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Investigation of the application of aerobot technology at Venus

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Abstract

Robotic aerovehicles, or aerobots, can perform long duration detailed studies of planetary surfaces and atmospheres in three dimensions. Here we explore specific abilities of an aerobot mission to Venus using two concept missions: the Balloon Experiment at Venus (BEV) and the Venus Flyer Robot (VFR). Oscillating between 40 and 60 km altitude, the BEV is designed to collect atmospheric data over a nominal lifetime of weeks as well as image the surface. The VFR, with its ability to descend to the surface, can collect cm–m scale visible and near-infrared images of the surface, collect compositional and dynamical data of the lower atmosphere, and measure the composition of the Venus surface with a snake-mounted detector. These concept missions are used to calculate sample aerobot trajectories and descent scenarios which utilize variations in wind speed, altitude and surface slopes to maximize data collection. The trajectories are applied to two example geotraverses across Atla Regio and Ovda Regio. Data collected at these or similar targets by an aerobot can address several unresolved questions about Venus such as the nature of the lower atmosphere and atmosphere-surface interactions and the presence or absence of continental crust.

1. Introduction

Since 1961, over 20 missions (orbiters, landers, balloons, and probes) have been sent to Venus. The near global mapping of the surface provided by the Magellan orbiter did much to propel our understanding of the geologic history of the planet. However several major questions about Venus remain unresolved, for example: (1) the composition of the lower atmosphere (< 20 km), (2) the nature of the superrotation of the atmosphere, (3) the nature of atmosphere-surface interactions, (4) the geochemical variability and

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composition of the crust and (5) the nature of the venusian interior. Due to the importance of these questions, a mission to Venus is highly ranked in the most recent Decadal Solar System Exploration Survey [1].

One method of investigating Venus is with robotic aerovehicles, or aerobots. Aerobot technology for planetary applications has been developed at the Jet Propulsion Laboratory and utilizes a balloon filled with a reversible fluid to control buoyancy [2]. A reversible fluid changes phase at some temperature and pressure that causes the balloon to oscillate around an equilibrium altitude. Trapping the condensed fluid will cause the balloon to remain negatively buoyant and allow excursions to a planetary surface. This technology is particularly useful at Venus where the high surface temperatures (740 K) and pressures (90 bars) preclude long duration surface studies. Aerobot technology provides the unique opportunity of long duration, detailed studies of planetary atmospheres and surfaces in three dimensions.

This paper is a study of the types and scale of investigations that can be accomplished with an aerobot at Venus. To do this, we utilized technical details of two concept mission studies: the Balloon Experiment at Venus (BEV) [3] and Venus Flyer Robot (VFR) [4] (Note: the VFR Concept mission has been since renamed Venus Geoscience Aerobot (VGA) [48]). We find that such missions allow acquisition of cm-meter scale images of the surface at various wavelengths to complement the existing synthetic aperture radar (SAR) data provided by Magellan, examination of the composition and dynamics of the active venusian atmosphere over space and time, and measurement of the chemical composition of the surface at several target areas. Such measurements are key to further understanding of the workings of Venus, and by comparison, the other terrestrial planets including our Earth. Measurement capabilities of these aerobot missions are placed in context of our present knowledge of Venus and science objectives for its exploration.

2. Background, science objectives and proposed measurements

2.1. An aerobot mission in the Venus upper atmosphere—the balloon experiment at Venus (BEV)

The BEV aerobot is designed to oscillate at altitudes of $\sim$ 40–60 km in the Venus atmosphere [3]. We assume for this study that the aerobot carries a near-infrared imager (such as the Navigation Optical Sensor Experiment (NOSE) system proposed by DiCicco et al. [3]), a gas chromatograph/mass spectrometer to measure atmospheric composition, a nephelometer and meterological package to measure cloud properties and dynamics, and high-resolution radiometric tracking capabilities. The BEV system is designed with a mission lifetime of 1 week in the atmosphere. Here we discuss the Venus environment accessible by the aerobot and science questions that can be addressed with this technology.

2.1.1. Venus atmosphere

2.1.1.1. Composition. The enigmatic nature of Venus is primarily a consequence of its massive, dense CO_2-rich atmosphere, which obscures the surface from traditional methods of observation. Questions regarding the Venus atmosphere and its effect on the planet may be narrowed down to three key issues: 1. what were the circumstances surrounding Venus' planetary and atmospheric formation; 2. which interactions occur between the atmosphere and the surface and role have they played through time; and 3. what processes control the differences between the atmosphere of Venus and those of the other terrestrial planets? Examination of the composition of the atmosphere both spatially and temporally is required to address these questions.

The composition of Venus represents a critical data point for models of solar nebula formation and planetary accretion and differentiation. The oxygen isotopes calculated for the Earth and Mars suggest that these two bodies formed from separate oxygen isotope reservoirs [5], implying a lack of homogeneity in the solar nebula. Estimates of the oxygen and carbon isotope ratios in the atmosphere of Venus (both calculated from CO_2 abundances) would provide valuable information about the oxygen isotopic composition of the Venus atmosphere and, by extrapolation, about the composition of the solid planet. In addition, measurements of inert gases (K, Ar, Xe, Ne) may suggest differences between the origin and evolution of the atmosphere of Venus and the Earth and Mars [6,7]. For example, a relatively high K/Ar ratio, when compared to the ratio of these gases for Earth and Mars, might suggest a younger age for the bulk of the venusian atmosphere and thus require a revision of models of primordial atmospheric origin.

Current estimates of H_2O abundance of the venusian atmosphere show it to have 4–5 orders of magnitude less volatiles than terrestrial values [8]. This requires that either the primordial abundance of volatiles on Venus was different than Earth, which is difficult to explain within current models of solar system formation [9], or Venus lost its primordial water over time. The latter explanation is supported by the D:H of Venus, which is $100\times$ greater than that of the Earth [8]. However, this measurement was made on a single cloud droplet that clogged the Pioneer Venus mass spectrometer during descent [7]. The loss of water on Venus can be accomplished by several methods including photodisassociation, which is dependent on atmospheric circulation, reaction with iron in surface materials, reaction with other reduced gas species, such as CO, and recycling into the interior [10]. Accurate measurements of atmospheric gas species are required to examine these loss mechanisms. Determination of abundances of volcanic gases such as SO_2 and H_2O would also provide important limits on current models of resurfacing.

In summary, a set of key atmospheric constituents and physical characteristics must be quantified in a three-dimensional sense in order to further our understanding of the origin and evolution of Venus and its atmosphere:

1. Atmospheric abundances (vertical and latitudinal) of constituents such as SO_2, CO_2, CO, COS and H species (H_2S, HCl).
2. H_2O abundance.
3. Oxygen isotope ratios (CO_2).
4. Atmospheric abundances of trace isotopes (K, Ar, Ne, Kr).
5. Temperature and wind speed of the atmospheric column.

These measurements can be made by a gas chromatograph/mass spectrometer and temperature sensors aboard the BEV. Wind speed can be determined from precise radio tracking of the aerobot.

2.1.1.2. Circulation and dynamics. The BEV will serve as a platform from which we can study atmospheric circulation and dynamics at altitudes above and below the cloud layers. A better knowledge of the circulation of the clouds is crucial to understanding the superrotation of the venusian atmosphere, and a major component of atmospheric circulation is due to solar heating and thermal tides. Thermal tides (diurnal variations in solar heating) result in transfers of mass in the Venus atmosphere, where atmospheric pressure becomes low where the temperature is hot, and vice versa [11]. Thus the sun may impart angular momentum directly into the atmosphere and thus drive the west-to-east superrotation at cloud level [12]. This hypothesis can be tested by pressure and temperature measurements taken by an aerobot directly from the atmosphere during the entire oscillatory phase, and also temperature measurements derived from a radiometer. These thermal emission readings can be compared to those taken of the Venus night side from the Earth and Pioneer Venus, whose dissimilar readings remain open to interpretation [11].

Atmospheric circulation also relies on meridional winds and eddies, about which we know little at any level in the venusian atmosphere with certainty. Present thinking is that meridional circulation is vertically layered with a Hadley cell near the surface, one near the cloud tops, and one in between, but this model has yet to be confirmed [11]. Knowledge of the dynamics of meridional winds and eddies is necessary to differentiate between competing models for the formation and maintenance of Venus' atmospheric superrotation; parameters that can be measured simply with temperature, pressure, and horizontal and vertical components of wind velocity with the BEV. The BEV also provides lateral and vertical mobility and a long lifetime (relative to probes and previous balloon missions) in the Venus clouds.

