In Situ Exploration of Venus' Clouds by Dynamic Soaring

Expanding Sampling Capabilities through Energy Harvesting

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Abstract

The clouds of Venus may be the next frontier in planetary exploration. It will be impossible to understand Venus' climate until a sustained, *in situ* investigation of this region is undertaken. An unidentified agent or agents in Venus' clouds absorbs about half the incident solar energy. Furthermore, it is highly variable in time and space. Therefore we are ignorant of how Venus' climate is forced, even as we now see evidence for decadal climate oscillations. How stable is Venus' climate? What might the investigation of Venus' climate tell us about climate stability in general and specifically for the Earth?

What is needed is a long duration scientific expedition to the clouds of Venus. The extremely harsh acidic acid environment not withstanding, the pressures and temperatures in Venus' clouds are Earth-like. Sensors and instruments however must be protected from liquid particles and reactive sulfur gases with a *p*H from 0 to -2. A vehicle that can dwell within the clouds for weeks, circumnavigating Venus many times could provide data on the physical and chemical properties of Venus' cloud layer aerosols and atmosphere.

Vehicles deployed in Venus' cloud layer will either need to have sufficient battery capacity to continue functioning while traveling around the dark side of the planet, expend a large amount of energy to maintain position on the sun lit side, or make use of alternative methods to provide propulsive power to the system. Fortunately, the rapid movement of the atmosphere also creates locations conducive to energy harvesting, including dynamic soaring, a proven method to extract energy from atmospheric wind shear. Dynamic soaring has propelled the fastest small-scale aircraft in the world, and provides the energy necessary for the long-endurance low-level flights of birds across oceans. The locations in Venus' atmosphere that are favorable for the use of soaring techniques provide not only energy to maintain altitude, but sufficient wind-relative velocity to navigate to desired global locations. Strong upward winds exist near the low latitudes that create vertical movement of the atmosphere. Additionally, large areas of the atmosphere on Venus contain characteristically high wind shear, particularly at the cloud interface and above high elevation ground structures.

A deployable unmanned aircraft system (UAS) could not only survive in the harsh wind environment of Venus, but also simultaneously perform targeted sampling of the atmosphere while continuously extracting energy, even during the night. The design will be based on proven dynamic soaring platforms, but will be constructed in such a manner that allows for deployment from a standard (PV-sized) aeroshell. Additionally, materials selection and construction methods will be finalized that ensure long-term survival in the corrosive cloud-top environment. The proposed system is small enough to allow up to eight aircraft to be deployed from one aeroshell, or a smaller number can be used as secondary payloads on other primary vehicles such as a balloon or dirigible vehicles.

