three options discussed here. As the scope of the science expands, the number of elements and the system mass and complexity increase, driving a corresponding increase in cost, except when the infusion of technology (such as SEP) can effect a net savings.

In particular, compare the atmosphere sample return and the surface sample return missions, where the system mass actually decreased for the more ambitious mission. This decrease was caused by the adoption of a more optimal VAV architecture (which uses three stages instead of four) and by the use of SEP for the return to Earth. The former of these, the improved VAV, would certainly apply to the atmosphere mission and should reduce estimates somewhat in the next study. The latter, the use of SEP, would also reduce the mass of the atmosphere sample return system but at a net cost increase to the mission, whereas the use of SEP is enabling for the single launch surface sample return mission and is a clear cost savings over funding a second launch vehicle, which in turn is only part of the cost increase of a dual-launch mission.

There are a number of significant technology issues faced by this mission. Finding a balloon material which can survive both the vacuum and cold of space and the hellish conditions at the surface of Venus and then lift more than a ton through clouds of sulfuric acid is non-trivial. The propellant grains in the VAV will be more protected but will still have to work after an extreme pressure cycle. The whole VAV system design and the hardware for rendezvous and capture of the sample in orbit will require significant work beyond the products of the Mars Sample Return project. The fast-control biconic aeroshell for the atmosphere skimmer mission has little heritage, at least publicly. And ballutes, of course, while offering tremendous advantages for many missions besides these, still exist only on paper. It is only the successful resolution of these issues which will finally allow us to label any of these missions "low cost."

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