An aerobot like the BEV could also have the capability of monitoring electrical discharges detected by Pioneer Venus and Venera probes. While these discharges have been interpreted to be lightning, it is uncertain at which altitudes they form and the frequency of events. There is also tantalizing evidence that electrical events cluster above the Beta-Atla-Themis Region and thus may be associated with volcanism [13]. We suggest optical and acoustic measurements of the night side of Venus for this purpose. Sound waves should propagate over long distances in the venusian atmosphere and have the added potential benefit of high interest to the general public.

2.1.2. Proposed imaging strategy

A primary goal of the further exploration of Venus is to obtain imagery of the surface at various wavelengths to complement the Earth-based and orbital SAR image data sets we have presently. These images will serve to help determine the surface characteristics responsible for variations in backscatter seen in the radar; these variations are a function of grain size, surface roughness, and electrical properties of the surface rocks. The BEV, designed to oscillate at altitudes of $\sim$ 40–60 km [3], provides an opportunity to perform infrared remote sensing of the surface from within the atmosphere of Venus. Our preliminary study of the optical properties of the venusian atmosphere poses several constraints on a balloon-mounted imager and data collection procedures for the BEV [3].

The thick atmosphere of Venus presents many problems for optical remote sensing, particularly as we have little knowledge about the optical properties of the lower atmosphere. Turbulence in the thick atmosphere may pose problems with seeing, in the astronomical sense, where the angular resolution of features on the surface is blurred. The seeing from different altitudes, in conjunction with blurring from balloon motion, constrains the maximum resolution achievable by the imager. Atmospheric scattering constrains the wavelengths of light useful for studying the surface from different altitudes. At higher altitudes, less of the light coming from below is directly reflected from the surface and more light is scattered in random directions by the atmosphere, so the signal of reflected light from the surface becomes lost in a fog. The magnitude of this effect is dependent on the wavelength of the light. Models predict that light in the 1 μm range is likely to be useful from 40 km altitude, the bottom of the aerobot's oscillation [14]. At slightly longer wavelengths, the atmosphere becomes more opaque to solar radiation, and at shorter wavelengths, atmospheric scattering worsens. Emissivity at 1 μm band may also provide information on variations of iron in the Fe^{2+} state, for example the minerals olivine and pyroxene, if the temperature of the surface is well understood [15]. Areas of higher abundance of these minerals will appear darker than areas with lower abundance. The abundance of these minerals is important in understanding the variety of volcanic products on the surface of Venus, as olivine and pyroxene become less normative from basaltic compositions to rhyolitic compositions.

A primary feature of a 1 μm imager is its ability to detect surface temperature variations and convert them to altitude variations that can be then compared to the Magellan topography data in order to determine position of an aerobot relative to the surface. However, the imager will probably not detect altitude variations in the daylight, because a 1% variation in surface reflectance in the 1 μm band (easily attained by variations in mineralogy or grain size) is four orders of magnitude larger than the entire amount of thermal emission from the surface at this wavelength [16].

During the Venus night, the thermal signal from the surface will no longer contain reflected sunlight and may thus indicate surface temperature due to altitude or, potentially, heat flow associated with volcanism. However, a surface without temperature variation could still exhibit variations in thermal emission due to variations in grain size and mineralogy. For example, grain size is an important factor in controlling the strength of thermal emission spectra at wavelengths greater than 5 μm when the grain size approaches the wavelength being observed [17], although less is known about emissivity of minerals around the 1 μm wavelength. A change in elevation on the Venus surface of 500 m equates to a 4.5 K temperature change, which produces the same variation in radiance as a change in the emissivity of the surface from 0.95 to 0.82. Fig. 1 shows a hypothetical 1 μm image of a venusian volcano that illustrates this variation. This conical volcano is 1 km high, and has two fresh lava flows on it with a higher emissivity value (0.92) than the rest of the volcano (0.88). To simulate the scattering of 1 μm light from 40 km altitude, half of the signal is uniform gray. The resulting difference in contrast from these effects is shown in Fig. 1a, where the camera has been exposed so that the brightest pixel is saturated. In Fig. 1b, noise has been added to the image at a 1% level, and the result is stretched for maximum contrast in Fig. 1c. The difference in emissivity between the fresh flows and the background is 0.04, the same as the difference in 1 μm reflectance between weathered and unweathered basalt on the Earth. If the BEV/VFR relies on an autonomous navigation system that correlates emissivity to topography, the aerobot will need to filter out variations in the 1 μm signal due to compositional differences to obtain accurate positioning. Basalt may be oxidized on the surface of Venus [18], producing a thermal signal that may approximate terrestrially weathered basalts. The return of a picture such as Fig. 1 from an aerobot will, when correlated with SAR imagery, help to examine composition of the surface of Venus and the recent geologic history of the planet.

2.2. An aerobot mission with surface excursions—the Venus flyer robot (VFR)

The VFR concept also employs reversible fluids for altitude control. This craft is further enabled by a mechanism to trap the condensed fluid at the top of an oscillation causing the balloon to remain negatively buoyant and sink to the Venus surface. We assume that such a vehicle would have the instrument package described for the BEV, above, a visible/near-infrared multispectral imaging system as well as an X-ray fluorescence detector mounted within a flexible snake that could hang from the balloon and measure surface major-element composition.

2.2.1. Venus lower atmosphere

2.2.1.1. Composition. One of the most puzzling aspects of Venus is the markedly different evolutionary path it has taken compared to Earth. Venus, so similar to Earth in size, mass and presumably composition, somehow retained a much more massive atmosphere than Earth, resulting in a runaway greenhouse [10]. The most important key to resolving this puzzle of atmospheric evolution resides in the lower 20 km of the atmospheric column, where nearly 80% of the atmospheric mass exists [19]. Any modeling of the history and evolution of the atmosphere requires better estimates of the abundance of its major and minor constituents. For example, [20] have suggested

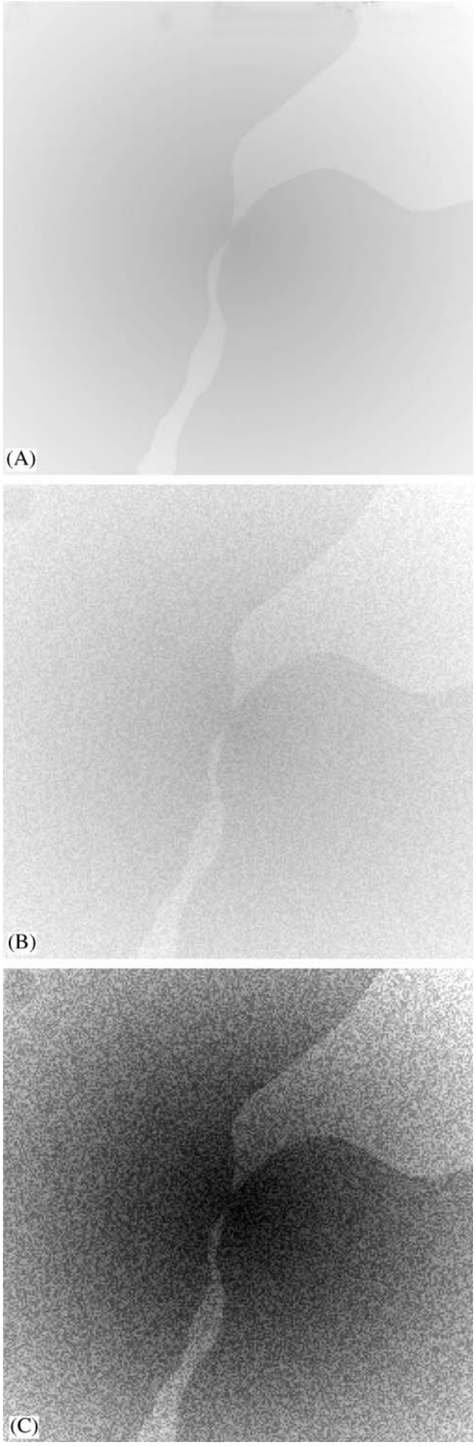

Fig. 1. Hypothetical image of a 1 km high conical ‘volcano’ viewed at 1 μm from 40 km altitude during the Venus night. Two ‘flows’ of different emissivities corresponding to fresh terrestrial basalt emanate from the volcano. (a) In this image, half of the signal is uniform gray to represent the expected 50% scattering of light at 40 km altitude. (b) One-percent noise is added to the image in (a). (c) The same as (b), but stretched for maximum contrast. The ‘flows’ are readily discernible in these images and may offer information on variations in flow composition at high-resolution. Image is 100 km across.