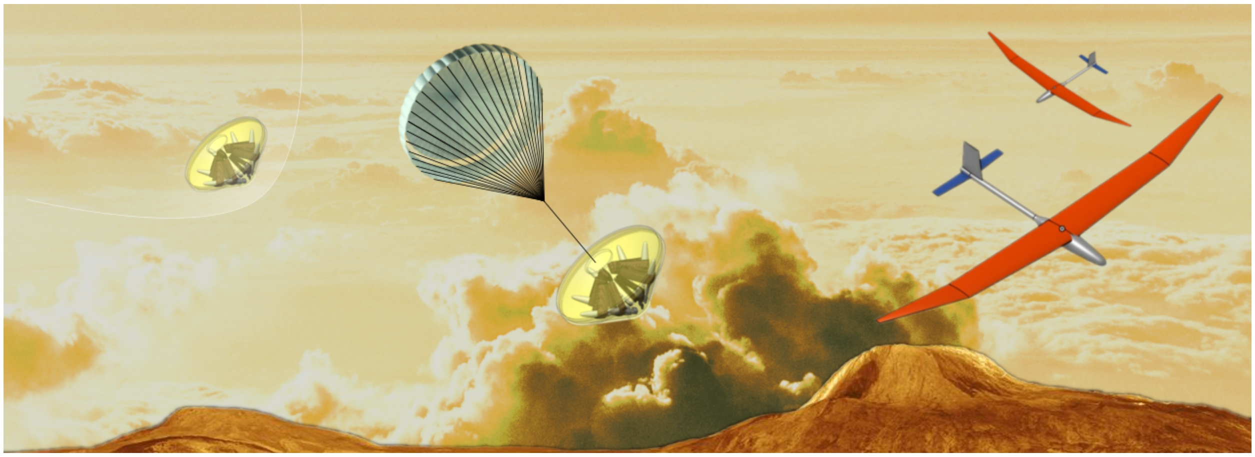

Figure 1: Deployment overview of a fixed-wing, energy harvesting vehicle, including atmospheric entry via aeroshell, parachute descent, and multiple air vehicle deployment.

1 Introduction

Spacecraft have explored the solar system for the last 50 years, but the clouds of Venus remain *terra incognita*. Atmospheric entry probes have passed through the cloud layers, making measurements, but the composition of cloud aerosols and of the main absorber of sunlight within the clouds is unknown.

What is known about the region of Venus' clouds is daunting. The *p*H of the liquid cloud aerosols varies from 0 at the top of the clouds to about -2 near the turbulent lower cloud base. Most aerosols are sulfuric acid/water droplets, from 0.1 to 10 μm in diameter. They are comprised of about 75 percent H_2SO_4 near the cloud tops, and about 90 percent H_2SO_4 at the cloud base

The upper cloud is a globally homogeneous photochemical haze layer 10 km thick. Volcanic sulfates are converted to acid by photochemical oxidation and reaction with water vapor. The products of these reactions are liquid aerosols that grow as they fall through the sulfuric acid vapor in the clouds. In the extremely hot, dense lower atmosphere of Venus, the sulfuric acid aerosols vaporize as they fall, creating a reservoir of condensible gas just beneath the clouds. Venus' lower and middle clouds form in updrafts, where sulfuric acid and a small amount of water vapor and other trace gases condense onto cloud condensation nuclei.

Most of the sunlight that isn't reflected back into space is absorbed in the clouds. Only about 2 percent makes it to the surface. Venus' weather is driven by intense solar heating of the upper cloud. This makes it fundamentally different from Earth, whose weather is driven mostly by the absorption of sunlight at the ground. Heating within the clouds and the differential absorption of solar energy between the equator and poles drives Venus' unique global circulation.

The sulfur cycles below, within, and above the Venus clouds have been modeled using PV GCMS data [1] and ever more sophisticated models [2, 3]. However, large gaps in our knowledge of the chemistry of Venus' clouds prevent an understanding of how the clouds affect its climate. Reconnaissance of Venus' clouds must involve a comprehensive analysis of the aerosols and sulfur chemistry in a wide range of locations within the atmosphere.

Models and direct observation of the atmosphere of Venus have shown that the environment above the cloud layer is incredibly dynamic [4–6]. The strong and persistent vertical shear conditions at Venus' cloud tops are ideal for sustained energy-harvesting soaring. Favorable environments for the use of soaring techniques provide not only energy to maintain altitude, but sufficient wind-relative velocity to navigate to desired global locations. Convective activity originating in the middle cloud is a persistent and global feature of Venus' atmosphere. [7–11] Additionally, large regions of Venus' atmosphere contain characteristically high vertical wind shear, particularly near the cloud tops [12]. This phenomenon can also be observed on Earth as it causes the capping of convection in convective storms [13] and the formation of high altitude cirrus clouds[14], and is evident above mountain waves[15].

Both updrafts and regions of high vertical shear can serve as sources of energy for a fixed wing aircraft. However, for a mission to range over a large area of the planetary surface, the use of gravity waves and equatorial updrafts has limited value to the sampling mission. Therefore, the development program focuses on designing and testing aircraft and algorithms for harvesting energy near the Venus cloud tops. Intelligent flight path control can be used to combine dynamic soaring cycles in such a manner as to incrementally change position of the craft and provide nearly global mobility. Additionally, the flight path is ideal for systematic *in situ* study of Venus' clouds. On the upper branch of its trajectory, the aircraft traverses the upper cloud. The composition of gases and aerosols can be measured throughout the upper cloud. The bottom of the arc is an ideal location for obtaining near-IR images of the surface.

Of additional benefit is the simplification of operating on the dark side of the planet. Since propulsive power is supplied through the flight path, energy can be devoted to control surface actuation and onboard systems, generally a much smaller portion of the overall energy budget. It is plausible that making use of the abundant solar energy on the sunlit side could allow for charging batteries that last through the traversal of the dark side. Furthermore, energy sources such as an external turbine will be considered that can provide energy regardless of the presence of sunlight.

Finally, the use of rigid, deployable aircraft rather than inflatable structures simplifies the required deployment mechanism. Rather than waiting for the vehicle to be inflated with a lighter-than-air gas, a simple mechanism can be used to deploy components from a compact configuration in a matter of seconds. This has been employed on earth for tube launched UAS, which have been successfully deployed at a very high relative speed over hurricanes for atmospheric research [16, 17].

2 The Science Case for *In Situ* Investigation of Venus' Clouds

The clouds of Venus may be linked to past volcanism, and their stability over geological timescales is not well established. The clouds are a major reservoir of hydrogen and sulfur, but both these species are gradually lost from the atmosphere. Water vapor is lost at the top of the atmosphere, and SO_2 reacts readily with carbonates and some silicates at the surface.

Lee et al., 2019 [18] recently showed that the UV albedo of Venus varies on timescales of about 10 years. The unknown agent or agents responsible for these changes actually absorb over a broad spectral range and into visible wavelengths. The amplitude of these albedo changes was large - 40% from 2006 to 2017. These authors showed that the anomalous increase in zonal wind speeds that had been noted but not understood [19], can now be seen as due to increased absorption of sunlight in the clouds. This very large change in climate forcing over a decade was caused by the unknown near-UV absorber. The chemistry of Venus' atmosphere is therefore linked to the general circulation and to the distribution of its clouds.

VEXAG identified several high priority investigations that should be performed by an *in situ* mission to the clouds of Venus. The proposed vehicle would be ideal to address the second VEXAG goal to understand the dynamics and composition of Venus. Direct insertion and deployment into the winds at Venus' cloud tops would help to measure the dynamics of the deep atmosphere, accomplishing VEXAG Goals Objective, Investigation (GOI) II.A.DD. Additionally, flying in the clouds with sufficient mobility allows for investigating VEXAG GOI II.A.MP, mesoscale processes, and most of Goal II Objective B, to understand the atmospheric radiative balance, interactions between chemical species, cloud aerosols, the unknown absorber and volcanic gas input to the atmosphere. A vehicle capable of descending into the lower cloud deck could take near-IR images of the surface as well as altimetry to produce images with 10 times the sharpness of current orbital images. Therefore, an *in situ* cloud mission can provide the necessary data to investigate the possible hydrous origins of surface minerals as well as support the search for geologic evidence of crustal recycling, VEXAG GOI I.A.HO and I.A.RE respectively. The proposed system will also be able to address VEXAG Goal III, to understand Venus geologic history and surface/atmosphere interactions. A vehicle capable of imaging the surface in near-IR from deep within the clouds (or below them) could provide new imaging and spectral data for achieving II.A, Understanding the geologic processes that shaped the surface of Venus, and II.B How do the surface and atmosphere interact?. Near-IR imaging coupled with an altimeter would provide higher fidelity mapping of the surface emissivity, and hence aid in VEXAG GOI III.A.GH, III.A.GC, and III.A.GA, and III.A.4. These are investigations of Venus' geologic history, geochemistry, and geologic activity. Investigations III.B.LW, local weathering, and III.B.GW, global weathering would also benefit from vastly improved near-IR imagery of the surface.

3 Aerial Vehicles for Venus Exploration

In situ investigations of Venus' atmosphere and clouds have been considered a high scientific priority for several decades [20]. A diverse array of vehicle types have been proposed [21]; a brief overview of those platforms is provided here.