that the atmospheric abundance of H_2O near the surface (< 30 km altitude) is much less than was previously estimated (< 45 ppm). Because H_2O is an important greenhouse gas, this requires the abundance of other greenhouse gases to be much higher than models currently dictate to yield the temperature gradient observed on Venus. The deciding factors regarding the efficient retention of gases such as CO_2, and the extent of the contribution of other gases such as SO_2 and H_2O to the runaway greenhouse observed on Venus, can be addressed using precise estimates of abundances of these gases throughout the atmosphere and as a function of altitude. Additionally, if the primitive gas ratios were retained, Venus may be used as an end member model for the early stages of the Earth's atmosphere [10].

Since the atmosphere is potentially closely coupled with the surface, knowledge of how the various atmospheric species react with the surface rocks is crucial to any understanding of geologic, as well as atmospheric, formation and evolution. Constraining the current rock cycle would allow limitations to be placed on past rock cycles, which may have played an important part in retaining the bulk of greenhouse gases. Thus, constraint of the vertical and longitudinal abundance of reactive gases such as sulfur and carbon species, and water vapor, is a key to modeling the various weathering cycles at work on Venus. For example, it has been hypothesized that ancient H_2O could have been permanently trapped in hydrous SiO_2 species on the surface [21]. If, however, H_2O levels in the lower atmosphere are below the stability level for hydrated SiO_2 [22], as has been suggested in some studies (e.g., [20]), then a large reservoir of primordial H_2O is either precluded or must have dissipated by some other mechanism. In addition, it has been suggested that the presence of volatile phases such as metal halides at high altitude may be responsible for low altitude hazes observed by Pioneer Venus [23]. Definitive answers depend upon the abundance of very small (< 2 mm) particles in the lowest 6 km of the atmosphere. Essential to studies of surface–atmospheric interaction, then, is a clear understanding of the compositional, thermal and dynamic characteristics of the lowest 20 km of the atmosphere, that portion in closest contact with the surface.

2.2.1.2. Circulation and dynamics. Atmospheric dynamics in the lower atmosphere are critical to the understanding the large-scale circulation of the atmosphere. The superrotation of the venusian atmosphere is a function of the absorbed solar radiation and the transfer of angular momentum into and within the atmosphere. Measurements by Pioneer Venus probes show that highest density of angular momentum of the atmosphere lies between 10 and 40 km within the equatorial zone of the planet; in contrast, Earth has $\approx$ 200X less excess angular momentum distributed in middle and high latitude winds [11]. The transport of angular momentum is nominally accomplished by eddies and circulation whose motions and longevity are poorly understood. Additionally, as one source of excess atmospheric angular momentum is interaction of the atmosphere with the venusian surface, the atmospheric dynamics may reflect the rotation of the solid body [11]. The angular momentum density can be calculated from the retrograde zonal wind velocity and atmospheric density, both of which can be measured on an aerobot such as VFR.

2.2.2. Venus surface

2.2.2.1. Composition. Earth and Venus are similar in size and bulk density, thus we expect that they may exhibit similar geologic processes and products. Samples analysed by the Venera landers demonstrated the presence of basalt on the surface [24] which we can correspond to low-lying plains in the Magellan data (e.g., [25]), which cover $\sim$ 80% of the surface of Venus. It is impossible with the present data to establish if these sampled rock types are representative of the Venus surface as a whole or in part. The rocks sampled by the Venera and Vega probes show a range of basalt types [26] that may represent evolved magma compositions [27]. Magellan images reveal volcanic domes [28,29] and volcanoes [30] that appear to be composed of viscous magmas (Section 3.2.2). Modeling has shown that a range of magma types are possible on Venus, from high-magnesium komatiites to high-silica tonalites [31]; Venus' atmospheric chemistry has also led to predictions of carbonate and sulfate magmas on Venus [32].

A range of magma types may also explain some of the structural and morphological differences between terrain types seen on Venus by Magellan. Approximately 8% of the surface is covered by tessera terrain, which can be seen as large (1000 km across) plateaus that rise 1–4 km above mean planetary radius. Tessera terrain is highly deformed by compressional and extensional structures, resulting in a rough, and therefore bright, appearance in the radar. These plateau highlands are very similar topographically to terrestrial plateaus such as the Tibetan and Colorado plateaus. Plateaus are high-standing either because they are areas of thickened crust, they are compensated thermally, or they are less dense than the surroundings such as the terrestrial continental crust which is more evolved (higher silica content; granitic rocks) than the basaltic ocean basins. The tessera are the primary candidates for evolved magmas on Venus, if this is the case, than Venus would join Earth as the only bodies in the solar system known to have tertiary crust (33; see Section 3.2.2. for discussion of primary, secondary and tertiary crusts). This has important implications for Venus surface processes (material strength and weathering), interior processes (mantle dynamics, distribution of heat sources within the mantle) and the geological history of Venus, a planet whose surface records only the last 500 Ma.

As a target for an aerobot, tessera terrain has the advantages of standing several kilometers above mean planetary radius (MPR), being large in areal extent (up to 1000 km), and being abundant near the equator. Tesserae also contain important volcanic features. Intratessera plains (ITP) are abundant within the tesserae and necessarily have erupted through the thickened tessera crust (Fig. 2). The composition of ITP can be compared to the composition of the widespread plains to look for evidence of any ‘crustal’ component in the ITP lavas. This will test the hypothesis that tesserae are sites of older ‘proto-continental’ crust generated before the surface we see presently; there may be several eras of tessera formation preserved in the tesserae. If the roots of tesserae are becoming denser due to the transition of basalt to eclogite, this may be manifested as SiO_2-rich melts in the tesserae [31]. Variations in different ITP of different ages as determined by the radar data the ITP temporally may show the vertical and compositional evolution of magma source region.

Other sites of geochemical importance:

1. Plains-tessera boundaries. The VFR can take geochemical measurements of the surface across a plains-tessera boundary to better understand the nature of this contact and obtain measurements of plains at a relatively high altitude.

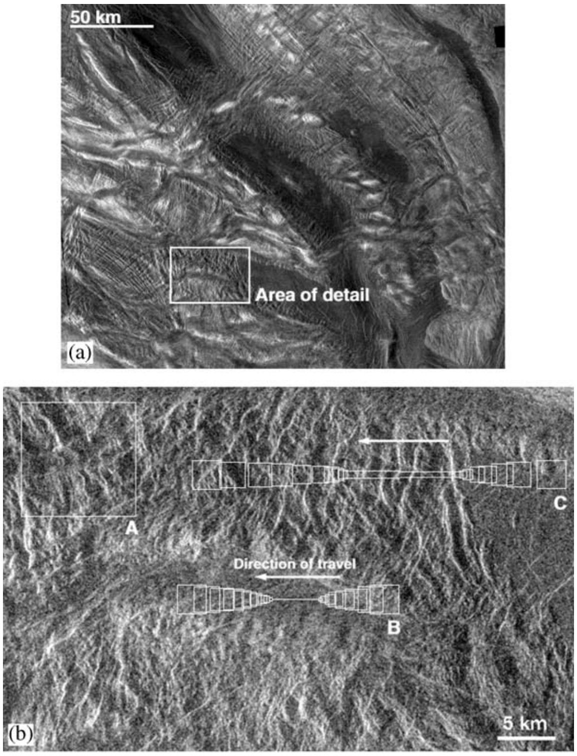

Fig. 2. Imaging frames sizes and positions for example aerobot trajectories—tessera terrain. (a) context image for (b) detail. The frames (white boxes) are overlain on tessera terrain in Ovda Regio. An intratessera plain lies on the eastern edge of the area in detail. North is at the top of the image. (A) This 10 × 10 km frame corresponds to an image taken at 40 km altitude with a 15° field of view (see Fig. 6). The resolution is expected to be 40 m/pixel. (B) These frames correspond to an aerobot descent to the surface using the wind velocity profile depicted in Fig. 5. The first frame (the easternmost frame) is at 10 km altitude and has a resolution of 10 m/pixel. Frames are taken every 7.5 min. The aerobot descends to the west until it reaches the surface; the final frame taken before landing has a resolution of 1 m/pixel. If the aerobot floats 10 m above the surface, resolutions as high as 1 cm/pixel can be attained. The aerobot drifts along the surface for approximately 2 h and travels 4 km (straight line) and then ascends back to 10 km altitude. (C) These frames correspond to a trajectory where the aerobot descends to 2 km altitude and stabilizes there (see Fig. 8). The first frame is at 10 km altitude with a resolution of 10 m/pixel. Frames are taken every 7.5 min. The aerobot descends until it reaches an altitude of 2 km where the resolution is 2 km/pixel. The aerobot floats at approximately 2 km for 2 h and travels 9 km distance before ascending back to 10 km altitude. Magellan SAR image (portion of F-MIDR 00N104; 75 m/pixel).