3.1 Descent Probes

Since 1965, 16 probes have entered Venus' atmosphere and descended to the surface [22]. These vertical snapshots of Venus' atmosphere have provided a consistent picture of zonal winds with altitude. Cloud structure, however, varied significantly in these descent profiles. While the globally averaged vertical structure of the clouds indicates 3 layers from 48 to 65 km, several Venera probes found a minimal or non-existent lower cloud between 48 and 51 km. The patchiness of the lower cloud was confirmed by Galileo NIMS near-IR spectral images of the clouds as it passed by Venus on the way to Jupiter [23].

3.2 Balloons

Largely due to the success of the Soviet Vega balloons, a number of US researchers have proposed balloons with scientific payloads to fly in Venus' clouds [24]. However, balloons suffer from a number of disadvantages with respect to scientific priorities for Venus that are considered the most essential. A survey of possible aerial platforms for Venus, the science that could be performed, and the technological challenges, was recently commissioned by NASA [21]. The *in situ* investigation of Venus' atmosphere and clouds can be facilitated in a number of ways scientifically, using fixed wing aircraft rather than balloons. The main differences, in order of priority, are: control of flight path for targeted investigations, greater controllable altitude range for *in situ* experiments, and unobstructed 4π steradian field of view for optical investigations.

The Vega balloons were at the mercy of prevailing winds, and so flew westward with the prevailing winds for about 2 days each. Although this was about 1/3 around the planet, there was no control over the flight path, and the balloons remained between 50 and 55 km. The ability to traverse in latitude and altitude is vital for *in situ* sampling of cloud aerosols and unknown atmospheric constituents. The upper cloud of Venus contains an unidentified substance that absorbs about half of all the sunlight that penetrates the clouds [25]. Its distribution within the Venus clouds is highly heterogeneous and ephemeral, although it is a primary driver of Venus' climate. *In situ* sampling of the upper clouds is most likely the only way that it will be identified, but it will be necessary to fly to specific locations in the Venus clouds to perform these measurements. A balloon payload to accomplish the same thing would depend mostly on a fortuitous path through the clouds. Control of the flight path is also essential for investigating the various dynamical phenomena that have been observed remotely at different latitudes and local times of day, in order to understand the local wind fields and how they contribute to Venus' atmospheric superrotation.

3.3 Aerobots

The extreme conditions of Venus' atmosphere has led some authors to propose vehicles that are hybrids of superpressure and zeropressure baloons [26]. A variety of phase change materials to adjust buoyancy over a wide range of pressures has also been suggested [21]. Variable altitude balloons are capable of exploring Venus' atmosphere from near the surface to the cloud tops, with some limited horizontal navigation. Additionally, although this provides greater ability to perform sampling across the desired altitude ranges, the transitions are relatively slow.

3.4 Rotorcraft

Multi-rotor solution for exploration of planetary bodies, which has received a significant amount of attention recently [27], provides the ability to combine atmospheric profiles with prolonged ground-based sampling. This solution is relatively compact, and comparatively easily to deploy. However, it must accommodate the limited power output of a light weight RTG by spending prolonged amounts of time on the ground charging a bank of batteries to be used during flight. This clearly is not an option for the exploration of Venus due to it's harsh lower-atmosphere. Additionally, the turbulent upper atmosphere may cause significant control issues for such a craft.

3.5 Fixed Wing Aircraft

To the knowledge of this group, only one heavier than air vehicle for the exploration of Venus has been proposed [28–31]. This vehicle exclusively makes use of a large wing surface area for providing solar power to an electric propulsion system. To solve the issue of not being able to operate for extended periods of time on the dark side of the planet, the authors proposed that it could be possible to fly faster than the wind speeds around the desired sampling altitudes between 40 and 60 km. While this may be possible to achieve, it does limit the sampling range of the aircraft, and relies heavily on the fact that the efficiency of the solar power system will not degrade during long flights through the atmosphere.

4 Persistent Exploration with Dynamic Soaring

4.1 Introduction

Autonomous soaring has been shown in both simulation and flight tests to increase the endurance of small UAS. Recent work has focused on the development of automatic control algorithms for harvesting energy from relatively static features such as thermals [32] or ridge lift [33]. These algorithms exploit the structure of updrafts to keep the aircraft within an area where it can gain energy, leaving the updraft to perform any secondary tasks, or when the updraft's potential has dissipated. Other efforts have focused on utilizing wind-field gradients to add energy to the aircraft [34–36]. That work generally considers short flight paths designed to benefit from the structure of the wind field, and links the flight paths to a set of sensing goals. Limited work has also focused on energy extraction from gusts [37]. This requires a reactive technique to make use of the short term effects of turbulence to impart small amounts of energy to the vehicle.

A significant body of work has been published regarding automated dynamic soaring with UAS [33, 38, 39]. Recently, the focus of this work has been on expanding the dynamic soaring paths to include a mission objective. Although some applications have focused on observation of static targets [40], there has been significant investigation into path-following toward a remote objective [39, 41, 42].

4.2 Energy Harvesting

Dynamic soaring is achieved by climbing into an increasing wind gradient and turning back to descend through it. Given a large enough gradient and appropriate control of the flight trajectory this method can be used to harvest energy from the atmosphere without the use of on-board propulsion. This makes the practice particularly interesting for application to the exploration of Venus, where strong shear layers occur around the desired altitudes and span a large portion of the planet.

4.3 Tools

A simulation environment was created using a candidate aircraft model and control algorithms to achieve trajectories required for dynamic soaring through tracking an inclined orbit. The controller allowed variations of the tilt angle of the orbit, the radius, and the speed of the aircraft. Although wind speed from Venus models show that aircraft of the desired scale will not be capable of station keeping, the concept of flying an inclined orbit is still possible when considered in the wind frame.

For these simulations the aircraft airspeed was set to be constant and the excess energy generated was logged. In reality this energy would only be of benefit if it is captured by system, either through the acceleration of the aircraft, or converted to electricity by an on-board turbine. However, the purpose of these simulations was to compare trajectories and demonstrate energy gain. For that reason a total instantaneous power is calculated based on what is needed to maintain airspeed. It is then integrated and combined with kinetic and potential energy of the aircraft to assess how much energy the trajectory is gaining or losing over time.

4.4 Coupling with Venus Atmospheric Dynamics Models

The simulated flights made use of several different sources for generation of atmospheric parameters. The most simple representation consisted of wind fields that were based on probe data, essentially modeling the wind regime at the cloud tops. More detailed atmospheric models were also considered such as the one from Baker [7], which adds a convection component.

Of greater interest is the use of Large Eddy Simulations (LES) [11] to generate atmospheric parameters. This model contains a significant amount of detail, based mainly on the results of attempting