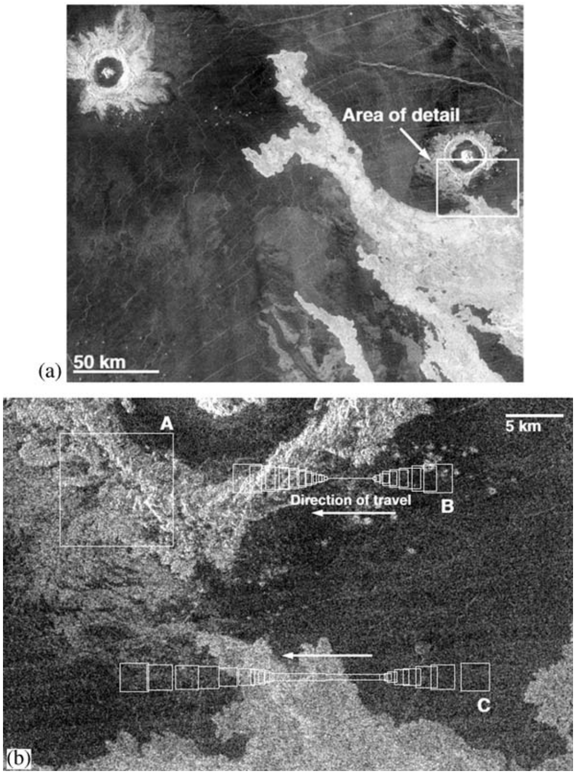

Fig. 3. Imaging frames sizes and positions for example aerobot trajectories—volcanic plains. See Fig. 2 for explanation. This area is located along the Atla geotraverse described in Section 3.2.1, Fig. 6. Portion of F-MIDR 00N189.

2. Steep sided domes. These domes range from 10–100 km in diameter and have an association with both tessera and coronae [28] terrains thought to have very different origins. Two major hypothesis have been put forth to explain the viscous magmas, evolved composition, or volatile enhancement of basalt in a reservoir [28]. The association with tessera could show importance of thickened crust and/or crustal contamination; the association with coronae could be related to abundant magma generation.
3. Coronae (Section 3.2.1). Coronae are hypothesized to be the surface manifestations of hot spots [34]. Hot spot volcanism has the potential of sampling magmas from deep within a planet. Coronae are most likely to record deep mantle compositions.
4. Volcanoes. See Section 3.2.1. below and Fig. 3.

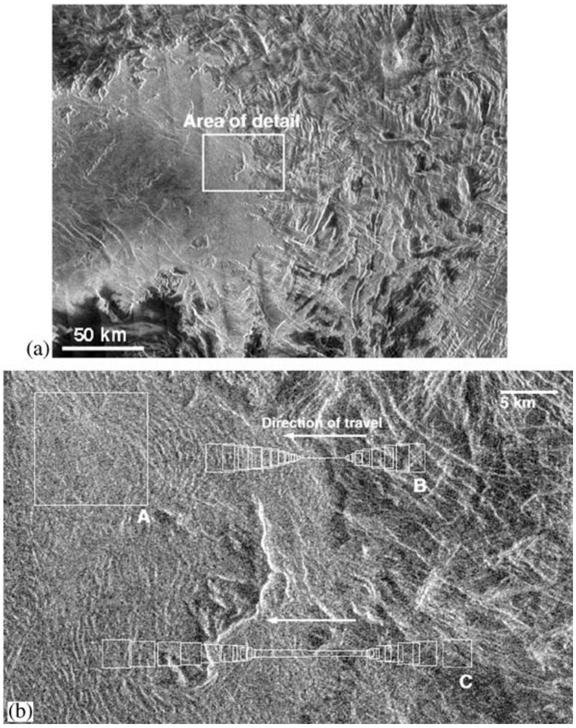

Fig. 4. Imaging frames sizes and positions for example aerobot trajectories—festoon flow. See Fig. 2 for explanation. This area is located along the Ovda geotraverse described in Section 3.2.2. Portion of F-MIDR 05S098.

5. Festoon Flow. See Section 3.2.2 below and Fig. 4.
6. Low emissivity materials at high altitudes. See following section.

2.2.2.2. Electrical properties. An important question which arose out the Magellan mission was the nature and composition of the “snowline” of low emissivity typically found on the highlands above $\approx$ 6053 km planetary radius. It has been proposed that these low emissivity values may correlate to a phase change where surface rocks chemically react with the atmosphere to produce high dielectric materials such as pyrite (FeS_2; [35–37]). The nature and abundance of these materials is debated from a geochemical view of stability of various species which depends on pressure, temperature, atmospheric composition and oxidation state at the surface, and also from the more basic standpoint of the interpretation of the emissivity signal. Specifically, the emissivity signal has contributions from the dielectric constant of the material and the surface roughness that need to be resolved to test the plausibility of the existence of candidate surface minerals [38]. As part of an attempt to answer this question, we put forward the idea of measuring the resistivity/conductivity of the surface of Venus with the electromagnetic wave approach on the VFR. Such data, combined with the high-resolution imagery obtained at the surface target will yield a much more complete understanding of the nature of the low emissivity highlands.

The Magellan radar system, in particular the altimetry and radiometry components, made surface reflectivity measurements of Venus possible. The analysis measured the time delay, strength and decay of the returning signals and was then correlated with measurements of the thermal emissivity of the surface. This then permitted approximate values of the surface dielectric constant to be calculated. However these values assumed the surface to be a poor conductor, and if the composition of the snowline is a good conductor (e.g., pyrite) then it is precisely the opposite case we would like to investigate. In fact it is the case of a good conductor that is ideally suited for airborne measurement.

Methods of electrical surveying are routinely used when one is investigating shallow subsurface geology on Earth. The most oft-used is probably the measurement of the resistivity to electrical current and there are a variety of techniques to evaluate it. The approach that interests us is the electromagnetic wave method because it can be used when direct contact with the surface is impossible, i.e. it can be an airborne measurement.

The essential features of the electromagnetic wave method are these: a primary electromagnetic field is produced by a transmitter near the surface (for Earth-bound surveys, within 100–200 m) which induces currents in surface and subsurface conductors. These currents give rise to a secondary electromagnetic field that must be detected by a receiver and then compared to the primary field. The ratio of secondary to primary field strengths can be as little as a few parts per million. Important information is also found in the phase difference of the two fields. Generally speaking, the two fields will be almost opposite in phase if the conductor is a good one, and close to 90° out of phase if the conductivity is small. For usual airborne measurements the frequency of the fields is 300–3000 Hz.

Direct application to the VFR project is not straightforward however. The problematic feature is obtaining the secondary field from the combined primary and secondary field that presents itself to the receiver. One approach requires the receiver and transmitter to be fixed with respect to each other and at least 10 m apart. Another relaxes the requirement that the transmitter and receiver be fixed, by using a primary field of at least two frequencies, however only phase information can be recovered and the separation distance is usually > 100 m. As it stands neither method seems compatible with the current specifications of the VFR. Other methods, such as the rotating field method (in which the primary field rotates) and the transient field method (in which the primary field is pulsed rather than continuous) also require a large separation.