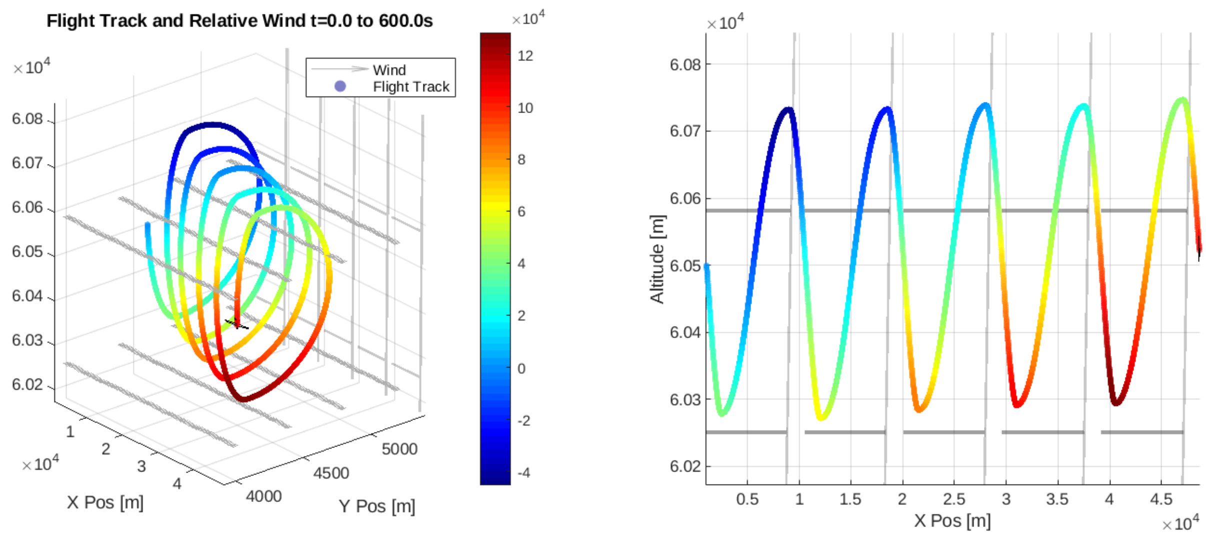

Figure 2: Results from a flight through the high fidelity model using the relative version of the dynamic soaring algorithm. The flight was conducted around 60 km in altitude over 600 seconds and shows relative energy gain as the color of the flight path.

to model the convective plumes (3 m/s) measured by the Vega balloons. These plumes occur mostly in the 46-55 km altitude range, where most of our flights are to occur. The LES provides a more accurate representation of the anticipated atmospheric conditions. Mesoscale models [43] and general circulation models (GCM) [44] can be employed to support planet-wide mission analysis. The flexibility of the flight simulation software also allows for the use of data from other GCMs, and the ingestion of data from empirical models such as Venus-GRAM, to be incorporated for future work.

4.5 Development Challenges and Risks

One of the largest risks for the system is the assumption that sufficient shear exists to maintain flight for the duration of the mission. Based on probe data and the latest GCM results, this seems to be a reasonable assumption, but further investigation is necessary. Alternative emergency propulsion methods could be considered, such as through an RTG or on-board battery that is charged using either an RTG, solar panels on the wings, or through a turbine that can be introduced into the stream during periods of strong energy gain by the aircraft.

Another risk is determining the location of the aircraft relative to the atmospheric structures it's using for energy harvesting. The possibility of including a small orbiter at one of the Lagrange points for localizing the aircraft has been considered. Additionally techniques are being tested to determine the wind field simply through analysis of on-board sensors.

Lastly, the aircraft will have to survive the Venus environment. Although the intended sampling mission will be performed in a regime that remains within operational pressure and temperature limits for materials and mechanisms commonly used on Earth, the corrosive environment presents a significant challenge. Work has begun to investigate survivability of various composites in this environment as well as the use of thin coatings for protection that could allow for more conventional building materials.

4.6 Demonstration of Feasibility

The aforementioned dynamic soaring algorithm was used to conduct several simulated flights through data generated from the latest WRF large eddy simulation that is part of the above GCM. Two sets of simulations were run, one at 55 km altitude and the other at around 60 km. 55 km was chosen as it is situated in the middle of the regime identified as scientifically significant. 60 km was chosen due to the large amount of vertical shear in the region. The plots in Figure 2 show the results from one 60 km flight.

Flights at both altitudes demonstrated a net energy gain. What is interesting to note about the results is that the average energy gathered per cycle

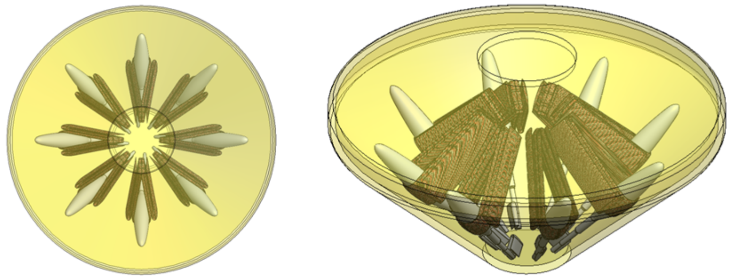

Figure 3: The Venus "Fly Trap" aeroshell configuration.

was larger at the 60km altitude, but the total energy gain in the system was larger for the flight at 55 km. Upon further examination, it became apparent that this was due to the presence of a positive vertical wind component through this part of the simulation.

Additionally, the simulated data were used to determine if anticipated downdrafts would result in the inability of the aircraft to maintain altitude to within a reasonable level. Examining the results from the LES at 59 km reveals that generally the magnitude of the vertical winds was around 3 m/s, making it small enough to have only a minor effect on total system energy.