However there seems to be some favorable aspects of the VFR setup. The snake attached to the VFR seems to be a natural place to house the receiver part of the system, if the snake can be made long enough. Further if, as we hope, the surface is highly conductive, then we should get a large secondary signal that would make detection less difficult. We can also expect advances in electronics to improve the signal-to-noise ratio. At this stage the dual frequency method appears to be the most promising for the VFR.

3. Example applications of aerobot technology

3.1. *Venus flyer robot trajectories and descent strategies*

3.1.1. *Background*

While some of the material technology needed to send an aerobot to the Venus surface ins in development [48–50], reversible fluid balloons have been tested in the Earth's atmosphere and have demonstrated their ability to perform oscillations about a mean altitude [2]. Future developments of the system will allow the balloons to temporarily descend to preselected target sites before ascending and resuming their oscillatory motion.

On the theoretical side, the performance model for balloons is well established (e.g., [46]) and has been recently extended to the case of reversible fluid balloons [47]. The predictions of the model are in good agreement with existing flight data. Besides the particularities of the balloon such as mass, reversible fluid being used and thermal properties of the balloon, one requires rather detailed knowledge of the atmosphere, winds, and heat input from the sun and from the ground. A number of these data could be collected during the proposed BEV mission.

3.1.2. *A model for Venus*

To evaluate the proposed BEV/VFR missions, we seek to compute the trajectories of a reversible fluid balloon in the venusian atmosphere. Although their Earth-bound counterparts are well understood; both experimentally and theoretically, we can at present only estimate a performance model for Venus. Ironically part of our uncertainty is because we lack the very information the BEV/VFR missions will bring us; in particular the circulation and thermal properties of the atmosphere. In what follows we indicate how our performance model was calculated and what estimates were made.

The motion of the balloon is most easily understood when we separate it into two parts: the vertical motion and the motion over the planet's surface, which we will call horizontal motion. The horizontal motion is determined solely by the atmospheric winds, in fact the balloon just moves with the wind. The vertical motion is subject to three forces: gravity, the buoyancy of the balloon, and a generalized drag force (which includes any vertical component of the wind). It is the buoyancy force which is the most problematic. Essentially we need to know how much of the reversible fluid is liquid and how much is gas. This requires us knowing how much heat from the sun, the atmosphere (including clouds) and the planet's surface is being absorbed, and how much is being reflected and emitted by the balloon. A complete account requires detailed knowledge of the balloon's materials and the balloon's environment at each point in time.

In our model we account for the horizontal motion of the balloon by considering a trajectory near Venus's equator, which fortuitously includes many surface features of great interest. Here Venera data indicate that the wind blows predominantly to the west with increasing speed as altitude increases (Fig. 5). Thus the trajectory of the balloon will remain in the equatorial plane. For simplicity we ignore suggestions in the Venera data of violent up- and down-drafts, believing their effect would cancel out on the average.

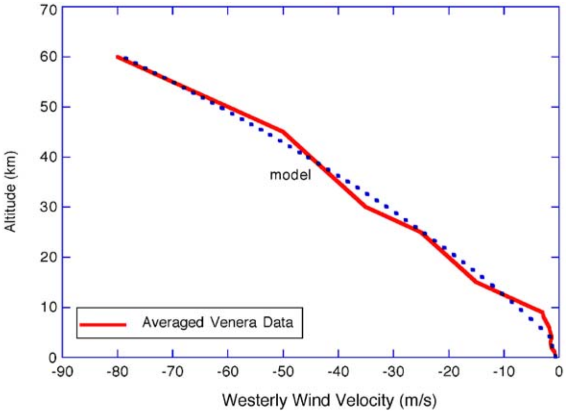

Fig. 5. Zonal (east to west) modeled wind velocity profile (dotted line) as a function of altitude. The model is fitted to the Venera 8 data (averaged day/night profiles).

We are indebted to Jack Jones for his estimates of the vertical motion of the balloon. For an ammonia/water reversible fluid balloon, we can expect oscillations between 40 and 60 km altitude. With the current specifications for the BEV mission, it is believed the upward and downward velocities will be 1.4 and 2.8 m/s, respectively. For the VFR mission velocities of 2 and 3 m/s are expected. The VFR also as the added ability to stabilize at lower altitudes, though probably with a slight upward velocity, estimated to be 0.1 m/s. The maximum time it can spend at these lower altitudes is assumed to be ~ 2 h. Similar to the lifetimes of the Venera Landez.

3.1.3. *Trajectories and descent strategies*

We can utilize our simple model to estimate the distances traveled and timescale of several example aerobot trajectories. Firstly we consider the motion of the aerobot in the upper atmosphere. Using the atmospheric constraints above, the model yields an oscillatory stage in which the VFR/BEV travels from east to west, completing a cycle every 5–6 h (Fig. 6). A displacement of 1000 km in this time predicts an orbit of the planet in around eight Earth days. A descent to the surface will take ~ 6 h and allow 1 h of imaging below 10 km altitude. In that time the VFR will

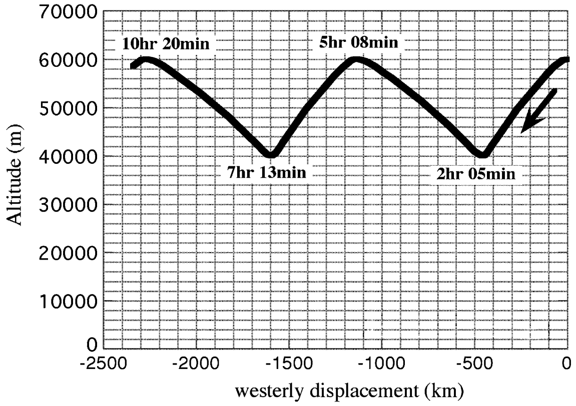

Fig. 6. BEV/VFR oscillation stage. The aerobot travels from west to east, oscillating between 40 and 60 km altitude, completing a cycle every 5–6 h (rise time ∼ 3 h at 2 m/s and fall time ∼ 2 h at 3 m/s). Surface images at 1 μm can be accomplished at the bottom of each oscillation which corresponds to a lateral distance of 1000 km. The frame size of such as image can be found in Figs. 2a, 3a, 4a.

obviously move significantly to the west and so it will be necessary for the VFR to have targeting capability if particular surface features are to be investigated. The ascent will be ∼ 9 h.

Next we have simulated a descent to the surface, initiated at the maximum altitude of 60 km from the east (Fig. 7). The VFR is carried almost 600 km lateral distance during the descent time of roughly 6 h. A descent velocity of ∼ 10 km/h will allow several hours of imagery measurements to be taken below 40 km altitude and ∼ 1 h of measurements below 10 km. This would be a typical VFR maneuver, with the time spent at the surface clearly dependent on its ability to withstand surface conditions; we assume a maximum of 2 h for surface measurements.

The ability of the VFR to stabilize at a given altitude will enable a low-altitude pass of the surface and allow for compositional analysis of the lower atmosphere. Such trajectories offer greater coverage than surface dives at cooler temperatures (see Figs. 2–4). Dives of this type will take advantage of the fact that the atmosphere becomes transparent to wavelengths less than 1 μm below 10 km. We have calculated the trajectories where the aerobot stabilizes at 2 km altitude (Fig. 8) and at 10 km altitude (Fig. 9). Examples of frame sizes corresponding to the 2 km dive are found in Figs. 2c, 3c, 4c.