Therefore, although greater understanding of the Venus atmosphere would improve the ability to predict the performance of the proposed craft, current data suggests it should be possible to achieve sustained flight as well as the ability to perform targeted sampling.

5 Payload and Mission Design

One of the main challenges for the mission is the design of the aircraft to fit within the vehicle designed to carry it into the upper atmosphere of Venus. It is assumed at this point that deployment will occur after slowing to sub-sonic speeds through aero-breaking and possibly the use of a parachute. Because of this assumption, the initial design for the vehicles has been for installation into a aeroshell. Figure 3 shows a candidate deployment setup in the aeroshell used by Pioneer Venus. This configuration fits the aircraft assuming that a mechanism can be found that will allow for the high aspect ratio wings to be folded and then deployed upon release. Several risk factors exist for this design as the aircraft will have to deal with relatively high g-loading during flight, and survive the corrosive environment.

Another challenge is wind field estimation for use in generation of energy harvesting flight paths. This will be made possible by combining vehicle *in situ* measurements with absolute location determined by tracking from Earth-based radio dishes and from spacecraft in the vicinity of Venus. Lagrange point orbiters, for example, would be ideal for relaying high bandwidth data from aircraft in the clouds.

The scientific demands of an *in situ* mission to Venus' clouds are broad. Payload mass is limited for any aerial platform. Extremely small (10 g) chemical sensors have been developed at Glenn Research Center, and miniaturized mass spectrometers have been developed at JPL that could fly on such a vehicle. Gas and aerosol handling in a highly corrosive environment is a crucial part of any *in situ* mission to the clouds of Venus, and will have to be developed for any future mission. In order to address the VEXAG Goals, Objective, and Investigations discussed in Section 2, optical instrument to measure sky flux, count aerosols, and determine their indices of refraction will also be needed. A notional and incomplete list of instruments that could obtain continuous data on the chemical and physical properties within Venus' clouds is shown in the table below.

Instrument	Mass	Power
P, T, accelerometer	50 g	100 mW
Solid state chemical sensors	10 g	100 mW
Net flux radiometer	2 kg	10 W
Downward looking camera	200 g	10 W
Polarizing nephelometer	2 kg	5 W
GCMS	5 kg	35 W
Tunable laser spectrometer	2 kg	20 W
Optical microscope	200 g	10 W
Imaging XRF spectrometer	5 kg	40 W
Fluorescence/biosignature	2 kg	10 W
Raman spectroscope	4 kg	35 W
Microwave altimeter	2 kg	50 W
EM Sounding	2 kg	5 W

6 Conclusions

The deeper mysteries of Venus' climate can only be solved by performing *in situ* investigations in Venus' clouds. Balloons, descent probes, fixed-wing aircraft, aerobots, and rotorcraft have all been proposed to achieve some of the VEXAG scientific objectives. To date, only the 2 Vega balloons and 16 entry probes have returned data from Venus. The chances for scientific success increase if the aerial vehicle has longevity, can fly at night, and is capable of navigating to interesting regions of the Venus atmosphere.

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References

[1] Oyama, V. et al. *Journal of Geophysical Research: Space Physics* **85,** 7891–7902 (1980). [2] Mills, F. P. et al. (2007). [3] Krasnopolsky, V. A. *Icarus* **299,** 294–299 (2018). [4] McGouldrick, K. et al. *Icarus* **286,** 118–133 (2017). [5] Tellmann, S. et al. *Journal of Geophysical Research: Planets* **114** (2009). [6] Sánchez-Lavega, A. et al. *Geophysical Research Letters* **35** (2008). [7] Baker, R. D. et al. *Journal of the atmospheric sciences* **55,** 3–18 (1998). [8] Ainsworth, J. et al. *Journal of Geophysical Research* **80,** 173–179 (1975). [9] Schubert, G. et al. *Journal of Geophysical Research: Space Physics* **85,** 8007–8025 (1980). [10] Fedorova, A. et al. *Icarus* **275,** 143–162 (2016). [11] Lefèvre, M. et al. *Journal of Geophysical Research: Planets* **123,** 2773–2789 (2018). [12] Hueso, R. et al. *Icarus* **217,** 585–598 (2012). [13] Marwitz, J. D. *Journal of Applied Meteorology* **11,** 166–179 (1971). [14] Jensen, E. J. et al. *Journal of Geophysical Research: Atmospheres* **101,** 21361–21375 (1996). [15] Eckermann, S. D. et al. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography* **133,** 1959–1975 (2007). [16] Cione, J. et al. *Earth and Space Science* **3,** 370–380 (2016). [17] Bryan, G. et al. *Unique Observations in Hurricane Maria (2017) using the Coyote Uncrewed Aircraft System (UAS)* in *AGU Fall Meeting Abstracts* (2017). [18] Lee, Y. J. et al. *The Astronomical Journal* **158,** 126 (2019). [19] Peralta, J. et al. *The Astrophysical Journal Supplement Series* **239,** 29 (2018). [20] Herrick, R. et al. *VEXAG, Goals, Objective, and Investigations for Venus Exploration* tech. rep. (NASA, 2014). [21] Cutts, J. A. et al. *Aerial Platforms for the Scientific Exploration of Venus* tech. rep. (Venus Aerial Platforms Study Team, 2018). [22] Bullock, M. A. et al. *Comparative Climatology of Terrestrial Planets* **1,** 19–54 (2013). [23] Carlson, R. o. et al. *Science* **253,** 1541–1548 (1991). [24] Baines, K. H. et al. (2005). [25] Esposito, L. W. *Journal of Geophysical Research: Space Physics* **85,** 8151–8157 (1980). [26] Rabinovitch, J. et al. *Aerobots to Explore Venusian Clouds* in *Venera-D Landing Sites Selection and Cloud Layer Habitabiliy Workshop* (Moscow, Russia, 2019). [27] Lorenz, R. D. et al. *John Hopkins APL Technical Digest, PRE-PUBLICATION DRAFT, www. jhuapl. edu/techdigest* (2017). [28] Landis, G. A. *Exploring Venus by solar airplane* in *AIP Conference Proceedings* **552** (2001), 16–18. [29] Landis, G. et al. *Atmospheric flight on Venus* in *40th AIAA Aerospace Sciences Meeting & Exhibit* (2002), 819. [30] Landis, G. A. et al. *Journal of Spacecraft and Rockets* **40,** 672–677 (2003). [31] Ashish, K. et al. *Flight analysis of a Venus atmospheric mobile platform* in *Aerospace Conference, 2014 IEEE* (2014), 1–14. [32] Andersson, K. et al. *Cooperating UAVs Using Thermal Lift to Extend Endurance* in *AIAA Infotech@Aerospace Conference* (Seattle, WA, Apr. 2009). [33] Sachs, G. et al. *Optimization of dynamic soaring at ridges* in *AIAA Atmospheric Flight Mechanics Conference and Exhibit, Austin, Texas* (2003), 11–14. [34] Sachs, G. *Ibis* **147,** 1–10 (2005). [35] Lissaman, P. *AIAA paper* **241** (2005). [36] Richardson, P. L. *Progress in Oceanography* **88,** 46–58 (2011). [37] Langelaan, J. W. et al. *Journal of Guidance, Control, and Dynamics* **34,** 1016–1030 (2011). [38] Chakrabarty, A. et al. *Journal of Guidance, Control, and Dynamics* **34,** 1002–1015 (2011). [39] Ariff, O. et al. *Journal of Navigation* **64,** 29–44 (2011). [40] Gao, C. et al. *Dynamic soaring surveillance in a gradient wind field* in (American Institute of Aeronautics and Astronautics, Aug. 2013). [41] Richardson, P. L. (2012). [42] Depenbusch, N. et al. *Receding Horizon Control for Atmospheric Energy Harvesting by Small UAVs* in *AIAA Guidance, Navigation, and Control Conference* (Toronto, ON, Aug. 2010). [43] Lefèvre, M. et al. *Icarus* **335,** 113376 (2020). [44] Lebonnois, S. et al. *Icarus* **278,** 38–51 (2016).