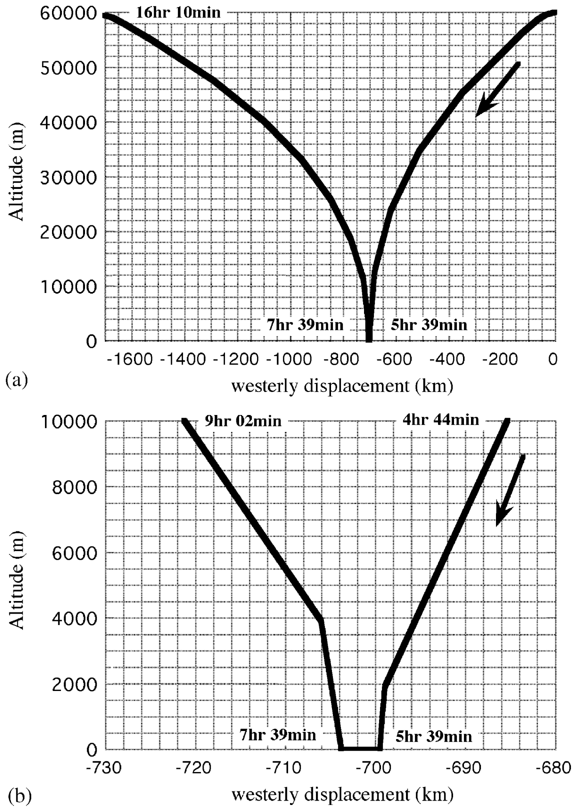

Fig. 7. (a) VFR surface dive. The aerobot begins its descent at 60 km altitude. The VFR is carried almost 600 km lateral distance during a descent time of roughly 6 h. The aerobot will drift ∼ 4 km along the surface. (b) Same trajectory as (a), but at altitudes < 10 km. Approximately 5 h is available for image at wavelengths less than 1 μm. Examples of imagery frame sizes corresponding to this portion of the dive are found in Figs. 2b, 3b, 4b.

We also consider two ‘specialist’ VFR descent trajectories. Considerable uncertainty remains as to the velocity of surface winds on Venus, especially when considering terrains at various altitudes. If the winds are indeed near zero at the surface, lateral mobility may be low. One way to increase lateral coverage by the aerobot at the surface is to utilize surface slopes, a scenario shown in Figs. 10 and 11. We consider such a trajectory with the added assumption that a wind blows down the highland slopes with a speed of 2 m/s. This trajectory is particularly useful for surface geotraverses that target the plains-tessera boundary along a tessera highland (Section 3.2.2). Successful targeting will require the VFR to predict its trajectory several hundred kilometers in advance.

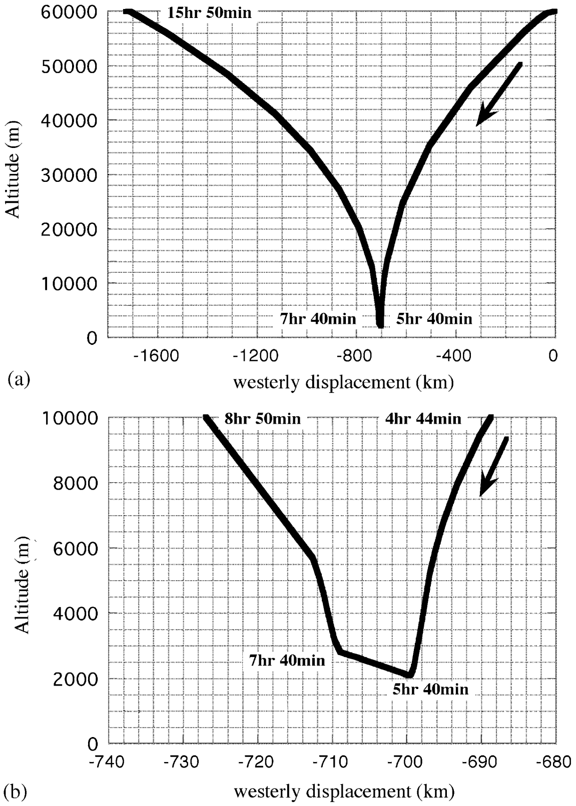

Fig. 8. VFR stabilization at 2 km altitude. (a) This trajectory is favorable for high-resolution imagery over longer distances than a surface dive utilizing both higher wind speeds and lower temperatures. The aerobot begins its descent from the east, reaching an altitude of 2 km in ∼ 6 h. The aerobot stabilizes for ∼ 2 h, traveling a distance of 9 km, before ascending back to 60 km in ∼ 8 h. (b) Same trajectory as (a), but at altitudes less than 10 km. Approximately 5 h of imagery will be available at these altitudes. Examples of imagery frame sizes corresponding to this portion of the dive are found in Figs. 2c, 3c, 4c.

We conclude with a plot of each of these trajectories along the geotraverse of Atla Regio outlined in Section 3.2.1 (Fig. 12).

We have been able to estimate possible trajectories of the VFR in the Venus atmosphere. There are a number of trajectories that it will be capable of, and it is apparent that all will be of immense value from an investigative point of view. The targeting capability of the VFR will be important and we will have to rely on the BEV program to provide more extensive information on the Venus wind patterns.

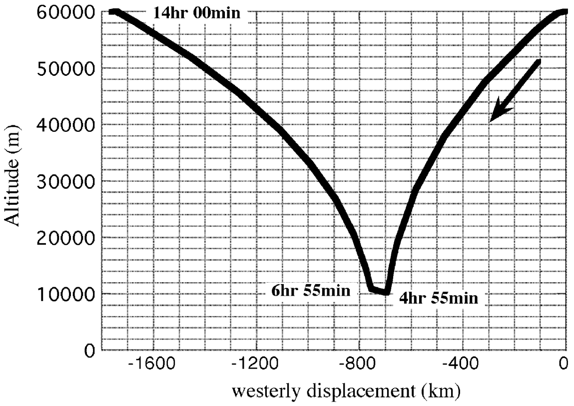

Fig. 9. VFR stabilization at 10 km altitude. The aerobot begins its descent in the east and reaches 10 km in ∼ 5 h. Two hours of information can be taken as the balloon drifts ∼ 7 km.

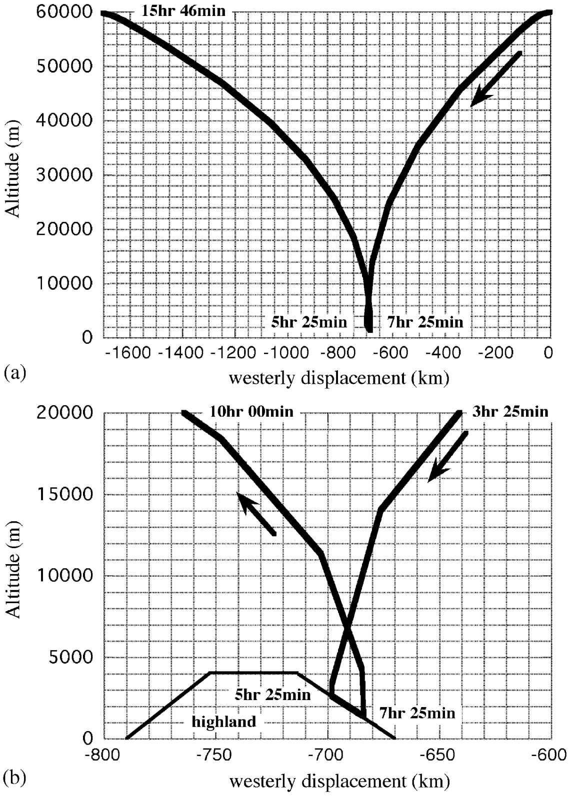

Fig. 10. Descent to the highlands from 60 km altitude, where the highland slope is facing towards the aerobot. The VFR enters from the east, touches down and drifts downhill for ∼ 20 km along the surface. Slope on highland is 5°. (a) Full trajectory. (b) Trajectory at altitudes less than 20 km.

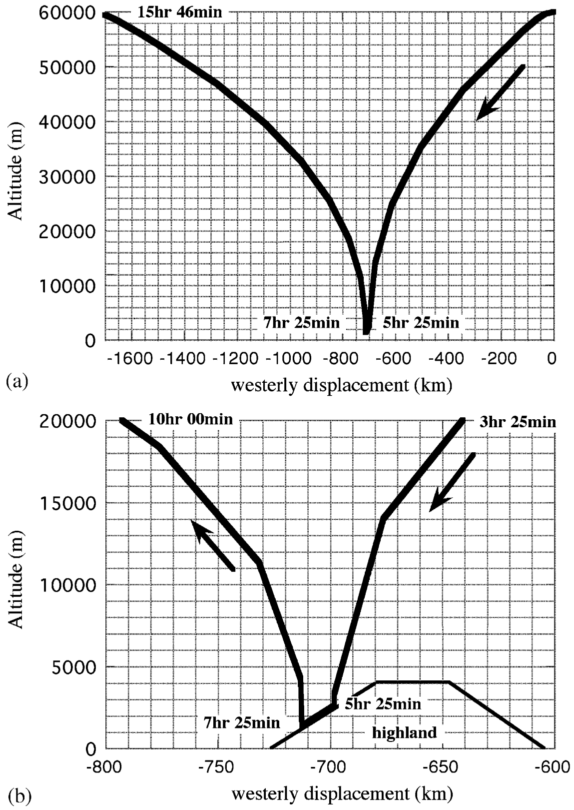

Fig. 11. Descent to highlands from 60 km latitude, where the highland slope is facing away from the aerobot. The VFR enters from the east, touches down and drifts along the surface downhill for ∼ 20 km. (a) Full trajectory. (b) Trajectory at altitudes less than 20 km.

3.1.4. Proposed imaging systems

Short of landing on the surface, the primary tool a balloon has for exploring the surface geology of Venus is an imaging system. An aerobot mission would give geologists a chance to see the surface of Venus in a few important wavelengths, at a resolution from 1–100 m or smaller. The 100 m data would provide a cross-check for the 75 m/pixel Magellan data, as well as regional context for "dives" to the surface. Data in the 1–10 m resolution range is essential for understanding the character of the surface and interpreting the geology on an outcrop scale.

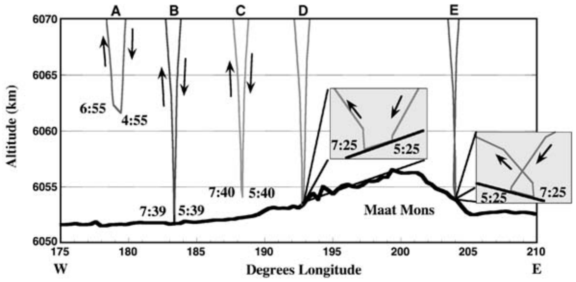

Fig. 12. Shown are five idealized VFR trajectories over Maat Mons on the volcanic highland Atla Regio (see also Fig. 13). Arrows denote aerobot direction. Trajectories are (from the west): (A) stabilization at 10 km altitude (see Fig. 9 for details). (B) surface dive (see Fig. 7 for details), (C) stabilization at 2 km altitude (see Fig. 8 for details), (D) descent to highland slope I with inset (see Fig. 11 for details), (E) descent to highland slope II with inset (see Fig. 10 for details). Numbers next to the trajectories denote time in hours and minutes from descent commencing near 60 km altitude.

The Venus atmosphere has a window of transparency between 0.5 and 1.04 μm [16] but the scattering of this light is too great to resolve surface features at shorter wavelengths from altitude. As discussed in Section 2.1.2 above, only images taken in the wavelength range of 1 μm are usable from the bottom of the balloon's oscillation. If the aerobot were to dive to within a kilometer of the surface, the scattering would be greatly reduced. At this level, multispectral images could be acquired to give geologists a wealth of information about the surface. Important questions that can be addressed by multispectral imaging in this narrow spectral window include:

- What is the oxidation state of the surface? Spectral measurements from Venera landers offered a tantalizing glimpse of what may be an oxidized surface [18]. This is important for determining the near surface environment, investigating the weathering of rocks on the surface (which could be correlated to recent volcanic activity), and could have important implications for the evolution of the atmosphere, as a sink for oxygen.
- What rock types other than basalt occur on the surface? The Venera landers measured tholeiitic basalt, but are there other areas (such as domes, festoon flows, or tessera) with a less mafic composition?

A minimum of five filters would be needed to do this adequately:

1.0 µm	pyroxene, olivine band, usable from high altitude
0.87 µm	Fe^{2+} band (high-temperature hematite), oxidation state of the surface
0.77 µm	point between iron absorptions to constrain albedo vs. absorptions
0.65 µm	red, Fe^{3+} band, oxidation state of the surface
0.55 µm	green, constrain iron absorption edge

Greater spectral resolution is, of course, preferable, but it also greatly increases the amount of data that then must be transmitted to Earth. It would also be useful to measure ambient light in the atmosphere on the same imaging chip, through a mirror or other device, averaging the pixels on the chip.

An imager with the spectral bands above, 256 × 256 pixels, and a 15° field of view, would provide the following data:

- Images at 1 µm at the low points of its oscillation (40 km), would cover 10 × 10 km, with a resolution of 40 m, three times better than Magellan (Fig. 2a). If the balloon is moving at 50 m/s at this altitude, images spaced less than 2 min apart will give stereo for the overlapping halves of the frames. Stereo coverage is essential because of the lack of shadows on the surface.
- When the VFR descends to 1 km altitude, it could utilize all of its filters, covering a 260 m swath, with a resolution of 1 m (Fig. 2c). If wind speed at this level is $\sim 1\,\mathrm{m/s}$, the camera would have to take pictures every 4.5 min for continuous coverage, or every 2.25 min for stereo coverage. At 524 kilobits/frame, five-color stereo coverage for 2 h (27 color frames, 26 monochromatic frames), covering an area of 0.26 × 7.2 km, would generate about 84 megabits of raw data.
- A camera at 10 m altitude would see a 2.6 × 2.6 m area with a resolution of 1 cm, enough to resolve large pebbles and outcrop details (Fig. 2b). If the wind moves the balloon at 1 m/s, the camera would have to take pictures every 2 s for the images to connect, twice as often for stereo coverage. The motion of the snake along the ground transmitting to the balloon and the motion of the balloon with respect to the ground could seriously degrade the images. Perhaps this type of imaging should be done only as the balloon lands and takes off. Data could be collected as the balloon is held at 1 km altitude during a descent sequence.

3.2. Example geotraverses utilizing the Venus flyer robot

A geotraverse is a geologic mapping exercise in which data are collected along a narrow strip of great length crossing a variety of terranes and geologic units. The geotraverse approach has several advantages that are well-adapted for the characteristics of aerobot operation. The chief advantage of geotraverse mapping is that it efficiently focuses attention on the longitudinal diversity of geologic units over a large region, but characterizes them at a uniformly larger map scale than is otherwise generally possible in a more regional geologic mapping study. The results enable integration of the detail local geologic processes of several large map scale geologic units over a broad region. When combined with more regional studies, such as those resulting from analysis of Magellan data, the results of a high-resolution geotraverse are applicable to the general interpretation of geologic units widely distributed over the surface of Venus.

3.2.1. Atla regio

A variety of geologic terranes may be sampled by a simple east to west traverse across the Atla Regio area. Atla Regio lies at the junction of three prominent rifts [39], Ganis Chasma, Parga Chasma, and Dali Chasma, and is the site of the greatest concentration of large volcanoes on Venus [40]. Much of the rifting in this area is relatively young based on cross-cutting relationships with impact craters. Therefore it is possible that volcanism in this region may be particularly young. In addition the surface directly west of Atla Regio is an area of extensive lowland plains, Rusalka Planitia. The great range in elevation also offers the potential for sampling the characteristics of surfaces occurring over a large altitude range, including areas of anomalously low emissivity associated with the summit region of Maat Mons. Together these offer the potential for sampling several of the significant geologic units of Venus along a near equatorial traverse.

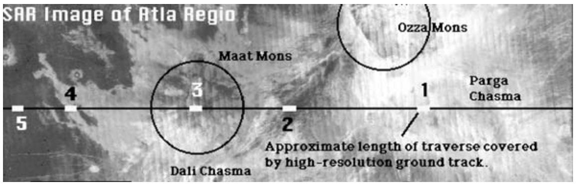

Fig. 13. Example geotraverse of atla regio on Magellan SAR image. The volcanoes Maat Mons and Ozza Mons are circled for reference. Numbers on the SAR image refer to specific targets discussed in the text. Several aerobot trajectories plotted onto this geotraverse are shown in Fig. 12. Image is ∼ 1800 km across.

The traverse is assumed to follow a descent from east to west along an equatorial path centered on the crest of Atla Regio (Fig. 13). In this area the geology is locally complex, but maintains a regional characteristic dominated by the large volcanic rise and rift junction centered near Ozza Mons at (4°N, 199.5°E). Traverses at different latitudes are therefore capable of crossing geologic features of widely varying characteristics.

Several detailed questions could be addressed along short descent tracks along a latitudinal band centered at 1°N. Five potential targets include Parga Chasma, Dali Chasma, Maat Mons, distal flows from Maat Mons, and Rusalka Planitia. Descent to either Parga Chasma or Dali Chasma offer the potential for examining the structure of rifts in an area of possibly young tectonism. A traverse of the summit region of Maat Mons could be made if the traverse occurred at 1°N and was centered at 194.5°E. Assuming the estimated traverse length within the lower atmosphere over which imaging may take place is ∼ 20 km, a traverse centered at this coordinate, for example, would be restricted to the summit region of Maat Mons. This would provide a detailed assessment of surface characteristics within the vent region of the volcano, but would also provide high resolution physical characteristics of the surface associated with an area of anomalously low emissivity values. This is one of the highest points on Venus and although, direct targeting of this point on the surface would require altitude control that was precise enough to hover 8–9 km above the mean global surface altitude, it would ameliorate the number of high temperature excursions needed to view the surface at high resolution.

Both Maat Mons and the chasmata are targets that provide for diversity in geologic processes. In contrast, the distal flows of Maat Mons and the broad surface of Rusalka Planitia are example of the large units that are easily targeted because of their size, and provide detailed ground truth about units of known probable geologic origin, but of large areal extent. The diversity of targets within Atla Regio demonstrates that many geologically interesting sites may be acquired along laterally restricted latitudinal bands. Thus aerobot technology is both directly applicable to the geologic investigation of the surface Venus and capable of targeting specific regions of particular significance in Venus science.

3.2.2. Ovda regio

One of the main objectives of the scientific study of Venus is the question of the formation and evolution of planetary crusts. Venus offers an opportunity to study secondary and tertiary crust and to link to an understanding of two major stages of continental formation on Earth. We propose three landing sites for consideration to address these problems. These are (1) volcanic plains (secondary crust), (2) tessera in Ovda Regio (deformed secondary crust and/or tertiary crust), and (3) the Ovda festoon (best candidate for tertiary crust). These can be accomplished by three touchdowns in the equatorial region of Venus using the VFR.

Tertiary crust forms by the reprocessing of primary and secondary crusts by several possible mechanisms; according to [33] the Earth's continental crust is the only presently known example of tertiary crust. One of the most distinctive morphologic volcanic signatures of evolved crust on Earth is the presence of steep-sided domes that form from the extrusion of viscous magma [28]. Features of similar morphology have been observed on the Moon [41] and Venus [28–30,42,43], and at least one occurrence on Venus may be linked to more evolved composition [25]. We have been analyzing several environments [31] and candidates for tertiary crust on Venus, specifically asking several questions, including: What is the evidence for post-formational evolution of tessera in terms of melting of thickened crustal roots and associated volcanism of potentially non-basaltic composition? As one of the main components of the plan for understanding tertiary crust, we report on the characteristics, setting, stratigraphic position and preliminary assessment of the petrogenesis of the distinctive festoon deposit [44,45] lying within some of the highest-standing tessera in Ovda Regio.

The festoon structure lies within Ovda Regio at about (6.5°S, 95.5°E) and is about 250 × 300 km in dimension. Ovda Regio is one of the most distinctive occurrences of tessera on Venus and this part of Ovda is one of the highest standing on the planet; the tessera at the edges of the festoon lie at about 6056.2 km, $\approx$ 4.4 km above MPR. Stratigraphic relationships show that the festoon overlies the tessera terrain; the morphology and internal structure of the two terrains contrast distinctly, digitate and lobate projections at the deposit edges follow preexisting structural troughs and fractures in the tessera, and there are kipukas of tessera within the festoon. The deposit itself is elongated in a NE–SW direction, parallel to structural trends in adjacent tessera. Interpretation of the underlying tessera as a product of downwelling and crustal thickening provides a basis for the assessment of petrogenesis of this deposit. On the basis of evidence for lava plains as tessera precursor terrain and the likelihood of a basaltic crust throughout the history of Venus, one of the main candidates for the origin of this deposit is the remelting of a basaltic crust initially derived from melting of a peridotitic mantle. Venera lander analyses of presently exposed plains lead us to consider the remelting of tholeiitic basalt under anhydrous conditions; melting of tholeiite basalt above 15–25 kb (about 53–88 km) begins at temperatures in excess of 1200 °C and in the eclogite facies (or in the garnet granulite facies, depending on the bulk composition). The melt that coexists with the eclogite assemblage (garnet and clinopyroxene) typically is quartz-normative and strongly enriched in SiO_2. Small degrees of melting ($<$ 20%) generate trondhjemites ($SiO_2 > 65\%$) whereas intermediate degrees of melting (20–50%) yield andesites and basaltic andesites. In contrast, the first melts obtained at lower pressures (10–15 kb; 35–53 km) appear to be relatively SiO_2 poor. For example, the liquids obtained by small degrees of melting at 8 kb (28 km) of high aluminobasalts are ferrobasalts containing only 42% SiO_2 and more than 20% FeO. In summary, large amounts of silicic magmas are generated at high pressures and large amounts of relatively SiO_2-poor, and highly fluid, ferrobasalts are obtained under more modest pressures. Thus, shallow crustal melting occurring in environments such as underthrust basaltic crust and basal melting of tessera crustal blocks less than about 50 km thick should result in the production of fluid ferrobasalts. Deeper crustal melting, such as that which might be occurring at the base of zones of very thick tessera, should produce more viscous SiO_2-rich melt products such as trondhjemites, andesites, andbasaltic andesites. The fact that the festoon deposit occurs at the highest elevations in Ovda Regio suggests that in terms of simple Airy isostasy this is an area of some of the thickest crust on the planet (and thus deepest melting), a conclusion consistent with apparent depths of compensation of 70 ± 7 km and Magellan gravity data. This petrogenetic model provides an independent estimate of crustal thickness, an estimate consistent with those from gravity data. Geochemical sampling by an aerobot mission will test this important hypothesis for the formation of tertiary crust on a planet other than the Earth.

4. Summary—the utility of aerobots in planetary exploration

Using the BEV and VFR concept mission studies, we have calculated some simple trajectories of an aerobot at Venus. An aerobot like BEV or VFR can circumnavigate Venus in eight Earth days, continuously collection compositional data between 40 and 60 km and collecting images of the surface below the clouds for an hour every 5–6 h. Surface dives allow longer ($\sim$ 6 h) observations below 40 km, including multispectral imaging below 10 km. These dives cover distances 100 of km and allow compositional measurements of the lower atmosphere. Trajectories can include the include stabilization at low altitudes for hours of observations. Dives to the surface produce multispectral stereo imaging at up to cm-scale resolution. Meter scale imaging spanning 10s of km can be directed to boundaries between geologic units of interest. Technology such as an XRF instrument mounted on a snake will allow compositional measurements of surface materials. Surface access can be maximized by utilizing local winds due to slope effects.

The next phase of the exploration of Venus will focus on understanding several fundamental characteristics of the atmosphere that are necessary to place Venus in context with the other terrestrial planets. These measurements include upper and lower atmospheric composition and atmospheric dynamics. A single aerobot mission is uniquely able to measure these critical parameters in three dimensions over the globe over time. An aerobot with decent capability also provides a mechanism to collect data at the surface for brief periods, and then return to the cooler altitudes. This type of mission has the potential to visit the surface at several key regions over its mission lifetime.

The following briefly assesses some characteristics of an aerobot type mission that enhance its "science value" with respect to other possible planetary missions.

A. New and unique resources of an aerobot:

1. Ability to explore the atmosphere in three dimensions over time.
2. Cheap, innovative method of surface exploration.
3. Can investigate lower atmosphere characteristics.
4. Applicable to several planets.

B. Major issues that could be resolved or addressed at Venus:

1. Large scale variability of surface composition on Venus.
2. Lower atmosphere chemistry and dynamics.
3. The superrotation of venusian winds.
4. Is Venus volcanically active?

C. Specific measurements provided by a Venus aerobot:

1. Multispectral imaging of surface in the 1–10 m gap, including the relationship between large scale morphology and small scale morphologies; lateral variations in lithology, block sizes.
2. Multiple surface analyses over different lithologies and chemical compositions correlated to those lithologies.
3. Extended traverse sampling sites enables definition and correlation of large-scale geologic units.
4. Monitoring of compositional and physical variations in atmosphere with altitude and latitude.
5. Variable resolution and high resolution imagery in regional context—essentially enables geotraverses with ground truth.

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